Hydrological extremes

**droughts**

**floods**
Impacts of floods

- Recent events in CH and Europe
  - Sardinia, Italy, Nov. 2013
  - Central Europe, 2013
  - Genoa and Liguria, Italy, 2011, 2014
  - Central Switzerland, 2007, 2005
  - Tessin, 2014

---

**Table: Impacts of Floods**

<table>
<thead>
<tr>
<th>Date</th>
<th>Area</th>
<th>Deaths</th>
<th>Damages</th>
<th>Claims</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/5-6/6/1992</td>
<td>Iran (17 Provinces)</td>
<td>63</td>
<td>3600</td>
<td>n.a.</td>
</tr>
<tr>
<td>29/6-9/7/1992</td>
<td>China (Fujan, Huanan)</td>
<td>324</td>
<td>232</td>
<td>n.a.</td>
</tr>
<tr>
<td>8/9-21/10/1992</td>
<td>Pakistan (Punjab)</td>
<td>1500</td>
<td>1000</td>
<td>n.a.</td>
</tr>
<tr>
<td>22-28/9/1992</td>
<td>Italy (Liguria)</td>
<td>4</td>
<td>175</td>
<td>n.a.</td>
</tr>
<tr>
<td>22-23/9/1992</td>
<td>France (Vaison la Roman)</td>
<td>42</td>
<td>260</td>
<td>n.a.</td>
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<tr>
<td>31/10-2/11/1992</td>
<td>Italy (Tuscany, Rome, Sicily)</td>
<td>3</td>
<td>712</td>
<td>n.a.</td>
</tr>
<tr>
<td>10-13/12/1992</td>
<td>USA</td>
<td>18</td>
<td>2000</td>
<td>850</td>
</tr>
<tr>
<td>28/3-3/4/1993</td>
<td>Ecuador</td>
<td>300</td>
<td>590</td>
<td>15</td>
</tr>
<tr>
<td>27/6-15/8/1993</td>
<td>USA (Mississippi/Missouri)</td>
<td>41</td>
<td>16000</td>
<td>1000</td>
</tr>
<tr>
<td>8-31/7/1993</td>
<td>India</td>
<td>953</td>
<td>7000</td>
<td>n.a.</td>
</tr>
<tr>
<td>19-31/7/1993</td>
<td>Nepal</td>
<td>1048</td>
<td>200</td>
<td>n.a.</td>
</tr>
<tr>
<td>23-25/9/1993</td>
<td>Switzerland (Brig)</td>
<td>2</td>
<td>400</td>
<td>n.a.</td>
</tr>
<tr>
<td>20-31/12/1993</td>
<td>Europe (Benelux, Germany, Great Britain)</td>
<td>14</td>
<td>1180</td>
<td>810</td>
</tr>
<tr>
<td>1/5-30/6/1994</td>
<td>China</td>
<td>1410</td>
<td>6000</td>
<td>n.a.</td>
</tr>
<tr>
<td>1-30/9/1994</td>
<td>Vietnam (Mekong delta)</td>
<td>300</td>
<td>135</td>
<td>n.a.</td>
</tr>
<tr>
<td>16-21/10/1994</td>
<td>USA (Texas)</td>
<td>20</td>
<td>700</td>
<td>175</td>
</tr>
<tr>
<td>2-6/11/1994</td>
<td>Egypt (Assiut, Sohag, Quena, Luxor, Sinai)</td>
<td>580</td>
<td>140</td>
<td>n.a.</td>
</tr>
<tr>
<td>4-6/11/1994</td>
<td>Italy (Po valley)</td>
<td>64</td>
<td>12500</td>
<td>65</td>
</tr>
<tr>
<td>19/1-5/2/1995</td>
<td>Europe (Benelux, Germany, France)</td>
<td>28</td>
<td>3500</td>
<td>750</td>
</tr>
<tr>
<td>24/7-18/8/1995</td>
<td>North Korea</td>
<td>68</td>
<td>15000</td>
<td>n.a.</td>
</tr>
<tr>
<td>5-12/9/1995</td>
<td>India</td>
<td>400</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>4-7/9/1995</td>
<td>Caribbean area (Anigues, Barbuda, Anguilla, Puerto Rico)</td>
<td>15</td>
<td>2500</td>
<td>n.a.</td>
</tr>
<tr>
<td>4-5/10/1995</td>
<td>USA and Mexico</td>
<td>28</td>
<td>3000</td>
<td>2100</td>
</tr>
<tr>
<td>28-29/10/1995</td>
<td>Thailand (Bangkok)</td>
<td>200</td>
<td>400</td>
<td>n.a.</td>
</tr>
<tr>
<td>6-15/2/1996</td>
<td>South Africa (Kwazulu-Natal, Johannesburg)</td>
<td>42</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>14-16/6/1996</td>
<td>Yemen</td>
<td>338</td>
<td>1200</td>
<td>n.a.</td>
</tr>
<tr>
<td>19/6/1996</td>
<td>Italy (Versilia)</td>
<td>13</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>1996</td>
<td>Spain (Southern Spain)</td>
<td>25</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>27/6-13/8/1996</td>
<td>China</td>
<td>2700</td>
<td>26500</td>
<td>386</td>
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<tr>
<td>18-26/7/1996</td>
<td>Canada</td>
<td>10</td>
<td>725</td>
<td>145</td>
</tr>
<tr>
<td>26-31/7/1996</td>
<td>North and South Korea</td>
<td>67</td>
<td>1700</td>
<td>n.a.</td>
</tr>
</tbody>
</table>
## Design values for flood protection/mitigation

<table>
<thead>
<tr>
<th>Object categories</th>
<th>Q₁</th>
<th>Q₁₀</th>
<th>Q₂₀</th>
<th>Q₅₀</th>
<th>Q₁₀₀</th>
<th>EFQ</th>
<th>PMF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature landscapes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-intensity farming areas</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-intensity farming areas</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single buildings; local infrastructure facilities</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure facilities of national importance</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed settlements; industrial facilities</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td>Qₐ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special objects; special risks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- **Full protection**
- **Limited protection**
- **No protection**

**Key:**
- Qₐ: Damage limit
- Qₐ: Hazard limit
- FQₐ: Annual flood
- FQ₁₀₀: Flooding occurring only once every 100 years (100-year flood)
- EFQ: Flooding occurring for extreme in hydrological and meteorological situations
- PMF: Probable maximum flood

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Federal Office for Water and Geology: Flood Control at Rivers and Streams. Guidelines of the FOWG, 2001 (72p.)

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Hydrology – Flood Estimation Methods – Autumn Semester 2017
Flood estimation methods (Flood Frequency Analysis)

Lecture content

- problem formulation
- hydrological models specific to flood frequency analysis
- deterministic methods
- probabilistic methods
  - direct at site
  - statistical regionalisation
  - indirect methods
- practice in Switzerland

Objective: to learn how to estimate a design flood, $Q_p(R)$

Skript: Ch. VII.12 → 16.2, VII.17
Coping with floods require to investigate four main questions:

- How frequently a flood of a given magnitude (i.e. a flood characterised by a return period $R$) occurs
- How high is the water level in the river for a flood of given magnitude
- Does the river overflow the levees and what is the extent of the inundated areas
- What are the best prevention and mitigation measures

→ Hydrology, flood estimation methods (flood frequency analysis)
→ Hydraulics, 1D / 2D unsteady flow propagation models
→ Hydraulics, 2D unsteady flow propagation models
→ Structural and non-structural measures, civil protection plans
Flood estimation methods – problem formulation (example)

• the bridge needs to be **designed** to withstand a water level corresponding to a **100 year return period flood**

\[ Q_{100} \]

• by means of **Flood Frequency Analysis (FFA)** we can estimate \( Q_{100} \) to feed a 1D steady flow hydraulic model

estimating the discharge for a given return period is one of the most frequent design problems in hydrology
Flood hazard probability - definitions

- $Q_p = \text{peak discharge}$

- **Hazard** = probability of occurrence, within a specific period of time in a given area, of a potentially damaging flow $\rightarrow 1 - F_{Q_p}$, where $F_{Q_p}$ is the non-exceedence probability.

- **Vulnerability** = degree of damage in probability terms inflicted on a structure by a natural phenomenon of a given magnitude.

- **Risk** = Hazard $\times$ Vulnerability $\times$ Potential Loss $\rightarrow \text{it includes explicit assessment of the “system”, i.e. river, protection system, goods and infrastructures at risk of damage}$

- $L = \text{time horizon for hazard/risk assessment}$

**HAZARD ABSOLUTE PROBABILITY**

$\Pr[Q_p > q(R)] \leftrightarrow Q_p(R)$

**HYDRAULIC RISK**

$\Pr[\text{system failure in } L \text{ years}]$

**HAZARD RELATIVE PROBABILITY**

$\Pr[Q_p > q(R) \text{ at least once in } L \text{ years}]$

**HYDROLOGIC “RISK”**

*absolute “risk”*:

$$R = \frac{1}{\Pr[Q_p > q]} = \frac{1}{1 - F_{Q_p}}$$

*relative “risk”*

$$r = 1 - \left[\frac{1}{1 - R}\right]^L = \left[1 - F_{Q_p}\right]^L$$
## Relative “risk”

### absolute “risk”:

### relative “risk”

<table>
<thead>
<tr>
<th>$F_{Qp}$</th>
<th>$R$</th>
<th>$L$</th>
<th>$r$</th>
<th>$F_{Qp}$</th>
<th>$R$</th>
<th>$L$</th>
<th>$r$</th>
</tr>
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<tbody>
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<td>10</td>
<td>5</td>
<td>41%</td>
<td>0.98</td>
<td>50</td>
<td>5</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>65%</td>
<td></td>
<td>10</td>
<td>18%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>10%</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>20</td>
<td>64%</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>99%</td>
<td></td>
<td>100</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td>0.995</td>
<td>200</td>
<td>5</td>
<td>2%</td>
<td></td>
<td>10</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>5%</td>
<td></td>
<td>20</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>22%</td>
<td></td>
<td>50</td>
<td>22%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>39%</td>
<td></td>
<td>100</td>
<td>39%</td>
<td></td>
</tr>
</tbody>
</table>

Hydrology – Flood Estimation Methods – Autumn Semester 2017
Flood estimation methods – overview (1)

Deterministic methods

- based on
  - local analysis of empirical historical evidence
    - envelope curves
    - empirical equations
  - concept of probable maximum precipitation (PMP)
    → probable maximum flood (PMF)

\[ Q_p = c \cdot A^b \]

WMO publ. 1045 on PMP
Flood estimation methods – overview (2)

Probabilistic methods

- **direct** → statistical analysis at site

- **indirect**
  - derived distribution techniques
  - statistical regionalisation
  - rainfall-runoff simulations

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Hydrology – Flood Estimation Methods – Autumn Semester 2017
Flood estimation methods are suitable for ranges of space and time scales depending on their characteristics:

- **direct at-site statistical methods** \(\rightarrow\) length of data record
- **statistical regionalisation** \(\rightarrow\) broad range of scales
- **indirect R-R methods** \(\rightarrow\) from small to very large scales depending on model complexity and rainfall input

\(\rightarrow\) SEE SLIDES SPECIFIC TO EACH METHOD
Deterministic methods
Deterministic methods (1/3)

• PROBABLE MAXIMUM FLOOD

ishlist reference concept for other methods (e.g. envelop curve)

ishlist greatest flood to be expected assuming concurrent occurrence of those factors that lead to maximum rainfall (probable maximum precipitation, PMP) and to favourable conditions to generation of maximum flood discharge → simultaneous max rainfall and max soil moisture

ishlist PMP = “greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year”

ishlist based on atmospheric physics theoretical considerations for the maximisation of local storm rainfall

→ see WMO, “Manual on Estimation of Probable Maximum Precipitation (PMP)”, publ. 1045

PROS

• established procedure

• (in the past) widely used for design of safety organs of large dams

CONS

• controversial concept

• contradictory concept: probable ↔ maximum

• high uncertainty associated with methods to estimate PMP

• NO FREQUENCY CHARACTERISATION
  (i.e. no R associated with the estimate)
Deterministic methods (2/3)

ENVELOPE CURVE

concept similar to that of PMF, but based on observed floods in a region

- greatest observed floods in a region are
  - normalized with respect to the basin area
  → specific discharge → \( q = \frac{Q_p}{A} \)
  - and plotted against the basin area

- a curve is drawn, which envelopes all the observed specific discharges

- the typical equation for envelope curves is
  \[
  q = \hat{q} + b \cdot A^{-\nu}
  \]

where \( \hat{q}, b, \) and \( \nu \) are empirical parameters

REMARKS

- the curve does not provide a frequency characterisation for the predicted \( q \)

- the observed values used to build the curve (may) have different return periods
  → estimates obtained from the envelope curve are not characterised by homogeneous return periods
Deterministic methods (3/3)

EMPIRICAL EQUATIONS

• concept similar to that of the envelope curve, based on a broad sample of large observed floods in a region

• they typically provide the value of the “largest flood” without a frequency characterisation

• \( Q_p \) is expressed typically as a function of basin area \( \rightarrow \) typical forms of the equations are

\[
Q_p = \frac{c}{A+b} \cdot d \quad \text{or} \quad Q_p = a \cdot A^b
\]

where \( A \) is the basin area and \( a, b, c \) and \( d \) are empirical parameters

examples of emp. eq. used in CH

• Kürsteiner (1917) \( \rightarrow \) \( Q_{\text{max}} = c \cdot A^{2/3} \) where \( A \) is the basin area, \( c \) a coefficient specific for the basin and \( Q_{\text{max}} \) in \([\text{m}^3/\text{s}]\) and \( A \) in \([\text{km}^2]\)

• Müller-Zeller (1943) \( \rightarrow \) \( Q_{\text{max}} = \alpha \cdot \psi \cdot A^{2/3} \) where \( A \) is the basin area, \( \alpha \) is a zonal coefficient, \( \psi \) is the runoff coefficient, \( Q_{\text{max}} \) in \([\text{m}^3/\text{s}]\), and \( A \) in \([\text{km}^2]\)

\[ \alpha = 20 \div 50 \]
Probabilistic methods

a) direct at site
Probabilistic methods – at site analysis (1/6)

two type of analysis based on

- **ANNUAL FLOOD SERIES (AFS)**, i.e. *based on the time series of the maximum values of the peak flows observed in each year*.

- **PEAK OVER THRESHOLD SERIES (POT)**, i.e. *based on the time series of the values of the peak flows observed in each year, which exceed a pre-defined threshold, $Q^*$*. 

![Diagram of annual peak flows](image-url)

- **annual peak flow**
- **peaks over a threshold**

$Q(t)$

$Q^*$

$t_1$, $t_2$, $t_3$, $t_4$

$T = 1$ year
Probabilistic methods – at site analysis (2/6)

ANNUAL FLOOD SERIES based estimation

- The observed annual maxima are treated as discrete random variable, $Q_i$, extracted from a continuous process
  - $Q_i = \max\{Q(t), (i-1)T \leq t \leq T\}$

- The AFS series is used to fit a theoretical (or empirical) probability distribution

  e.g.
  - EV1 or Gumbel distr. $\rightarrow F_Q(q) = e^{-(q-u)/\alpha}$
  - EV2 or Frechet distr. $\rightarrow F_Q(q) = e^{-(q_0/q)^\beta}$
  - GEV (General Extreme Value) $\rightarrow F_Q(q) = e^{-[1-k(q-u)/\alpha]^{1/k}}$

For a selected return period $R$ the peak flow can be estimated by substituting $F_Q = R - 1/R$ and then computing $Q$ by solving the CDF equation for $Q$

- e.g. EV1 $\rightarrow Q(R) = u - \alpha \cdot \ln\left(\ln\left(\frac{R}{R-1}\right)\right)$
Probabilistic methods – at site analysis (3/6)

PEAK OVER THRESHOLD based estimation

Hypotheses

- the observed peak o.t. flows are assumed to be characterised by the same probability distribution

\[ f_Z(Z_{t_1}) = f_Z(Z_{t_2}) = \ldots = f_Z(Z_{t_n}) \]

- the number of exceedances \( N(0, t) \) follows a Poisson distribution

\[ \Pr[N(0,t) = n] = \lambda^n t^n e^{-\lambda t} / n! \]

- for \( t = T = 1 \) year \( \Lambda = \lambda T \) = average number of exceedances per year

- the annual maximum is \( Q_p = \max\{Z_{t_i} : 1 \leq i \leq N[0,t]\} \)

\[ F_{Q_p}(q) = \Pr[Q_p \leq q] = e^{-\Lambda[1-F_Z(q)]} \]

where \( F_Z(\cdot) \) is the CDF of the exceedances

characterising \( F_Z(\cdot) \) and \( \lambda \) specifies entirely the CDF of the annual maxima
Probabilistic methods – at site analysis (4/6)

AFS ESTIMATION SUITABLE DISTRIBUTIONS

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Domain</th>
<th>Mean $\mu_x$</th>
<th>Variance $\sigma_x^2$</th>
<th>Skewness $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lognormal 2 par.</td>
<td>$(0, \infty)$</td>
<td>$\mu + \sigma^2/2$</td>
<td>$\mu (e^{\sigma^2} - 1)$</td>
<td>$(e^{\sigma^2} - 1)^{1/2} (e^{\sigma^2} + 2)$</td>
</tr>
<tr>
<td>$z = \ln x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f(x) = \frac{1}{x \sigma_z \sqrt{2\pi}} e^{-\frac{1}{2}(\ln x - \mu_z)^2}$</td>
<td></td>
<td>$\mu$</td>
<td>$\sigma^2_z$</td>
<td></td>
</tr>
<tr>
<td>Exponential</td>
<td>$(x_0, \infty)$</td>
<td>$x_0 + \beta$</td>
<td>$\beta^2$</td>
<td>2</td>
</tr>
<tr>
<td>$f(x) = 1 - e^{-(x-x_0)/\beta}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gumbel</td>
<td>$(-\infty, \infty)$</td>
<td>$b + \frac{0.5772}{a}$</td>
<td>$\frac{\pi^2}{6a^2}$</td>
<td>1.3</td>
</tr>
<tr>
<td>$F_x(x) = e^{-e^{-(x-u)/a}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Extreme Value</td>
<td>$(-\infty, \infty)$</td>
<td>$f(k)$</td>
<td>$f(k)$</td>
<td>$f(k)$</td>
</tr>
<tr>
<td>$F_x(x) = e^{-[1-k(x-u)/a]^m}$</td>
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</tr>
<tr>
<td>Pearson Type III</td>
<td>...</td>
<td>...</td>
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</tr>
<tr>
<td>Log Pearson Type III</td>
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</tbody>
</table>
Probabilistic methods – at site analysis (5/6)

POT ESTIMATION SUITABLE DISTRIBUTIONS

<table>
<thead>
<tr>
<th>CDF of the exceedances</th>
<th>CDF of annual maxima</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exponential</strong></td>
<td><strong>Gumbel (EV1)</strong></td>
</tr>
<tr>
<td>$F_Z = 1 - e^{\frac{x-q_0}{\vartheta}}$</td>
<td>$x \geq q_0$</td>
</tr>
<tr>
<td>$F_X = e^{-\Lambda e^{\frac{x-q_0}{\vartheta}}}$</td>
<td></td>
</tr>
<tr>
<td><strong>Pareto</strong></td>
<td><strong>Frechet (EV2)</strong></td>
</tr>
<tr>
<td>$F_Z = 1 - \left(\frac{q_0}{x}\right)^{1/k}$</td>
<td>$x \geq q_0$</td>
</tr>
<tr>
<td>$F_X = e^{-\Lambda \left(\frac{q_0}{x}\right)^{1/k}}$</td>
<td></td>
</tr>
<tr>
<td><strong>Generalized Pareto</strong></td>
<td><strong>General Extreme Value</strong></td>
</tr>
<tr>
<td>$F_Z = 1 - \left[1 - \frac{k}{\beta}(x - c)\right]^{1/k}$</td>
<td></td>
</tr>
<tr>
<td>$F_X = e^{-\left[1 - \frac{k}{\alpha_0}(x - \varepsilon_0)^{-1/k}\right]}$</td>
<td></td>
</tr>
</tbody>
</table>
REMARKS

- the parameters of the distributions are estimated by means of the usual methods (method of moments, least squares, maximum likelihood, ...)

- the extrapolation of the estimates for high return periods should be consistent with the numerosity of the data record (e.g. max $R \leq 2N$, with $N =$ record length)

- the POT method is best suitable
  - for shorter observational records (to extend the number of observations)
  - for highly variable basin flood response (to avoid missing secondary peak flows that are higher than some of the annual maxima)

- flood frequency distributions should always be plot together with their confidence interval (see statistics books)
Probabilistic methods
b) statistical regionalisation
Statistical regionalisation

- replaces at-site direct analysis for **ungauged sites** and/or for sites with short observational records
- can be used to extend at site analysis to higher return periods
- it is based on the concept that **basins with similar characteristics have similar flood response** ➔ HOMOGENEOUS REGION

\[
\begin{align*}
Q_{p_1}, A_1, & \quad \text{respectively AFS and drained areas of the i-th hydrometric stations in the homogeneous region} \\
Q_{p_x}, A_x, & \quad \text{peak flow and drained areas of the station for which } Q_p(R) \text{ is to be computed} \\
N_i, & \quad \text{record length at each station } i
\end{align*}
\]

**REQUIRED DATA**

- **AFS from flow gauging stations of a homogeneous region**
- hydrologic, thematic or statistical information to quantify the homogeneity of a set of basins
Statistical regionalisation – Index Flood method (1/3)

Procedure to compute the peak flow of an ungauged basin of area A for a return period R

A) Homogenous region

① identify a homogenous region for which AFS data are available

② estimate for each AFS its index flood, \( Q_i \)
  \[
  \text{e.g. mean of the population} \rightarrow \text{mean of the AFS} \rightarrow \hat{Q}_i \approx Q_i
  \]

③ find a suitable relationship between the estimated index floods and some basin characteristics
  \[
  Q_i = f(A_i)
  \]
Statistical regionalisation – Index Flood method (2/3)

B) AFS analysis and computation of $Q_{px}(R^*)$

1. **transform** each AFS to a dimensionless series by dividing each AFS value by the index flood

2. **pool** the dimensionless AFS to obtain a dimensionless data set of size $N = N_1 + N_2 + \ldots + N_m$ where $N_i$ is the numerosity of each of the $m$ AFS available in the homogeneous region

3. **fit a suitable probability distribution to the dimensionless AFS** → dimensionless flood growth curve

4. For a given return period $R^*$, **compute** from the dimensionless growth curve the value $Q^* = Q_{pi}/Q_i$

5. From the relationship $Q_i = f(A_i)$ **compute** for $A_x$ the index flood for the ungauged site $X$, $Q_{ix}$

6. **multiply the dimensionless value** $Q^*$ by $Q_i$ of the ungauged site to obtain $Q_{px}(R^*)$
Statistical regionalisation – Index Flood method (3/3)

REMARKS

• Estimation of the index flood
  – the most frequent assumption is that the index flood corresponds to the mean of the population of the observed AFS → a reasonable estimator is the mean of the observed AFS data
  – the relationships to estimate the index flood from watershed characteristics can use any of the climatological and morphological watershed features (e.g. area, slope, average permeability, max daily precipitation, etc.) → the scaling of the index flood with the watershed area is most frequently used → \( Q_i \propto A_i^m \)
  – \( Q_i \) can be alternatively expressed as function of the POT series underlying the dimensionless growth curve

\[
Q_i = \frac{m_{Q_{POT}}}{\varepsilon + \frac{\alpha}{k} \left(1 - \Lambda^k\right) \left(1 + k\right) + \frac{\alpha \Lambda^k}{1 + k}}
\]

where the POT series is Generalized Pareto Distributed, the resulting AFS distribution is GEV, \( m_{Q_{POT}} \) is the mean of the POT series, \( \alpha, k \) and \( \varepsilon \) are the GEV parameters and \( \Lambda \) is the mean number of exceedences per year

• Evaluation of the homogeneity of the region
  – often based on quantitative analysis of basin characteristics or AFS statistics, without rigorous testing
  – tests exist, which provide a quantitative measure of the homogeneity
    – generally based on some statistics (e.g. CV, statistical moments, ...)
    – strong dependence on the numerosity of the sample
Probabilistic methods

c) indirect R-R methods
Flood estimation methods based on R-R modelling

- R-R models can be used to estimate flood peaks for a given return period
- $R$ of $Q_p$ is the same as the rainfall input if the R-R model is linear
- Flood estimation based on R-R models is denoted as **DESIGN FLOOD APPROACH**

### REMARKS
- FEM based on R-R methods provides also **flood volume** and **duration**
- Useful for design of protection systems
Simplified R-R model for flood estimation – Rational Method (1/3)

Concept

- Peak flow for a given return period, $R$, is **linearly proportional to**
  - a **coefficient**, $c$, which accounts for
    - spatial distribution of rainfall
    - infiltration properties across the basin
    - the network response
  - the **watershed area**, $A$
  - the (constant) **rainfall intensity**, $i$, computed from the IDF for a return period $R$ and a duration $t_c$, which is specific to the watershed

**RATIONAL METHOD**

$$Q_R = c \cdot i \cdot A$$

Use

- **small basins** ($\leq 50 \div 100 \text{ km}^2$), **highly homogeneous**
- **low return periods**, $R \leq 50$ years
Simplified R-R model for flood estimation – Rational Method (2/3)

General parameter dependence on process and basin characteristics

• \( i = i(R, t_c) \) and \( i = H(R, t_c)/t_c \)

• \( c = k \cdot \phi \cdot \psi \), with
  - \( k \), parameter accounting for the spatial distribution of rainfall
  - \( \phi \) parameter accounting for infiltration across the basin
  - \( \psi \) accounting for the network response

and, in turn

• \( k = k(\Omega_t, t_c) \) with
  - \( \Omega_t \), parameters characterising the space-time rainfall patterns
  - \( t_c \), watershed characteristic time

• \( \phi = \phi(\Theta_t, t_c, i) \) with
  - \( \Theta_t \), parameters characterising the watershed infiltration capacity

• \( \psi = \psi(\Xi_t, t_c, i) \) with
  - \( \Xi_t \), parameters characterising the network structure and response → linear model → \( \psi = \psi(\Xi_t, t_c) \)
Simplified R-R model for flood estimation – Rational Method (3/3)

**Simplified parameterisation**

\[ Q_R = k(\Theta_r, t_c) \cdot \phi(\Theta_r, t_c, i) \cdot \psi(\Xi_r, t_c) \cdot A \cdot H / t_c \quad \Rightarrow \quad Q_R = \phi \cdot \psi(\Xi_r, t_c) \cdot A \cdot H / t_c \]

- neglected, \( k=1 \)
- lumped value, independent from \( t_c \) and \( i \)
- dependent on the underlying linear model

- with \( \phi \) estimated from tables, literature, joint records of event rainfall and runoff
- \( t_c \) estimated as the critical time leading to the max \( Q \) for the return period \( R \)

**Kinematic transfer (linear channel)**

\[ \psi(\Xi_r, t_c) = A(t)/A \quad \text{with} \ A(t) \text{ area drained up to time} \ t \quad \text{and} \ A= \text{watershed area} \]

\[ \Rightarrow \max Q_R \text{ reached for} \ t_c=\text{time of concentration, when with} \ A(t)/A=1 \]

\[ \max Q_R = \phi \cdot 1 \cdot A \cdot H / t_c \]

**Linear reservoir**

\[ \psi(\Xi_r, t_c) = 1 - \exp(-t_c/K) \quad \text{with} \ K = \text{linear reservoir storage constant} \]

\[ \Rightarrow \max Q_R \text{ reached for} \]

\[ \max Q_R = \max \{ \phi \cdot A \cdot (H / t_c) \cdot [1-\exp(-t_c/K)] \} \quad \Rightarrow \frac{dQ_R}{dt} \quad \Rightarrow \ t_c, \text{ which maximizes} \ Q_R \]
Practice in Switzerland
Practice of flood estimation in Switzerland

• No prescribed method at the federal and cantonal level
• Some Cantons issued guidelines
• The Confederation issued in 2003 a comprehensive guideline
• Consolidated habits generally dictate preference for a specific method among
  • statistical methods (direct, regionalisation)
  • lumped R-R models
  • empirical formulas
depending on design target

BAFU guideline

- Flow chart to decide among
  - statistical methods
  - lumped R-R models
  - regional methods

- Decision tree based on flow and rainfall data availability