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swarm

Co-funded by the Erasmus+ Programme of the European Union

Water Resources Modelling: Part2 - Reservoir operation

Evaluation of water availability and reservoir design

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Strengthening of master curricula in water resources management for the Western Balkans HEIs and stakeholders

Project number: 597888-EPP-1-2018-1-RS-EPPKA2-CBHE-JP

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Flow duration curves and empirical distribution curves

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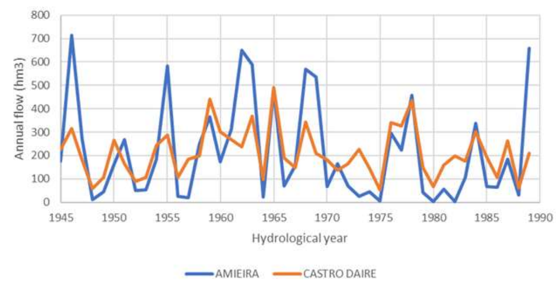
Four streamflow records

Hydrometric station	Watershed area (km2)	Average anual flow (dam3)	Runnof (mm)
CASTRO DAIRE (08J/01H)	288.17	211160	737
CUNHAS (04J/04H)	337.28	300041	890
PONTE MUCELA (12H/03H)	662.7	434818	656
QUINTA DAS LARANJEIRAS (06O/03H)	3487.49	939544	269
VIDIGAL (30F/02H)	18.57	4175	224



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Stream flow characterization: Magnitude

Hydrometric station	Watershed area (km2)	Average anual flow (dam3)	Runnof (mm)
CASTRO DAIRE (08J/01H)	288.17	211160	737
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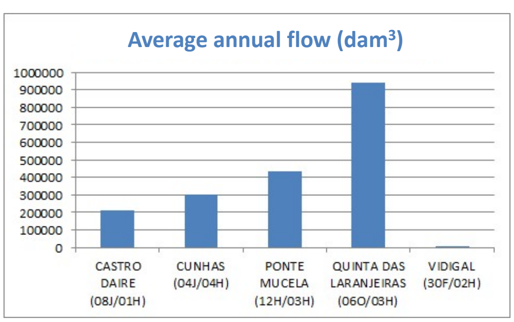

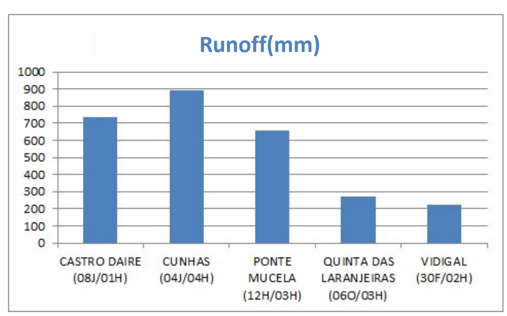

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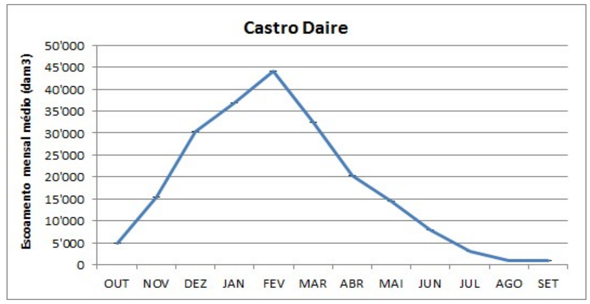
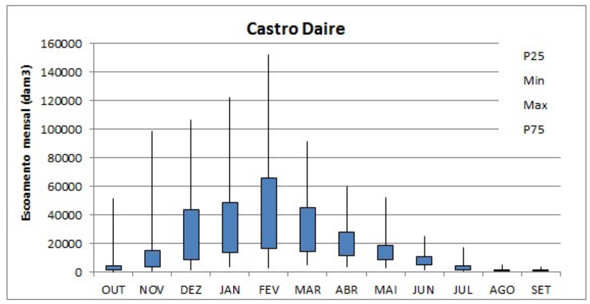
Stream flow characterization: Seasonality and flow variation

The graph of the average monthly flow shows us the magnitude of monthly flow and its seasonality



Box-Whiskers of montlhy flow shows us the flow variability around the average of mean or median.



Both these graphs do not provide any information on intra-monthy variability.

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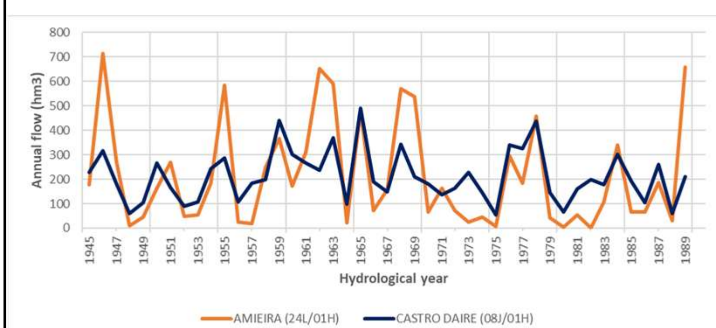
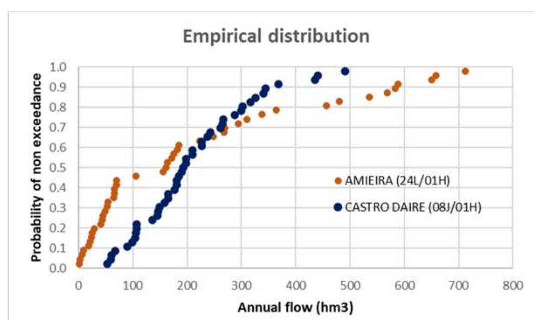
Stream flow characterization: Annual flow variability

- A time-series graph of annual flow says nothing on seasonality or intra annual variability
- The plot of the empirical distribution of annual flow is a simple way to represented interannual variability

	Castro Daire	Amieira
River	Paiva	Degebe
River basin	Douro	Guadiana
Area (km2)	288	1477
Avg. annual flow (hm3)	212	213
Avg. annual runnof (mm)	736	144
Std.Dev. annual flow (hm3)	110	204





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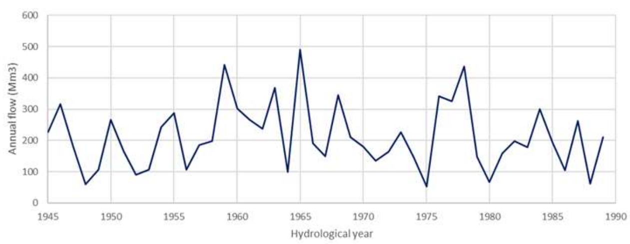
Problem

Assume that the domestic uses of 100'000 persons are to be satisfied from a given water course with the following flow record of annual values. Is it possible ?



Assuming a net unit consumption of 150 l/hab/day and an efficiency of 80%, the gross water requirements area:

- Gross unit consumption = 150/0,8 = 187,5 l/hab/day
- Daily water needs = 187,5 x 100000 = 18,5 dam^3
- Monthly water needs = 18,5 x 30 = 562,5 dam^3
- Annual water needs = 18,5 x 365 = 6843,8 dam^3

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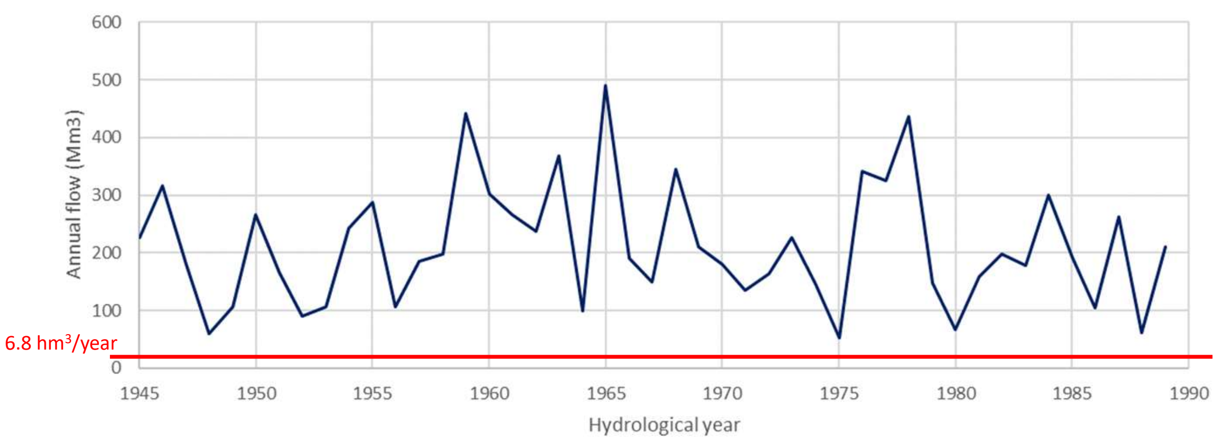
Annual flow



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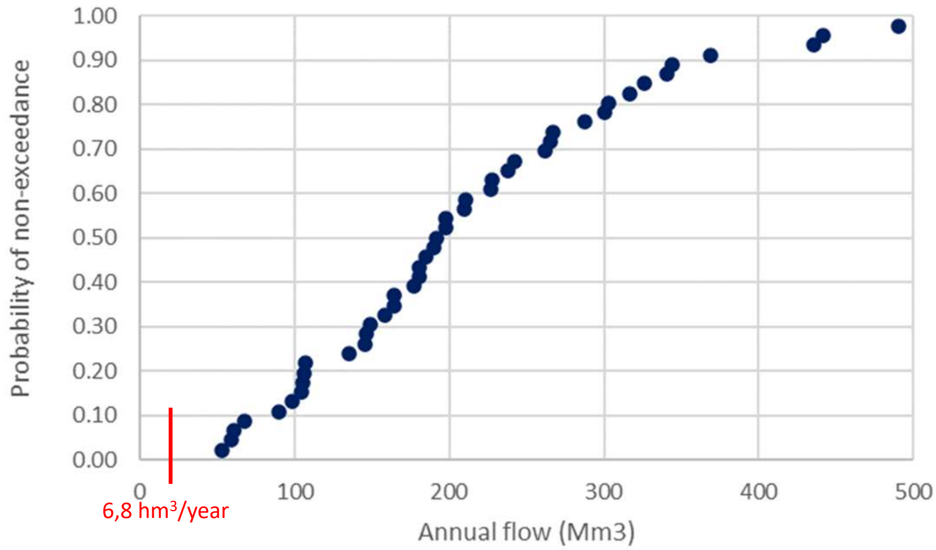
Empirical distribution of annual flow



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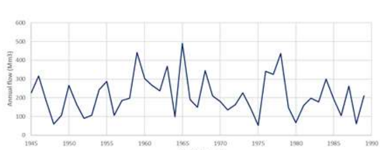
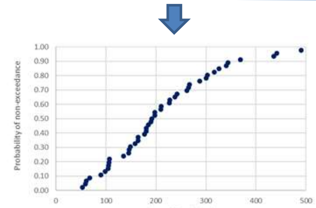
How to build an empirical distribution curve

Values in chronological order		Sorted values (from min to max)			Historical frequency of values less or equal to $X_{(i)}$	Probability of occurrence of values less or equal to $X_{(i)}$
Time	*Value*	*Order*	*Value*		*Frequency*	*Probability*
1	X_1	1	$X_{(1)}$	(min)	$1/N$	$1/N+1$
2	X_2	2	$X_{(2)}$		$2/N$	$2/N+1$
…	…	…	…		…	…
i	X_i	i	$X_{(i)}$		i/N	$i/N+1$
…	…	…	…		…	…
N	X_N	N	$X_{(N)}$	(max)	N/N	$N/N+1$





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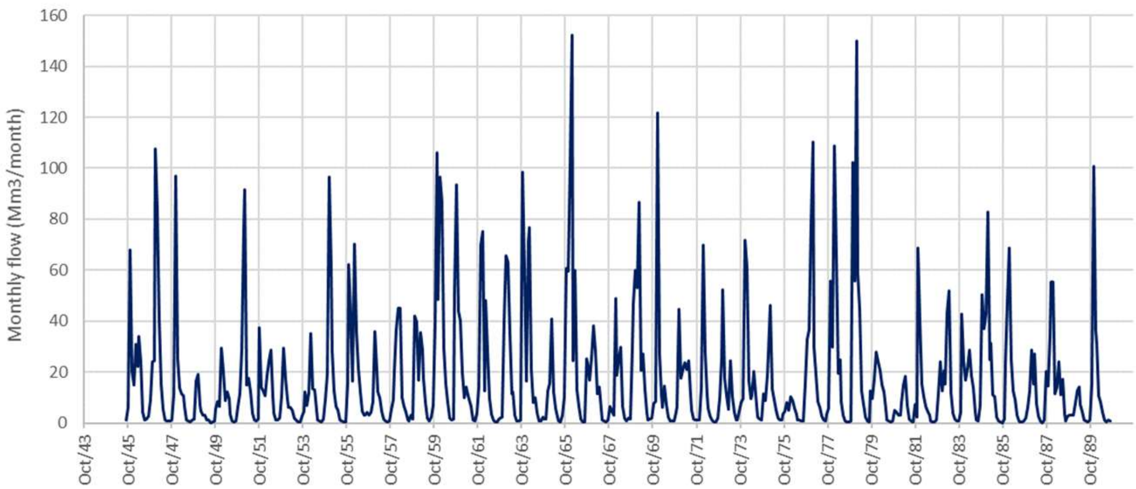
Monthly flow



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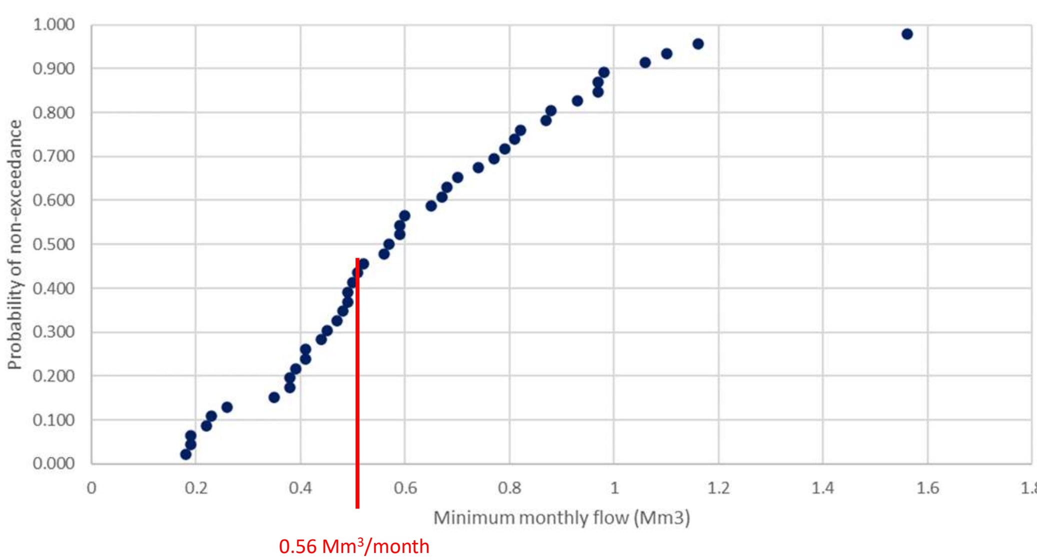
Empirical distribution of annual minimum monthly flow



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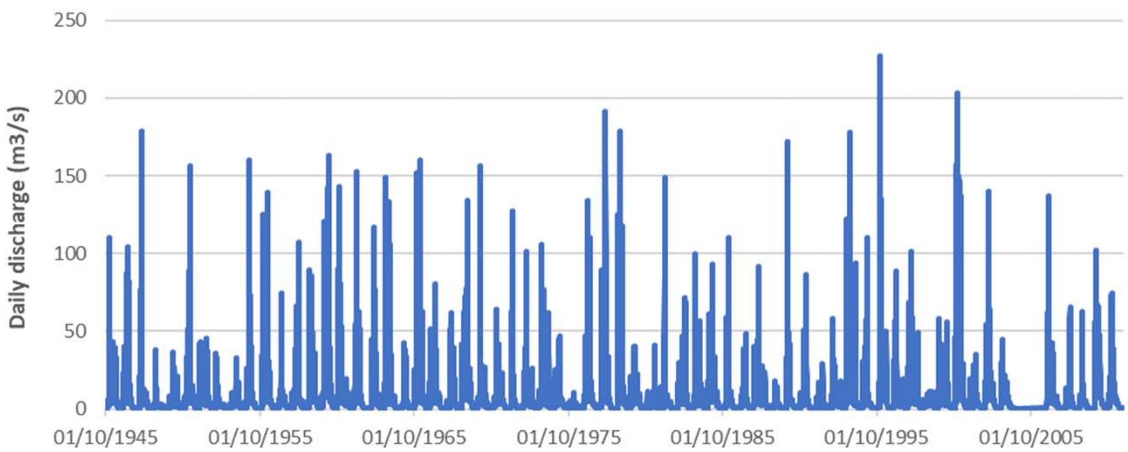
Average daily discharge



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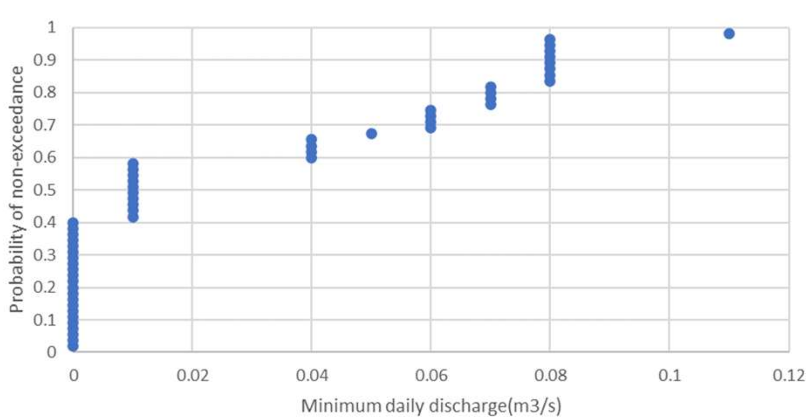
Empirical distribution of annual minimum average daily discharge



18,5 dam^3/day = 0,2 m^3/s

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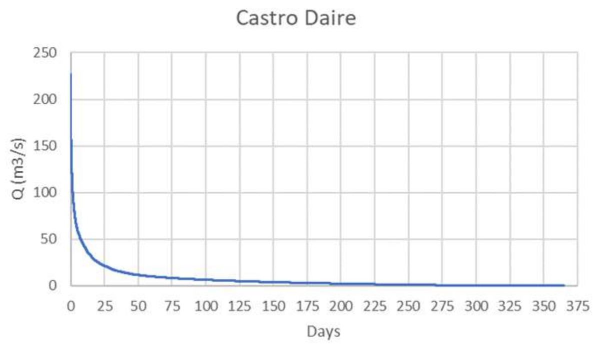
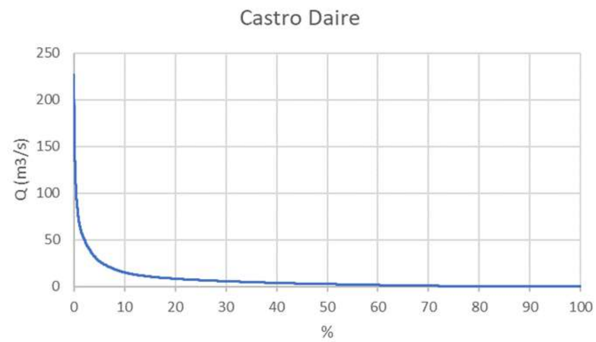
Flow average duration curves





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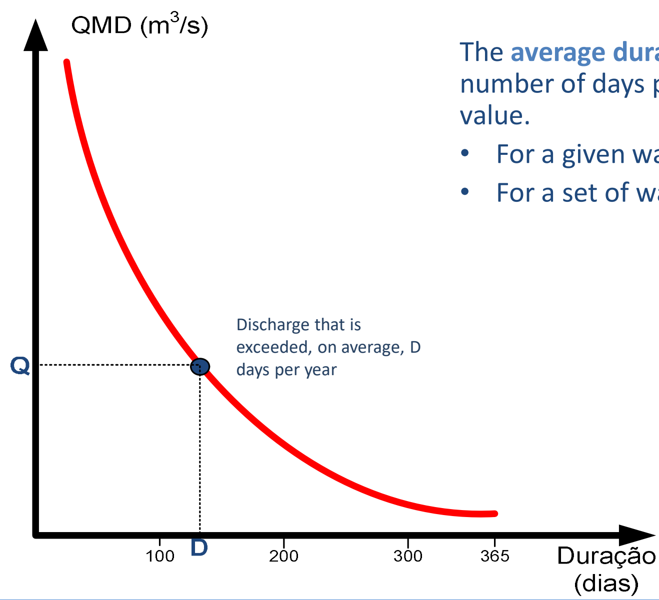
Flow average duration curve



The **average duration of a discharge** value is the average number of days per year that the discharge exceeds that value.

- For a given water year: flow duration curve
- For a set of water years: flow average duration curve

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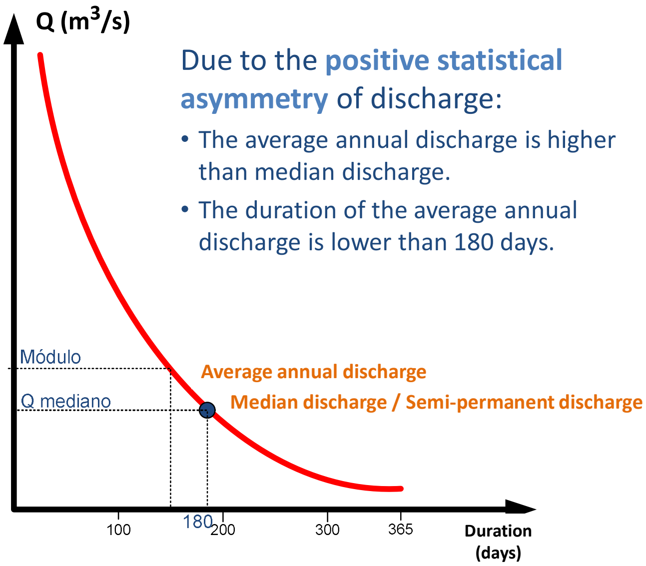
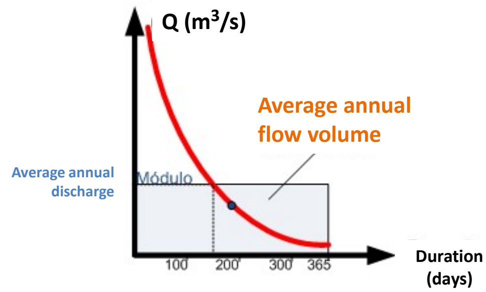
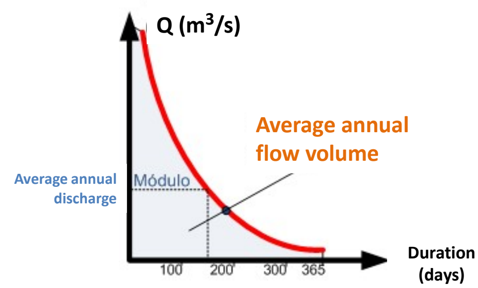
Average annual flow and semi-permanent flow

Due to the **positive statistical asymmetry** of discharge:

- The average annual discharge is higher than median discharge.
- The duration of the average annual discharge is lower than 180 days.







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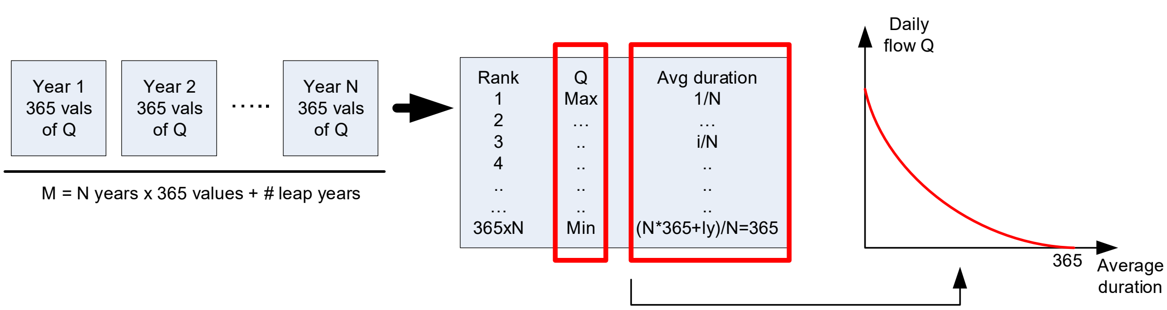
How to obtain a flow duration curve

- Get daily flow data from N complete hydrological values;
- Sort dataset from all hydrological years: from max to min;
- Assign a frequency value to each value: $i^{th}\ value$

$$Avg\ duration = \frac{i}{N}$$

$$Permanence\ frequency = \frac{i}{365 \cdot N}$$



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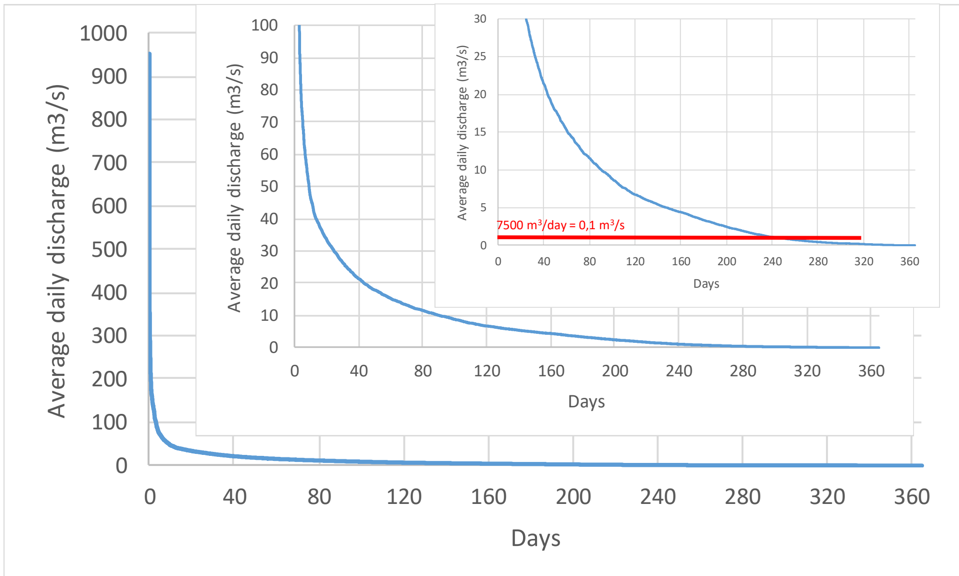
Previous problem: Flow duration curve



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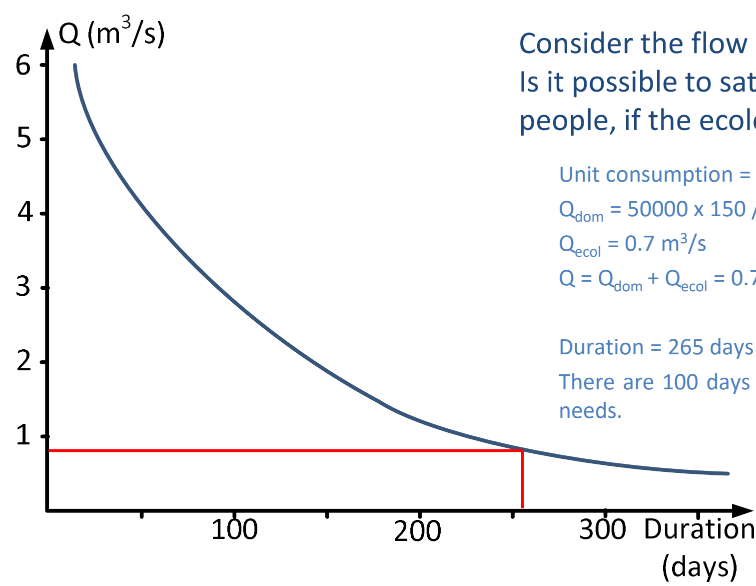
Application of flow duration curves: Water supply



Consider the flow average duration curve on the left. Is it possible to satisfy the domestic needs of 50,000 people, if the ecological requirements are 0.7 m^3/s?

Unit consumption = 150 l/hab/day

Q_{dom} = 50000 x 150 / 3600 / 24 = 90 l/s

Q_{ecol} = 0.7 m^3/s

$Q = Q_{dom} + Q_{ecol}$ = 0.79 m^3/s

Duration = 265 days

There are 100 days when it is not possible to satisfy the water needs.

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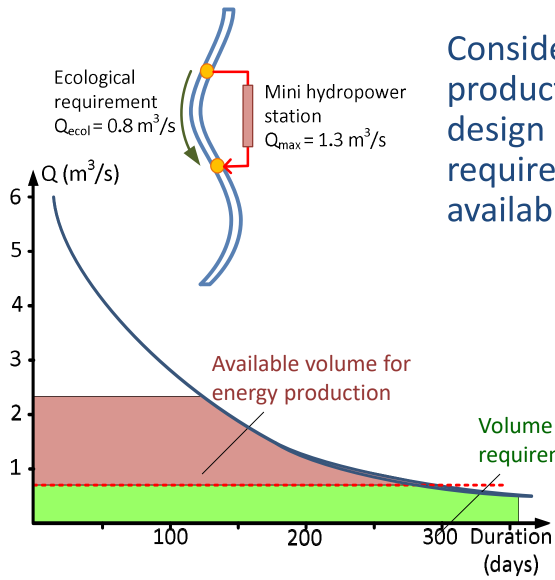
Application of flow duration curves
Energy production

Consider a water derivation for energy production at a mini power plant where the design flow is 1.3 m^3/s. Assuming an ecological requirement of 0.8 m^3/s, what is the volume available for energy production ?



Q (m3/s)	Duration (days)	Qturb (m3/s)	Vol (dam3)	
2.1	0.0	1.3		
2.1	125.0	1.3	14040.0	
2.0	140.0	1.2	1620.0	
1.5	170.0	0.7	2462.4	
1.0	240.0	0.2	2721.6	
0.8	280.0	0.0	345.6	
		Vtotal	21189.6	dam3

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Integrated River Basin Management

Reservoir Sizing and Operation

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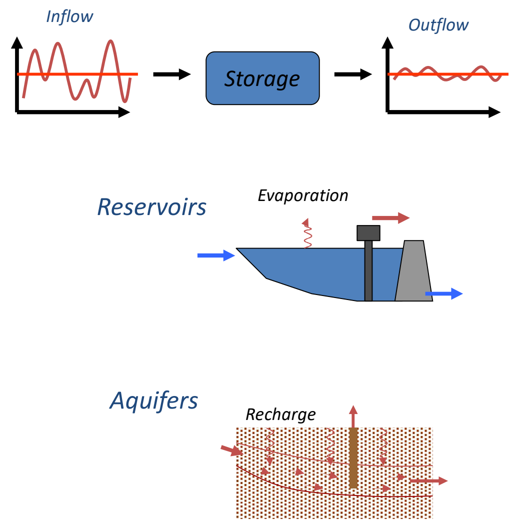
Water storage needs

- Reservoirs and aquifers offer the ability to temporarily store water and to phase water availability with water demand.
- The capacity to attenuate inflow variability and to satisfy large water demands increases with the reservoir capacity.
- Key question: **What is the adequate reservoir capacity to ensure the supply of various uses with a given reliability ?**
- Consequences of *oversizing*:
  - Higher investment;
  - Higher operating costs;
  - Larger environment impacts;
- Consequences of *under sizing*:
  - Inadequate water supply reliability;



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Storage coefficient

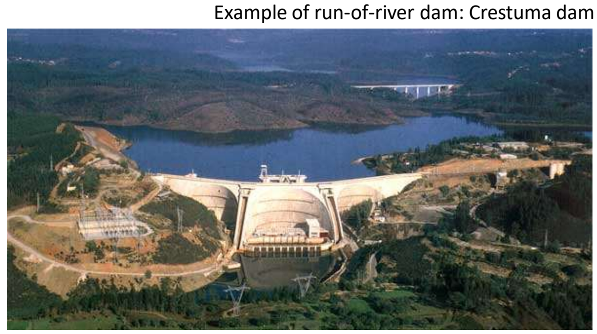
$$Storage\ coef. = \frac{Net\ storage\ capacity}{Avg\ annual\ inflow}$$

Storage coef. << 1 Run-of-river reservoirs

1 << Storage coef. < 1 - Storage reservoirs with intrannual flow regulation

Storage coef. > 1 Storage reservoirs with interannual flow regulation

Example of run-of-river dam: Crestuma dam



Example of a reservoir dam: Aguieira dam

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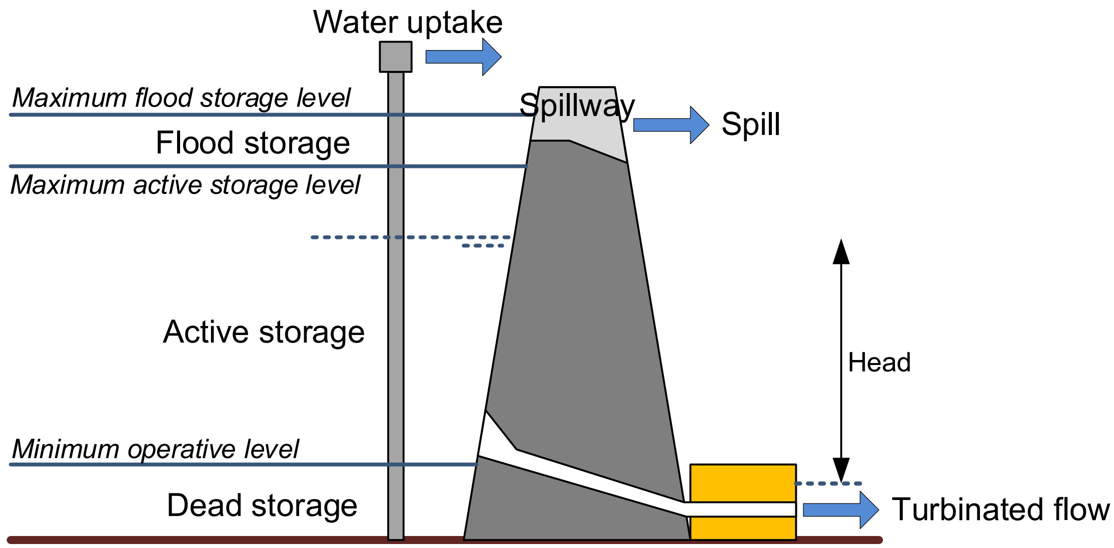
Reservoir storage zones



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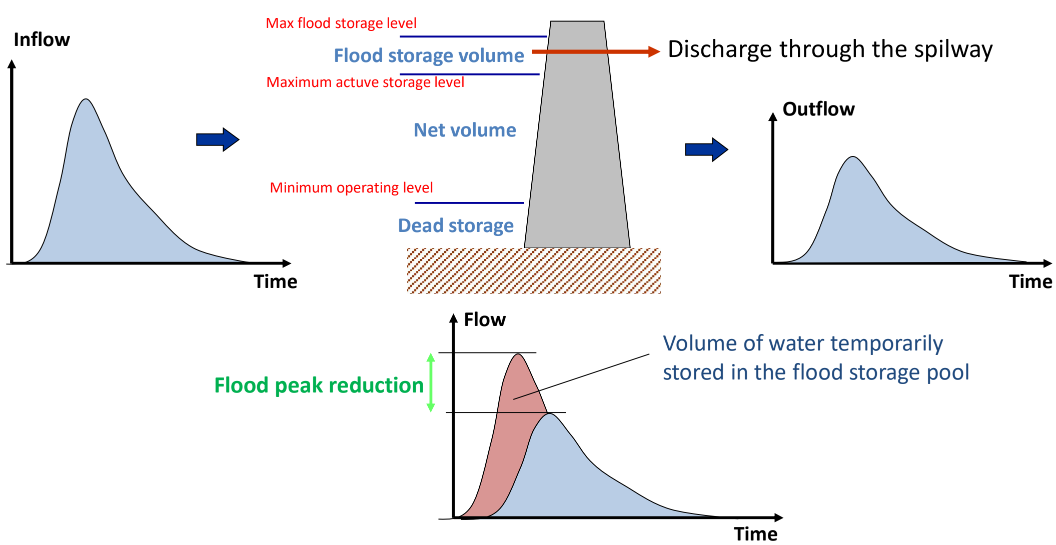
Sizing of flood control zones



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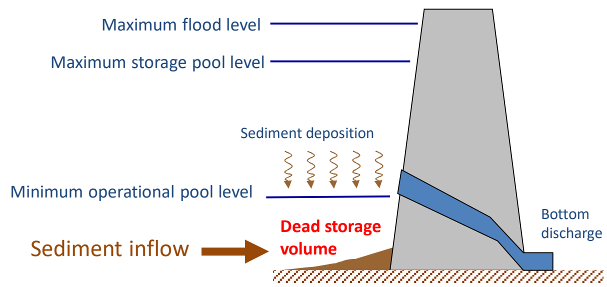
Sizing of the dead storage zone

- **Dead storage pool**: Volume below the lowest uptake level, which is usually not used for water demand satisfaction:
  - Sediment accumulates in this pool during the reservoir lifetime.
  - Water is usually of very quality, with low oxygen levels.
- The dead storage volume depends on:
  - Orography of the reservoir location;
  - Design of the dam and its abstraction infrastructures.
  - Reservoir sediment inflow.
  - Infrastructure lifetime.

Discharge at Xiaolangdi dam (Yellow river, China), in July 2012



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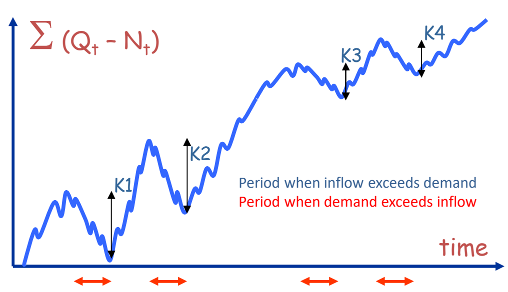
Sizing of the active storage pool

Sequent Peak Algorithm

Month	Flow, Q	Sum (Q – N)
Oct 1917	Q_1	$Q_1 - N$
Nov 1917	Q_2	$Q_1 + Q_2 - 2N$
Dec 1917	Q_3	$Q_1 + Q_2 + Q_3 - 3N$
Jan 1918	Q_4	$Q_1 + Q_2 + Q_3 + Q_4 - 4N$
…	…	…
Aug 1990	Q_{m-1}	$Q_1 + \ldots + Q_{m-1} - (m-1)N$
Sep 1990	Q_m	$Q_1 + \ldots + Q_m - mN$
Oct 1917	Q_1	…
Nov 1917	Q_2	…
Dec 1917	Q_3	…
Jan 1918	Q_4	…
…	…	…
Aug 1990	Q_{m-1}	…
Sep 1990	Q_m	…

- Assume a water demand N is to be satisfied from a river with flows Q_1, Q_2, .. Q_m. How large should the reservoir be, if evaporation is not considered and the demand is to be satisfied with a 100% reliability (at all time steps)?
- Let K net storage capacity of the reservoir:



$$K = Max\,(K_1, K_2, \ldots K_n)$$

$$K = max_k \left\{ max_k \left\{ \sum_{t=1}^{k} (Q_t - N_t) \right\} - \sum_{t=1}^{k} (Q_t - N_t) \right\}$$

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Sequent peak method

- The Sequent Peak Algorithm is an evolution of the mass curve method proposed by Rippl in 1883, originally thought to be solved by hand as a graphical method (Rippl diagram).
- It can be easily applied in Excel, as explained on the right. R_t is the required release to meet demand N.

Sequent Peak Method

Let K_t be the storage required in a time step t.

$K_t = R_t - Q_t + K_{t-1}$ if positive
= 0 otherwise

The maximum of all K_t is the required storage capacity for specified releases and flows.

time t	$(R_t - Q_t + K_{t-1})^+ = K_t$	
1	3.5 – 1.0 + 0.0 = 2.5	
2	3.5 – 3.0 + 2.5 = 3.0	
3	3.5 – 3.0 + 3.0 = 3.5	
4	3.5 – 5.0 + 3.5 = 2.0	
5	3.5 – 8.0 + 2.0 = 0.0	
6	3.5 – 6.0 + 0.0 = 0.0	
7	3.5 – 7.0 + 0.0 = 0.0	
8	3.5 – 2.0 + 0.0 = 1.5	
9	3.5 – 1.0 + 1.5 = 4.0	
1	3.5 – 1.0 + 4.0 = 6.5	
2	3.5 – 3.0 + 6.5 = 7.0	
3	3.5 – 3.0 + 7.0 = 7.5	K_a
4	3.5 – 5.0 + 7.5 = 6.0	
5	3.5 – 8.0 + 6.0 = 1.5	
6	3.5 – 6.0 + 1.5 = 0.0	repetition begins
7	3.5 – 7.0 + 0.0 = 0.0	

From Loucks and van Beek, 2017

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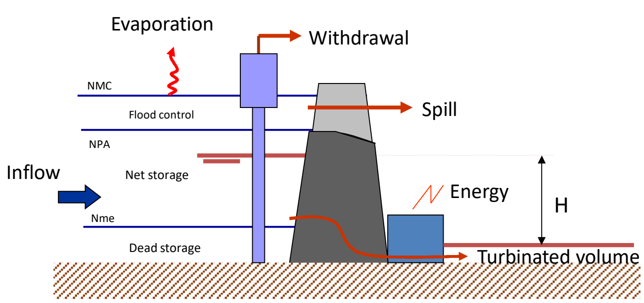
Sizing of active pool: mathematical modelling



V_{t+1} – Storage at beginning of month t+1
V_t – Storage at beginning of month t
K _ reservoir net capacity
E_t – Evaporation (volume) during month t
e_t – Evaporation (mm) during month t
Q_t – Inflow during month t
R_{1t} – Volume supplied to use 1 during month t
R_{2t} – Volume supplied to use e during month t
S_t – Spilled volume (through the spillway) during month t

Mass balance equation:

$$V_{t+1} = V_t + Q_t - E_t - R_{1t} - R_{2t} - S_t$$

Evaporation: $E_t (dam^3) = A_t (km^2) * e_t (mm)$

Spill: If $V_t + Q_t - E_t - R_{1t} - R_{2t} > K$ *there is spill:* $St = V_t + Q_t - E_t - R_{1t} - R_{2t} - K$

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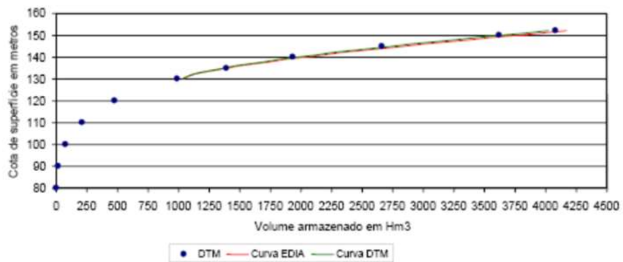
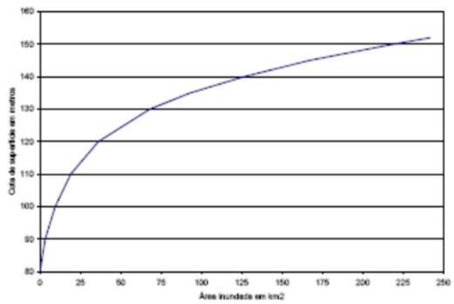
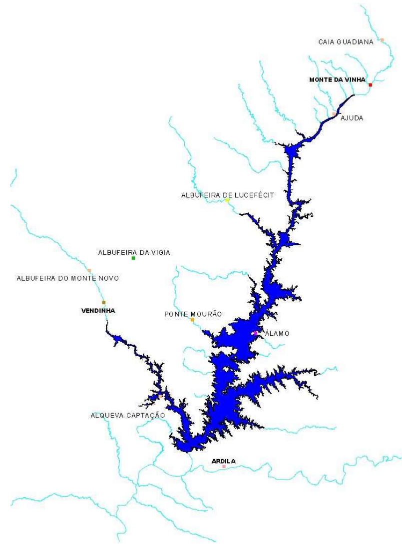
Elevation-volume-area curves: Example of Alqueva reservoir







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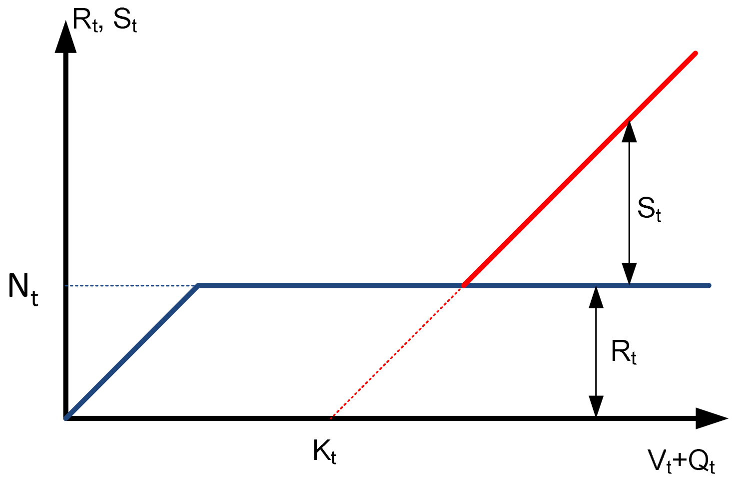
Standard operating rule for a single use

Release rule (Standard operating policy)



V_t- Storage
Q_t- Expected inflow
N_t - Water demand
K_t- Storage capacity
R_t- Supplied volume
S_t- Spill

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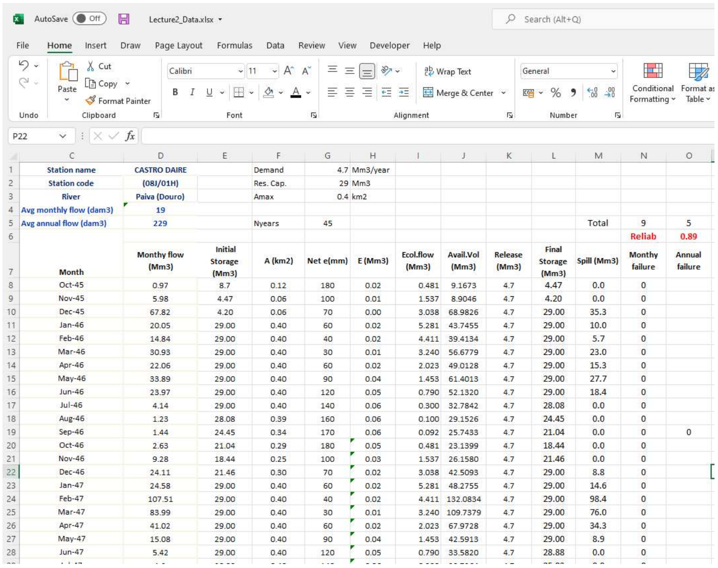
Simulation in MS Excel



	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Station name	CASTRO DAIRE		Demand	4.7	Mm3/year							
2	Station code	(08J/01H)		Res. Cap.	29	Mm3							
3	River	Paiva (Douro)		Amax	0.4	km2							
4	Avg monthly flow (dam3)	19											
5	Avg annual flow (dam3)	229		Nyears	45						Total	9	5
6												Reliab	0.89
7	Month	Monthy flow (Mm3)	Initial Storage (Mm3)	A (km2)	Net e(mm)	E (Mm3)	Ecol.flow (Mm3)	Avail.Vol (Mm3)	Release (Mm3)	Final Storage (Mm3)	Spill (Mm3)	Monthy failure	Annual failure
8	Oct-45	0.97	8.7	0.12	180	0.02	0.481	9.1673	4.7	4.47	0.0	0	
9	Nov-45	5.98	4.47	0.06	100	0.01	1.537	8.9046	4.7	4.20	0.0	0	
10	Dec-45	67.82	4.20	0.06	70	0.00	3.038	68.9826	4.7	29.00	35.3	0	
11	Jan-46	20.05	29.00	0.40	60	0.02	5.281	43.7455	4.7	29.00	10.0	0	
12	Feb-46	14.84	29.00	0.40	40	0.02	4.411	39.4134	4.7	29.00	5.7	0	
13	Mar-46	30.93	29.00	0.40	30	0.01	3.240	56.6779	4.7	29.00	23.0	0	
14	Apr-46	22.06	29.00	0.40	60	0.02	2.023	49.0128	4.7	29.00	15.3	0	
15	May-46	33.89	29.00	0.40	90	0.04	1.453	61.4013	4.7	29.00	27.7	0	
16	Jun-46	23.97	29.00	0.40	120	0.05	0.790	52.1320	4.7	29.00	18.4	0	
17	Jul-46	4.14	29.00	0.40	140	0.06	0.300	32.7842	4.7	28.08	0.0	0	
18	Aug-46	1.23	28.08	0.39	160	0.06	0.100	29.1526	4.7	24.45	0.0	0	
19	Sep-46	1.44	24.45	0.34	170	0.06	0.092	25.7433	4.7	21.04	0.0	0	0
20	Oct-46	2.63	21.04	0.29	180	0.05	0.481	23.1399	4.7	18.44	0.0	0	
21	Nov-46	9.28	18.44	0.25	100	0.03	1.537	26.1580	4.7	21.46	0.0	0	
22	Dec-46	24.11	21.46	0.30	70	0.02	3.038	42.5093	4.7	29.00	8.8	0	
23	Jan-47	24.58	29.00	0.40	60	0.02	5.281	48.2755	4.7	29.00	14.6	0	
24	Feb-47	107.51	29.00	0.40	40	0.02	4.411	132.0834	4.7	29.00	98.4	0	
25	Mar-47	83.99	29.00	0.40	30	0.01	3.240	109.7379	4.7	29.00	76.0	0	
26	Apr-47	41.02	29.00	0.40	60	0.02	2.023	67.9728	4.7	29.00	34.3	0	
27	May-47	15.08	29.00	0.40	90	0.04	1.453	42.5913	4.7	29.00	8.9	0	
28	Jun-47	5.42	29.00	0.40	120	0.05	0.790	33.5820	4.7	28.88	0.0	0	

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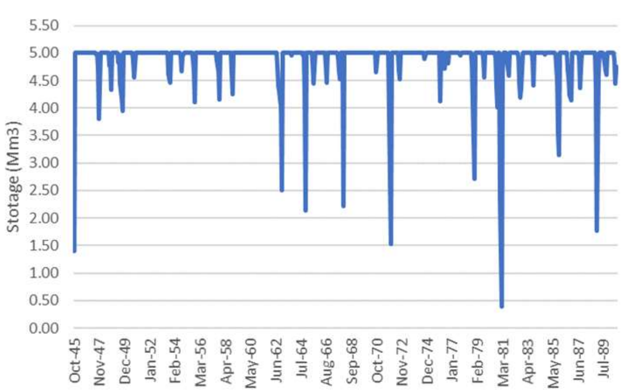
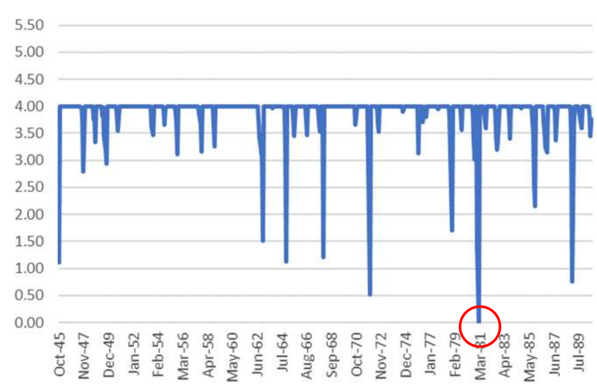
Results

K = 5 Mm³
N = 0.56 Mm³/month



K = 4 Mm³
N = 0.56 Mm³/month



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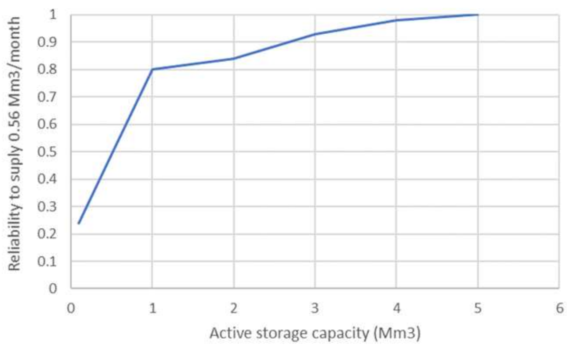
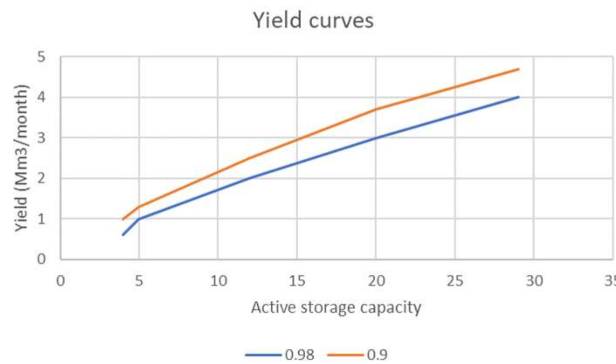
Reliability and yield curves





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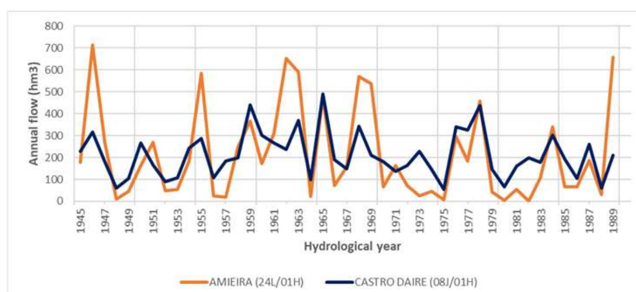
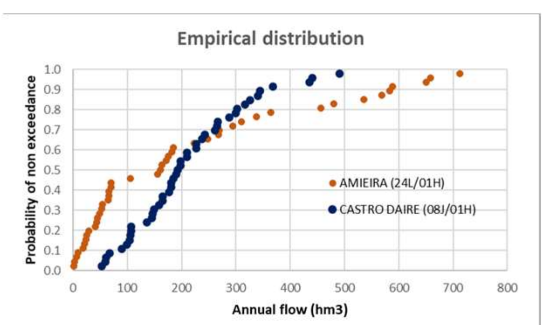
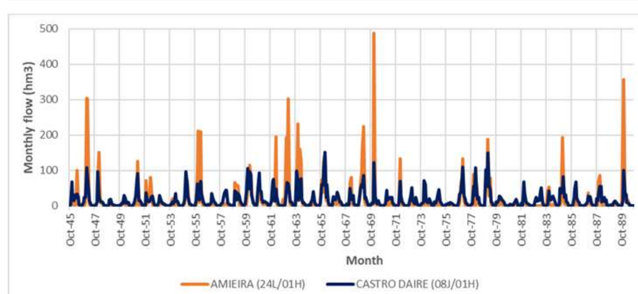
Reservoir simulation: Two sets of inflows

	Castro Daire	Amieira
River	Paiva	Degebe
River basin	Douro	Guadiana
Area (km2)	288	1477
Avg. annual flow (hm3)	212	213
Avg. annual runof (mm)	736	144
Std.Dev. annual flow (hm3)	110	204







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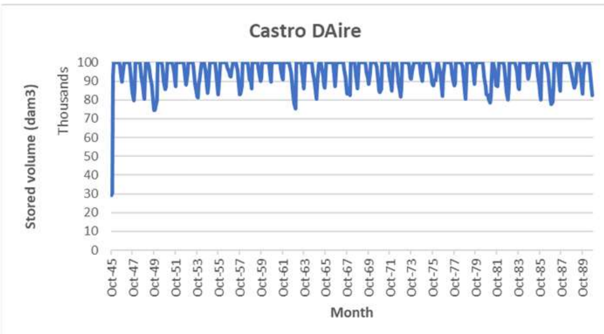
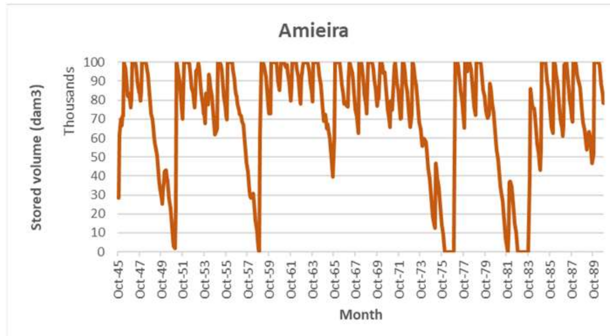
Reservoir simulation: Reservoir storage and water supply reliability

Reservoir storage capacity = 100 hm^3 *(100 Mm^3)*
Water needs = 5 hm^3 /month (~30% of average monthly flow)
Nº of years in the simulation = 45



0 monthly failures
0 annual failures
Reliability = 100%



24 monthly failures
6 annual failures
Reliability = 87%

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Performance criteria

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Definitions

- **Natural streamflow** – Flow not affected by humans
- **Unregulated streamflow** – Flow without any upstream storage or diversions
- **Regulated streamflow**
- **Demand** (target demand)
- **Release**
- **Spill** – Uncontrolled or un regulated release from a reservoir
- **Yield** – Controlled release from a reservoir
- **Firm yield** – Yield that can be met with a given reliability
- **Safe yield (US)** – Yield that can be met with 100% reliability over a particular time period (it should not be used.)

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Performance indicators

- **Expected benefits** (€):
- **Reliability:** Measures the ability to meet water demands;
  - Time : Reliability_T = #years without supply failures/ #simulated years
  - Volume: Reliability_V = Supplied volume/ Water needs
- **Vulnerability:** Measures the severity of supply shortages:
  - Supply shortage as a percentage of the demand;
- **Robustness**: Inverse of vulnerability
- **Resilience:** Measures the ability of the system to recover from a supply shortage;
  - Average duration of a supply shortage;
  - Number of months the demand is satisfied that follow a month where a supply shortage has occurred over the number of supply shortages (months when demand was not satisfied).

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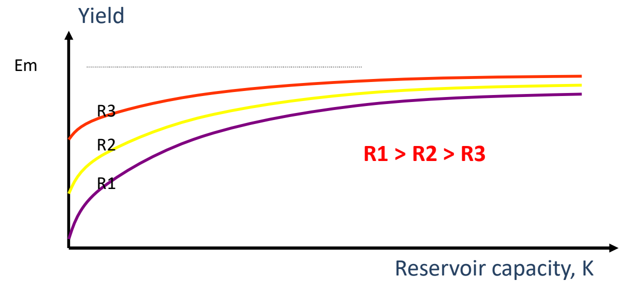
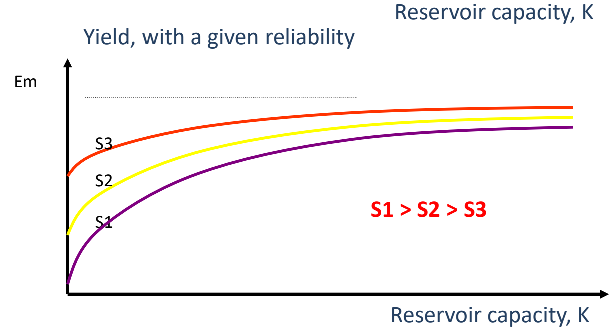
Yield vs storage vs reliability vs inflow variability

Yield vs
Storage capacity vs
Reliability



Yield vs
Storage capacity vs
Inflow variability



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