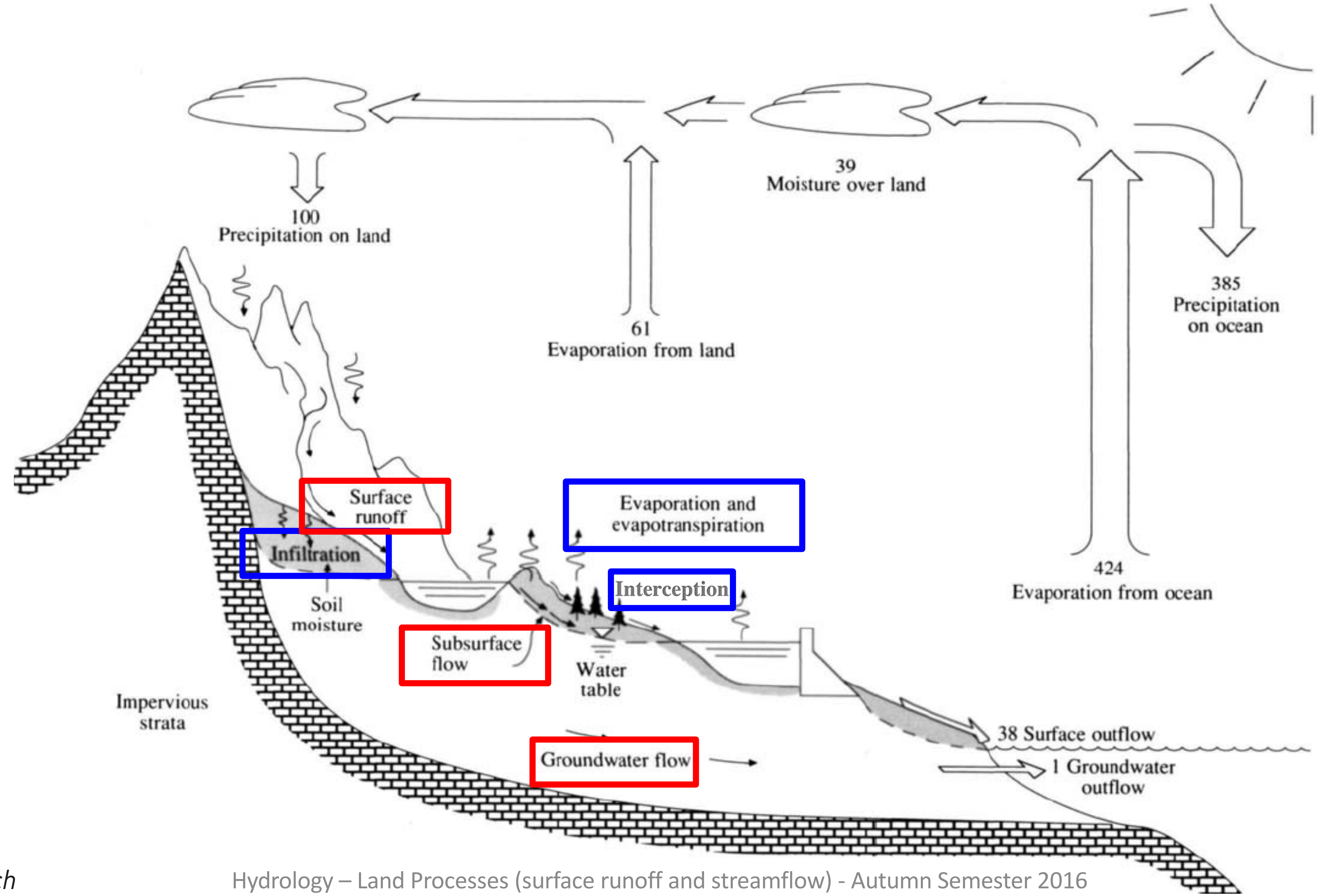
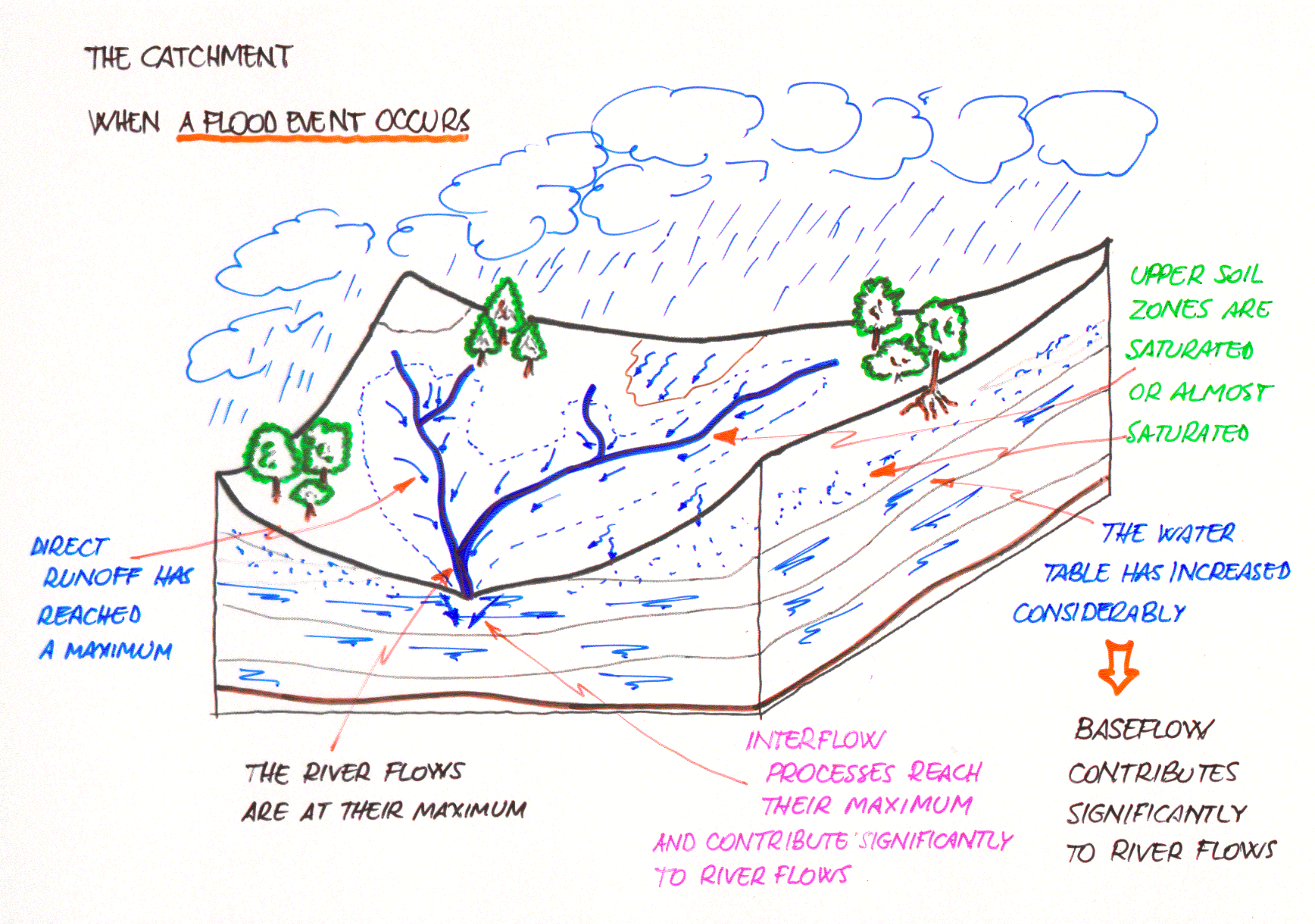
Land processes: surface runoff and streamflow



Land processes: surface runoff and streamflow



Land processes: surface runoff and streamflow

Lecture content

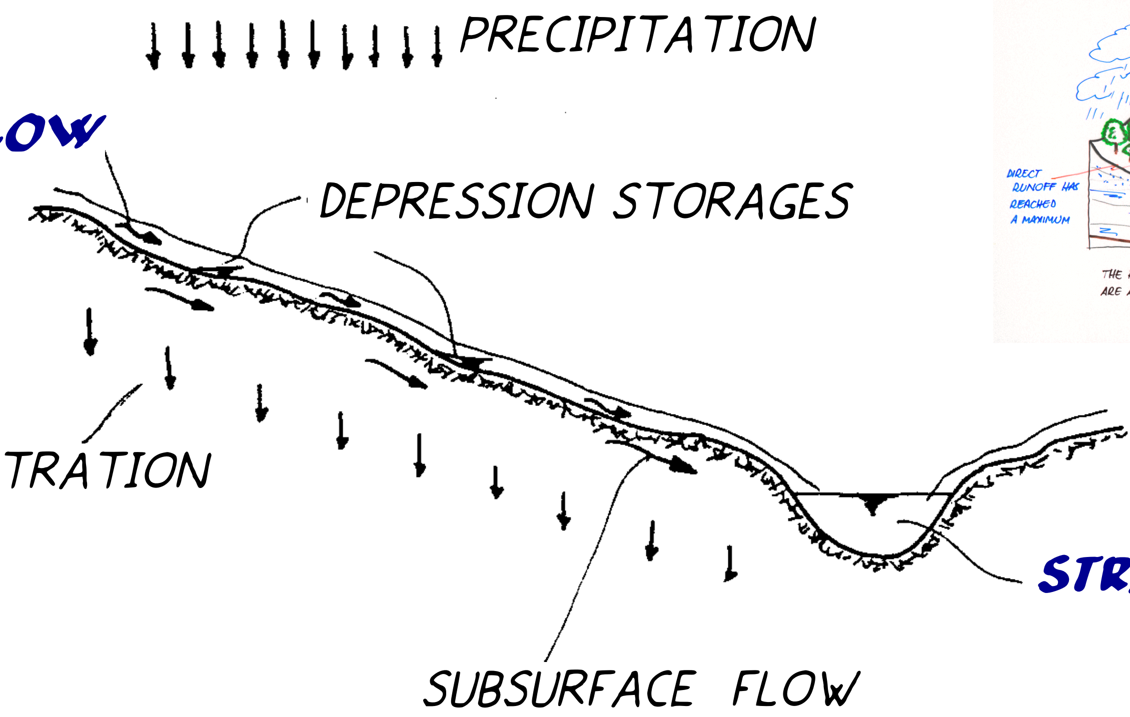
Skript: Ch. IV.6

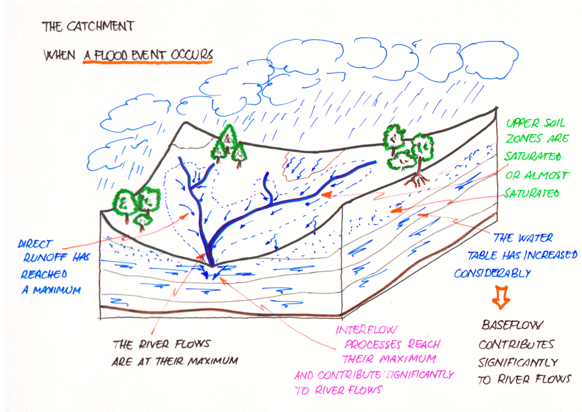
Ch. VI § 2.4

Surface runoff and streamflow processes

- *definition / characterisation*
- *influencing factors* (natural vs anthropogenic, flood hydrograph vs streamflow regime)
- *measurements and sources of data*
- *hydrograph analysis*
  - annual hydrograph and streamflow regimes
  - flow duration curve
  - event scale hydrograph analysis and baseflow separation

Surface runoff and streamflow: definition





Runoff generation mechanisms lead to

↳ ***overland flow = surface runoff*** → ***two-dimensional flow occurring on slopes or in ephemeral drainage patterns***

Concentration of surface runoff **into permanent natural drainage patterns** (river network) leads to

↳ ***streamflow (channel flow)*** → ***one- and/or two-dimensional flow occurring in river network channels***

Surface runoff and streamflow controls

NATURAL CONTROLS

- **climatic and hydrologic** patterns
  - ↳ *precipitation*
    - type (rain/snow), intensity, duration, space-time variability
  - ↳ *interception*
  - ↳ *evapotranspiration*
  - ↳ *infiltration*
- **basin** characteristics
  - ↳ *topography*
  - ↳ *elevation and aspect*
  - ↳ *vegetation cover*
  - ↳ *soil*
  - ↳ *geology*
  - ↳ *drainage network*

ANTHROPOGENIC CONTROLS

- **land use changes**
  - ↳ *urbanisation*
  - ↳ *agriculture*
  - ↳ *forest management*
- **water resources exploitation**
  - ↳ *irrigation*
  - ↳ *hydropower*
  - ↳ *water supply*
- **climate change**

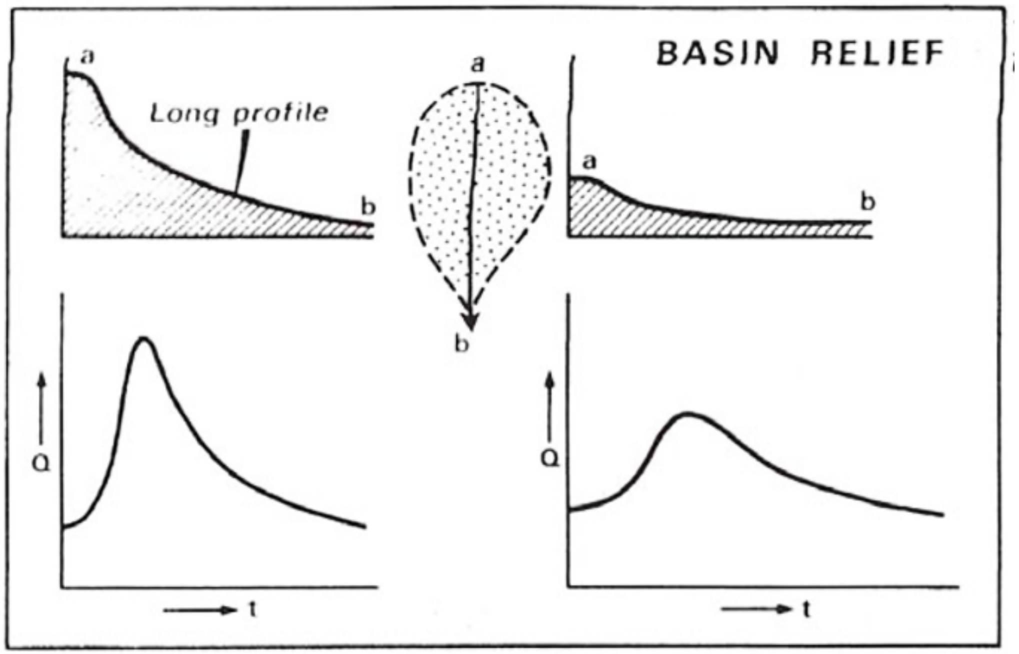
Basin controls: effects of elevation, aspect and orientation

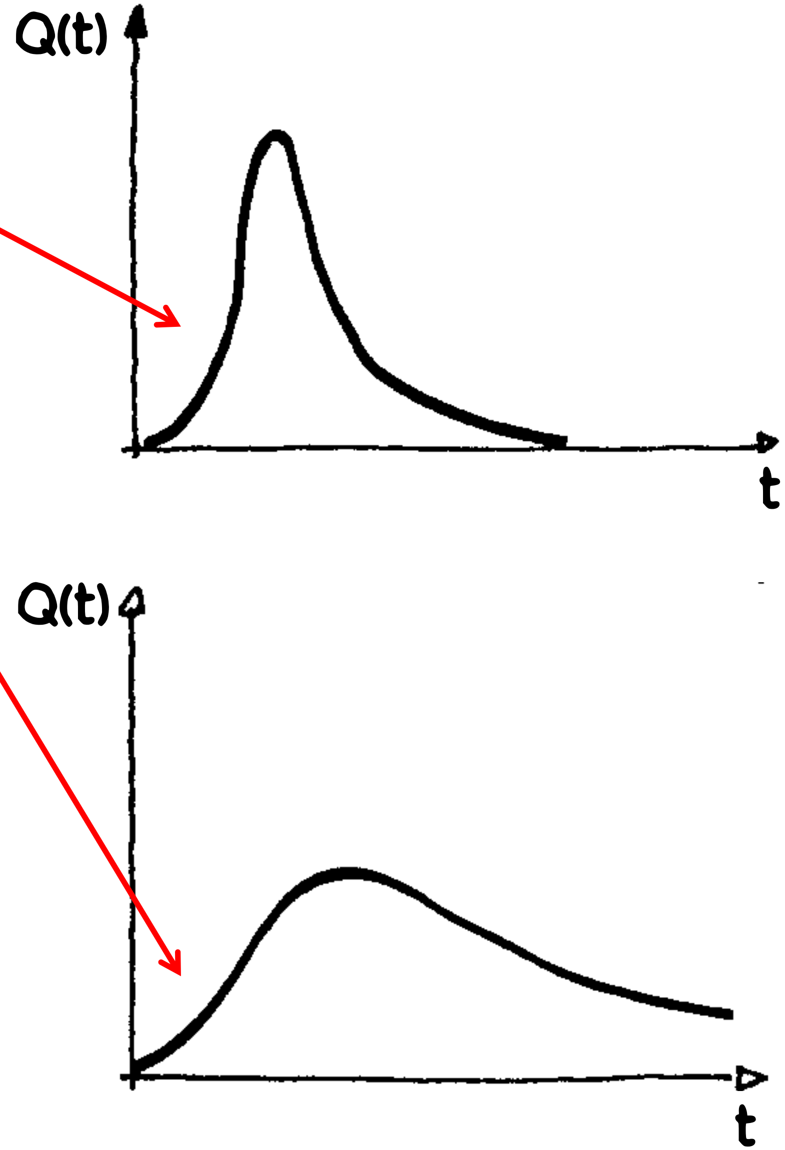
- **elevation** controls
  - *temperature decreases* at higher elevations
    - ↳ evapotranspiration decreases → *effects on soil water dynamics*
    - ↳ the proportion of snowall/rainfall increases → *effects on streamflow regime (distribution of flow across seasons)*
- **aspect** controls
  - *solar radiation and energy balance*
    - ↳ evapotranspiration → *effects on soil water dynamics*
    - ↳ vegetation patterns → *effects on infiltration/runoff generation*
- **orientation** controls
  - *the exposure to dominant winds and precipitation patterns*
    - ↳ rainfall regime → *effects on soil water dynamics and runoff generation*

Basin controls: effects of topography (slope)

slope controls

- *the basin response time*
  - ↳ **steeper** basin → ***faster*** *response*
  - ↳ **gentle** slopes → ***delayed*** *response*
- *runoff generation mechanisms*
  - ↳ soil **storage** / infiltration → *gentle slopes are characterised by* ***deeper soils***
  - ↳ soil **wetness** → ***steeper*** *slopes* ***drain faster***





Basin controls: effects of soil and vegetation cover

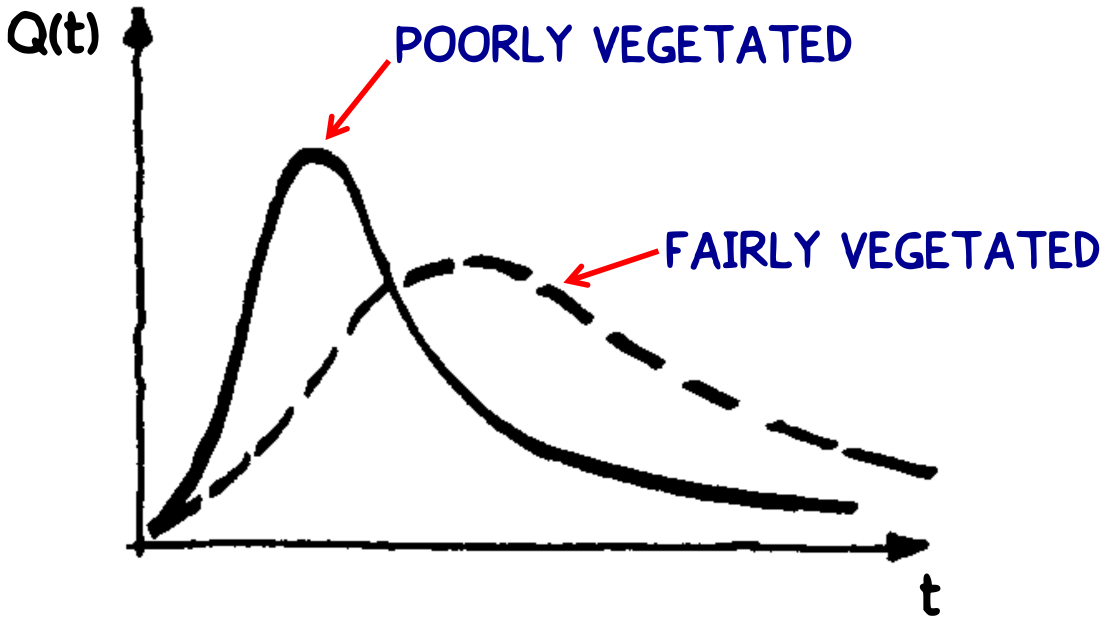
vegetation controls

- *interception*
- *evapotranspiration*
- *infiltration*

↓

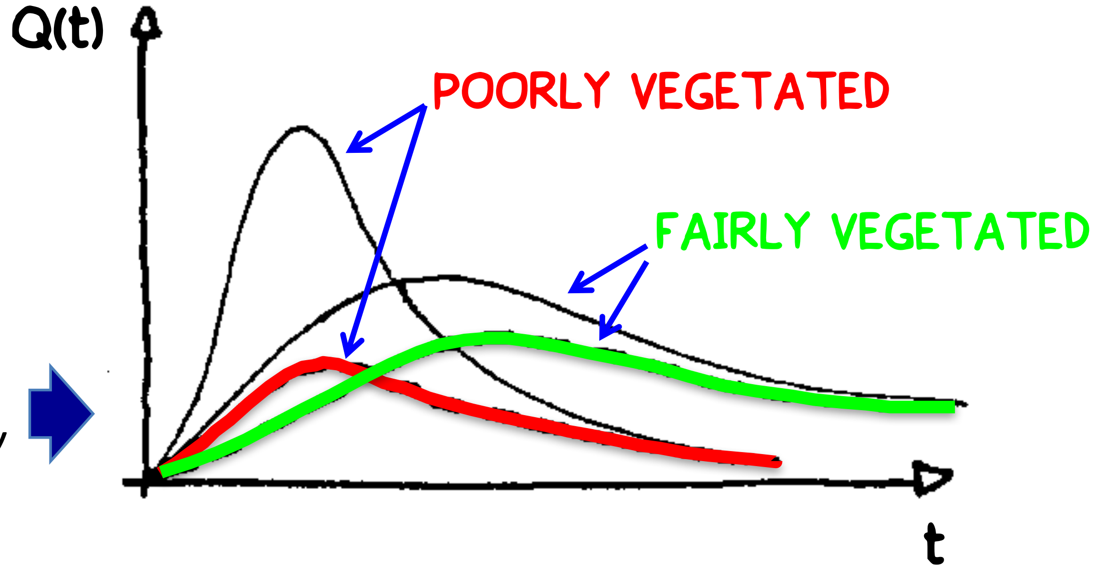
runoff generation mechanisms

basin storage capacity



NB vegetation, soil type and permeability influence each other

vegetated basin → *richer sub-surface flow and baseflow*



Basin controls: effects of geology and shape

geology controls the formation of the drainage network structure

🡻 effects on

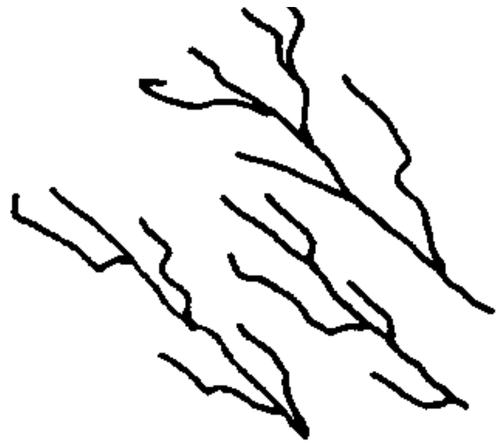
- ***drainage density***
  - ↳ ***storage capacity of the network***
  - ↳ ***runoff/streamflow travel path***

🡻 impact on

- ***runoff concentration***
- ***basin time response***

DENDRITIC NETWORK (most frequent, homogenous geology)

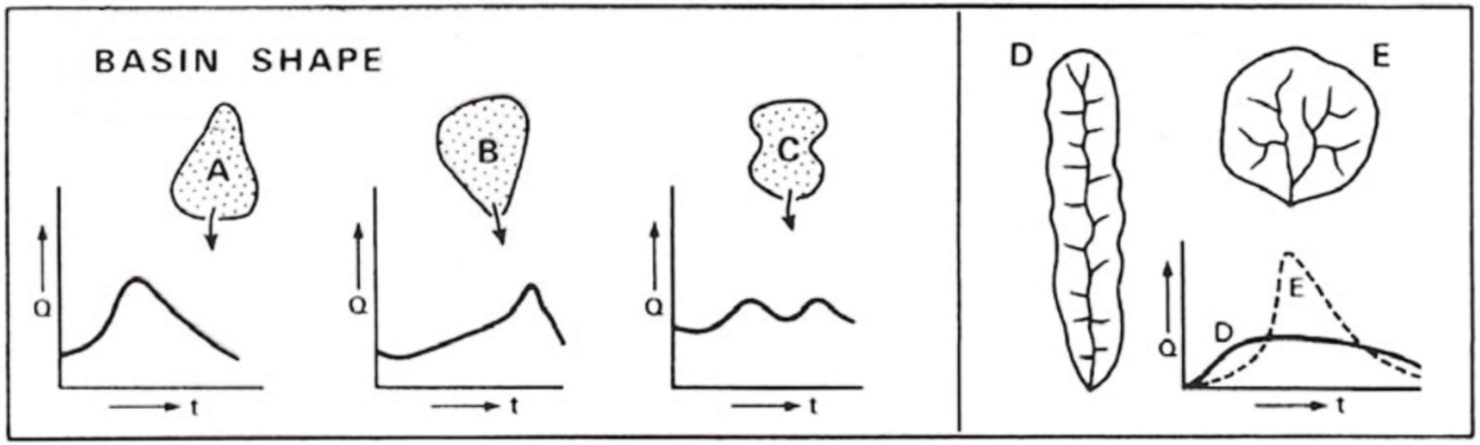
PARALLEL NETWORK (steep slopes, outcropping elongated resistant rock bands)



shape controls the temporal dynamics of basin response

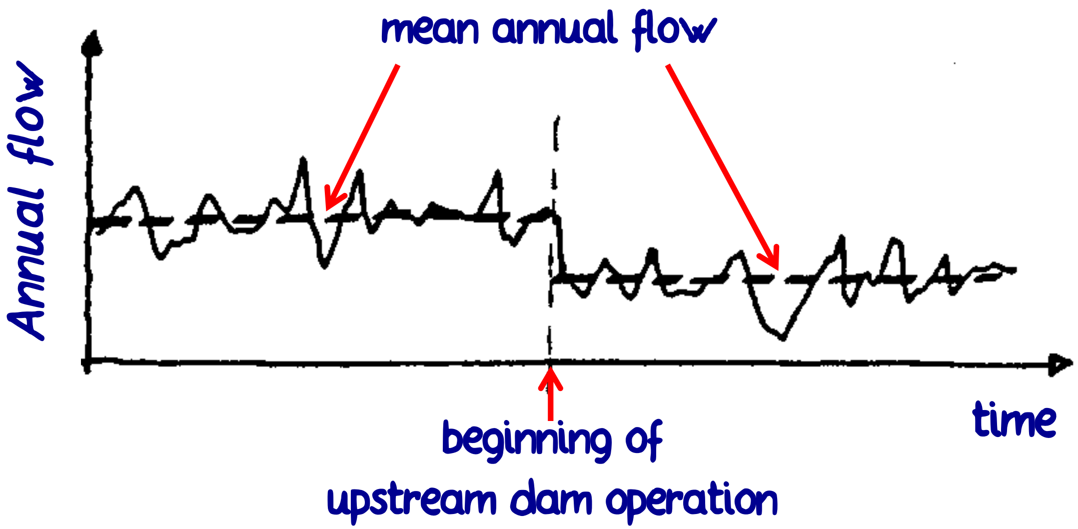
🡻

effects on hydrograph



Anthropogenic controls

- ***water exploitation*** through infrastructures modifies streamflow (and sediment transport) ***regimes and volumes*** by
  - ↳ storage and regulation (*hydropower, irrigation*)
  - ↳ abstraction (*irrigation, water supply*)



- ***basin topography changes*** due to ***agricultural practice*** and ***urbanisation***
  - ↳ local and average slope
  - ↳ drainage network

- ***basin response changes due land use and vegetation cover changes*** (e.g. deforestation, forest fires, agriculture, …)
  - ↳ infiltration capacity and soil water storage
  - ↳ evapotranspiration

Streamflow measurement

Measurement of ***surface runoff*** is complex → ***not available***

Measurement of ***channel flow (streamflow)*** is carried out by combining for a ***known channel geometry*** measurements of

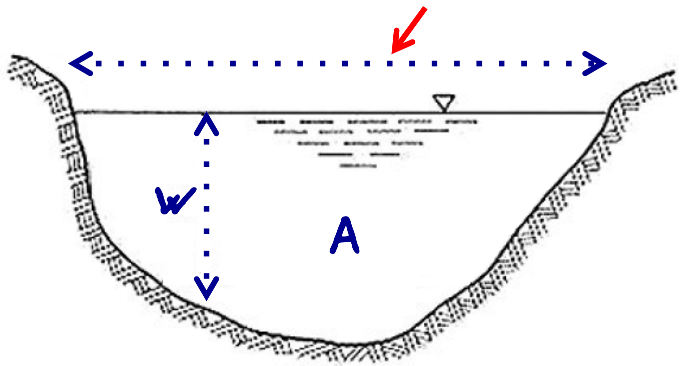
↳ ***water level, w***

↳ ***flow velocity, u***

$$\rightarrow \underbrace{Q = u \cdot A}_{\text{steady state}}$$

u = velocity

A = cross-section area, *f*(*w*, river width)



Streamflow, Q(t), is a flux → $[L]^3[T]^{-1}$ → [m^3/s], [m^3/day], …

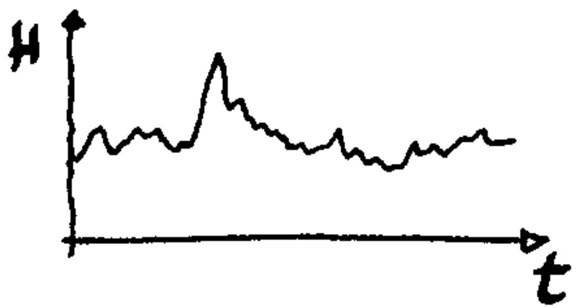
Data are typically available in the form of

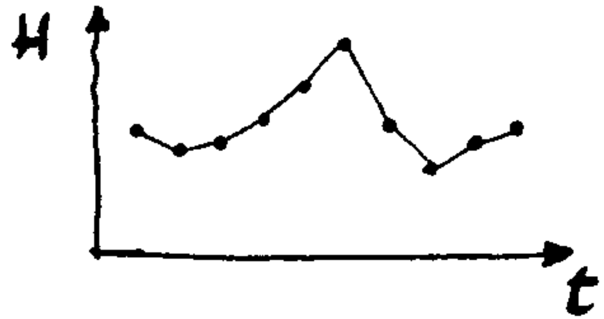
↳ ***water levels***

↳ ***flows (= discharge)*** → hourly, daily, monthly, and annual flow

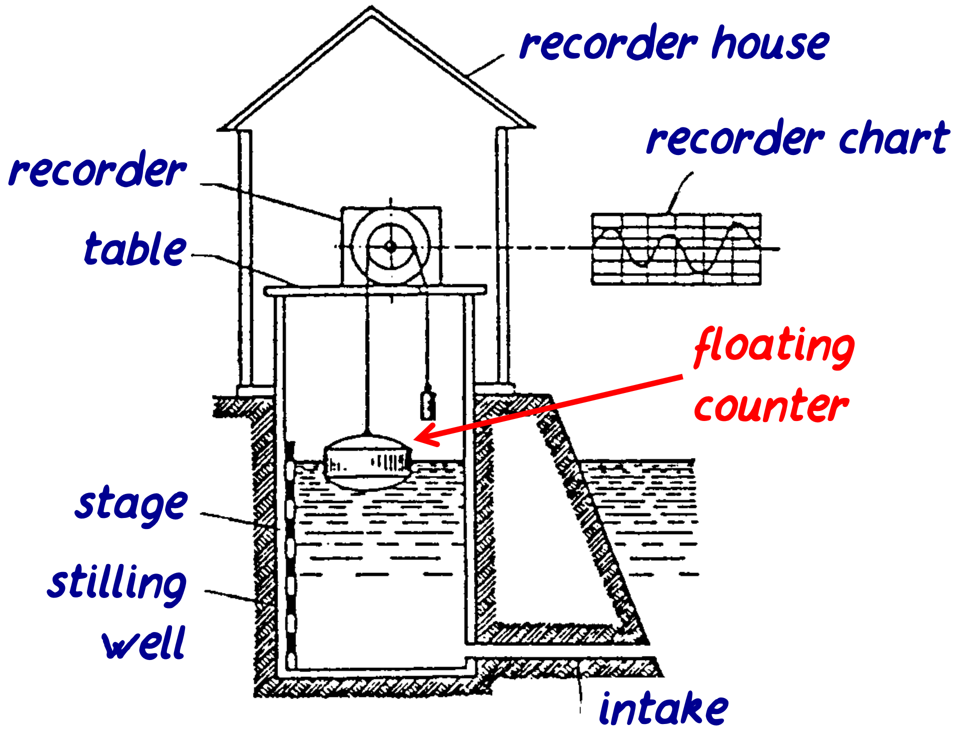
Streamflow measurement: water level (1)

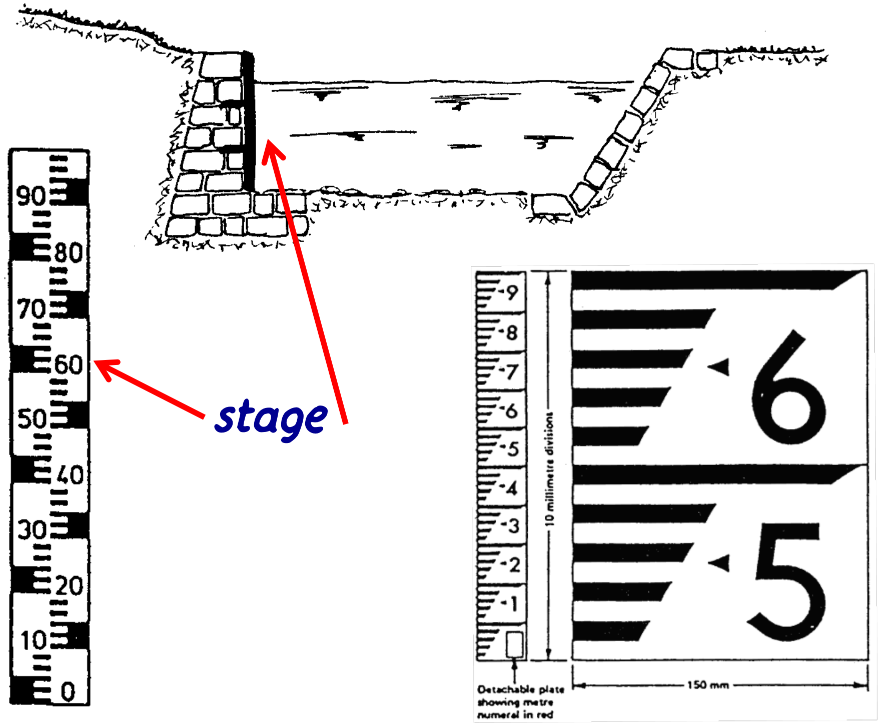
Water level measurements are both





- ***continuous*** (from automatic devices)
- and ***discrete*** (from manual readings)

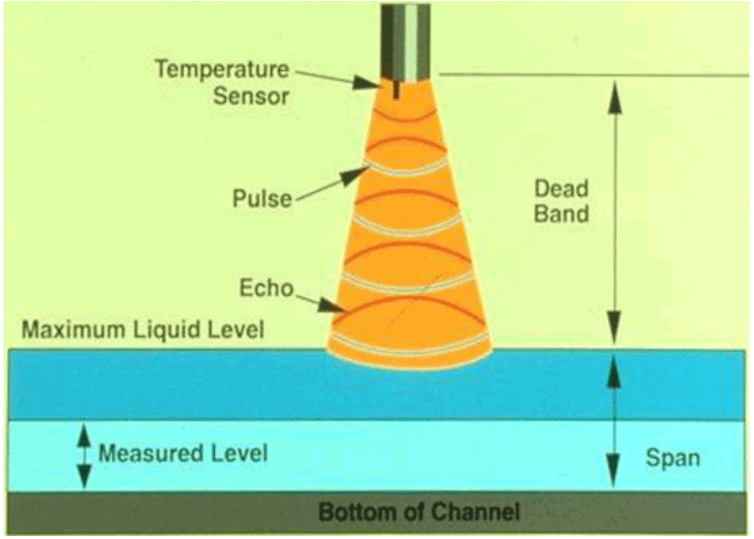




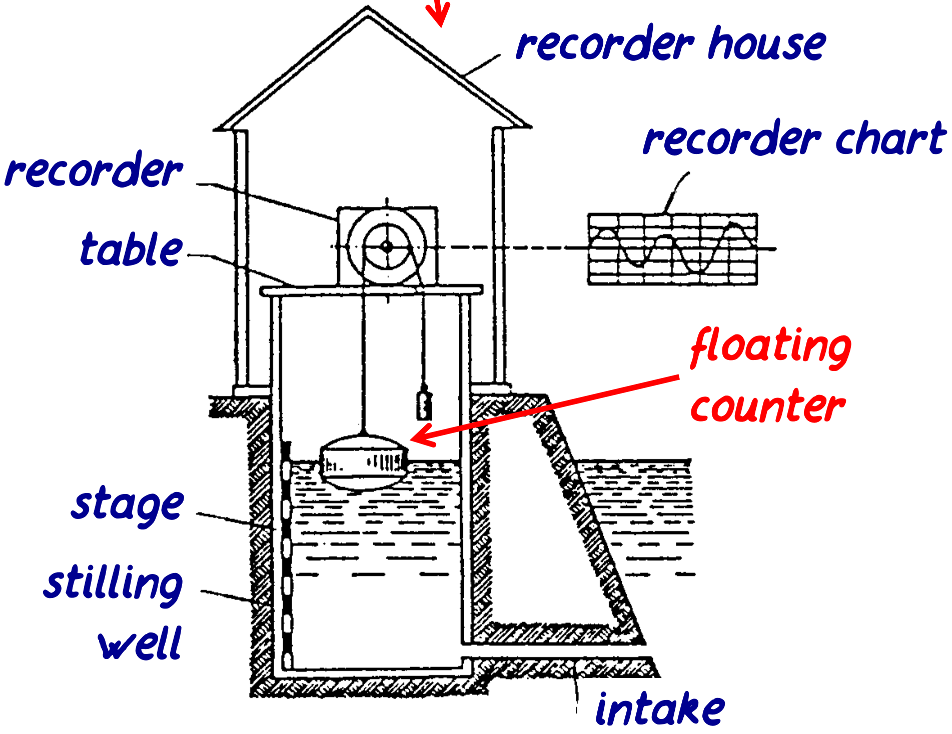
Streamflow measurement: water level (2)

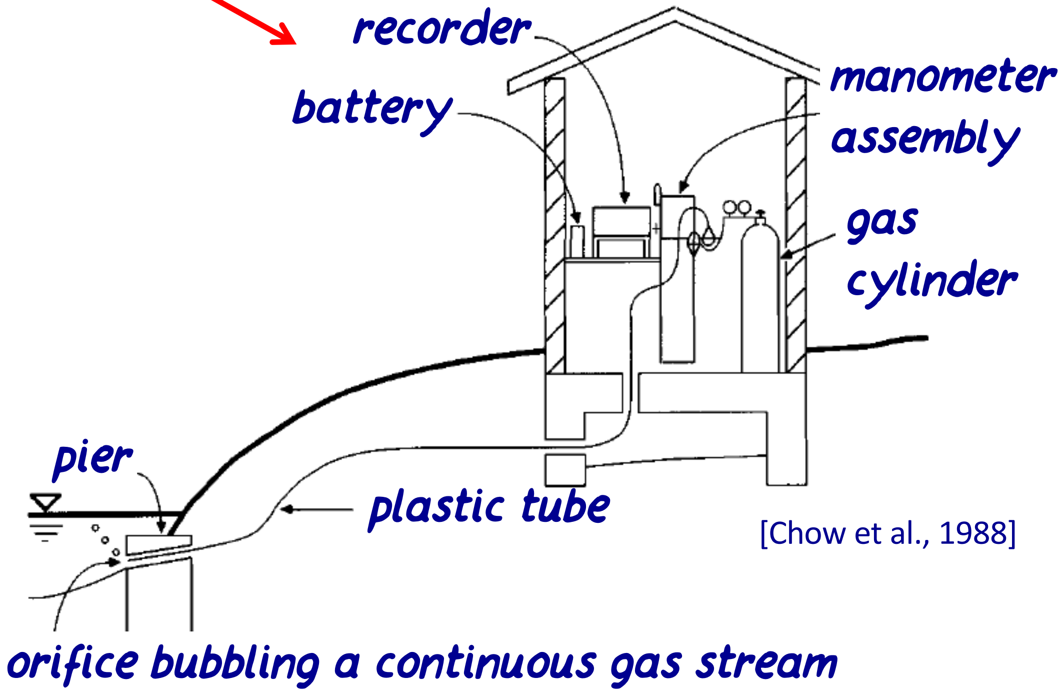
Typical water level measuring ***devices*** are

- ***ultrasonic gauges***
- ***pneumatic recorders***
- ***floating counters***



www.openchannelflow.com



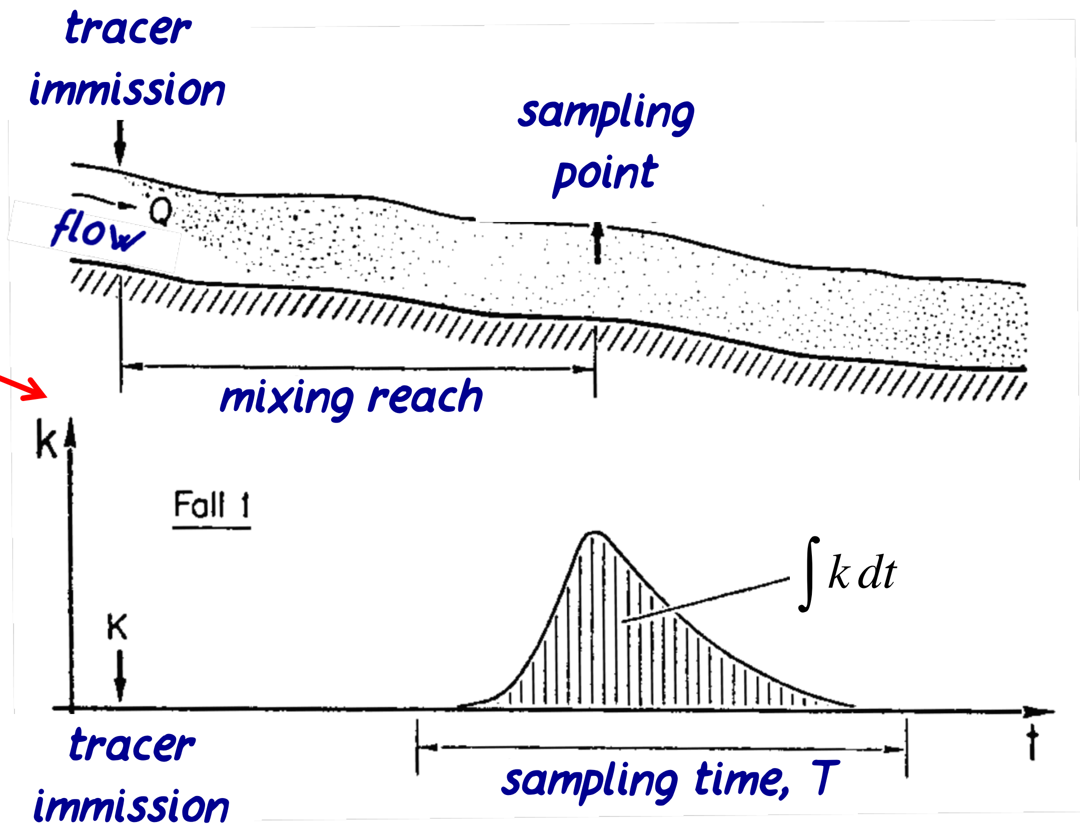


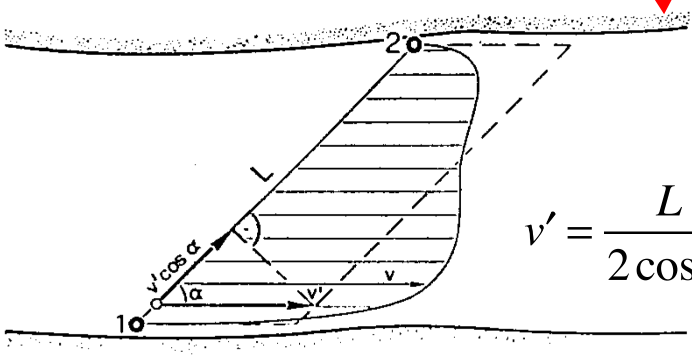
[Chow et al., 1988]

Streamflow measurement: velocity

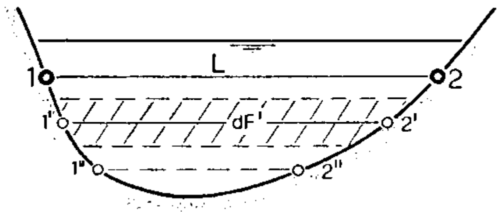
Velocity is measured by means of

- ***current meters (propellers)***
- ***flow measuring structures***
- ***acoustic doppler profiler***
- ***chemical methods***
- ***ultrasonic methods***



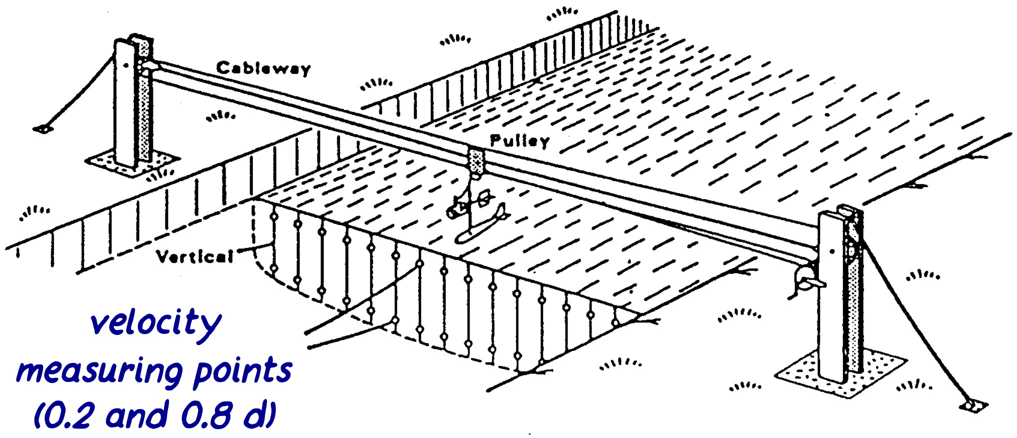


$$v' = \frac{L}{2\cos\alpha}\left(\frac{1}{t_1} - \frac{1}{t_2}\right)$$



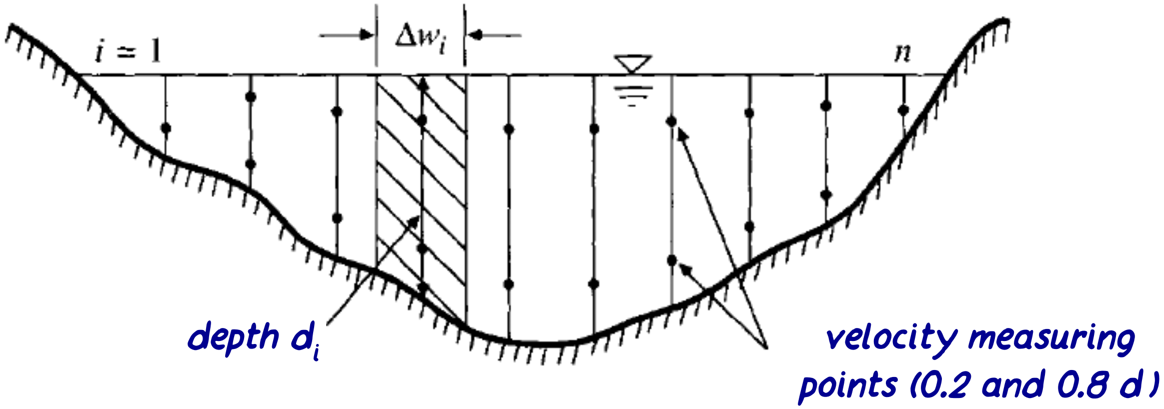
in steady state conditions → $Q = \dfrac{K}{\int_T k\,dt}$

Streamflow measurement: from velocity and water level to Q



At ***n*** regular ***intervals*** along the cross sections:

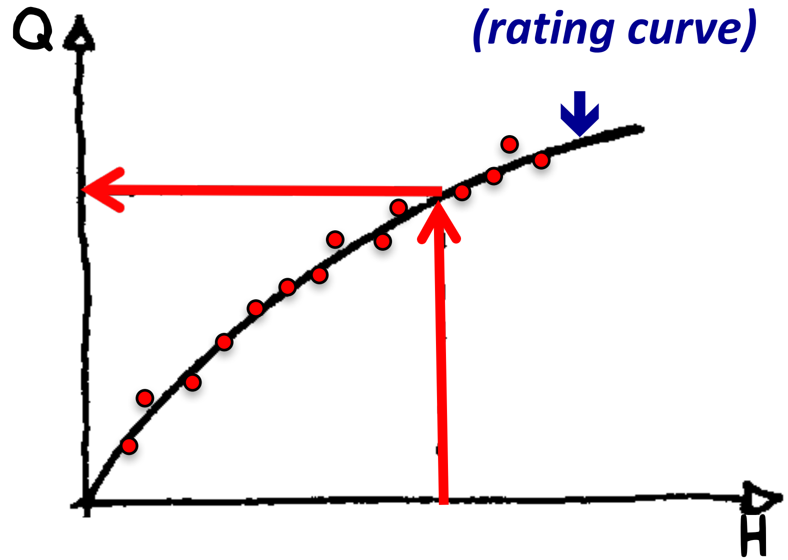
- ***depth measurement, d_i***
- ***velocity measurements at two depths ($0.2d_i$ and $0.8d_i$)***
- ***compute the discharge by integration***



$$Q = \sum_{i=1}^{n} \overline{v}_i \cdot d_i \cdot \Delta w_i$$

By ***repeating measurements*** and computation of Q for different depths in ***steady state*** conditions elaborate the

stage-discharge relationship (rating curve)



Rating curve: remarks

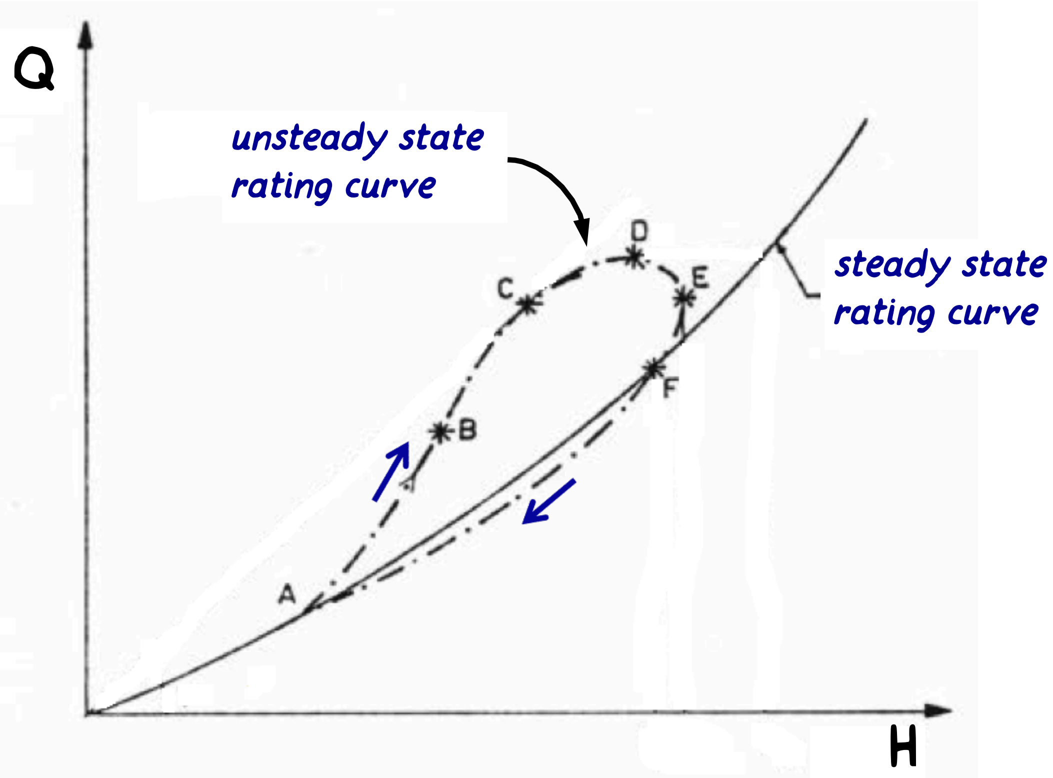
A rating curve is valid as long as

- ***the cross section does not change***
- ***for steady state conditions***

🡻

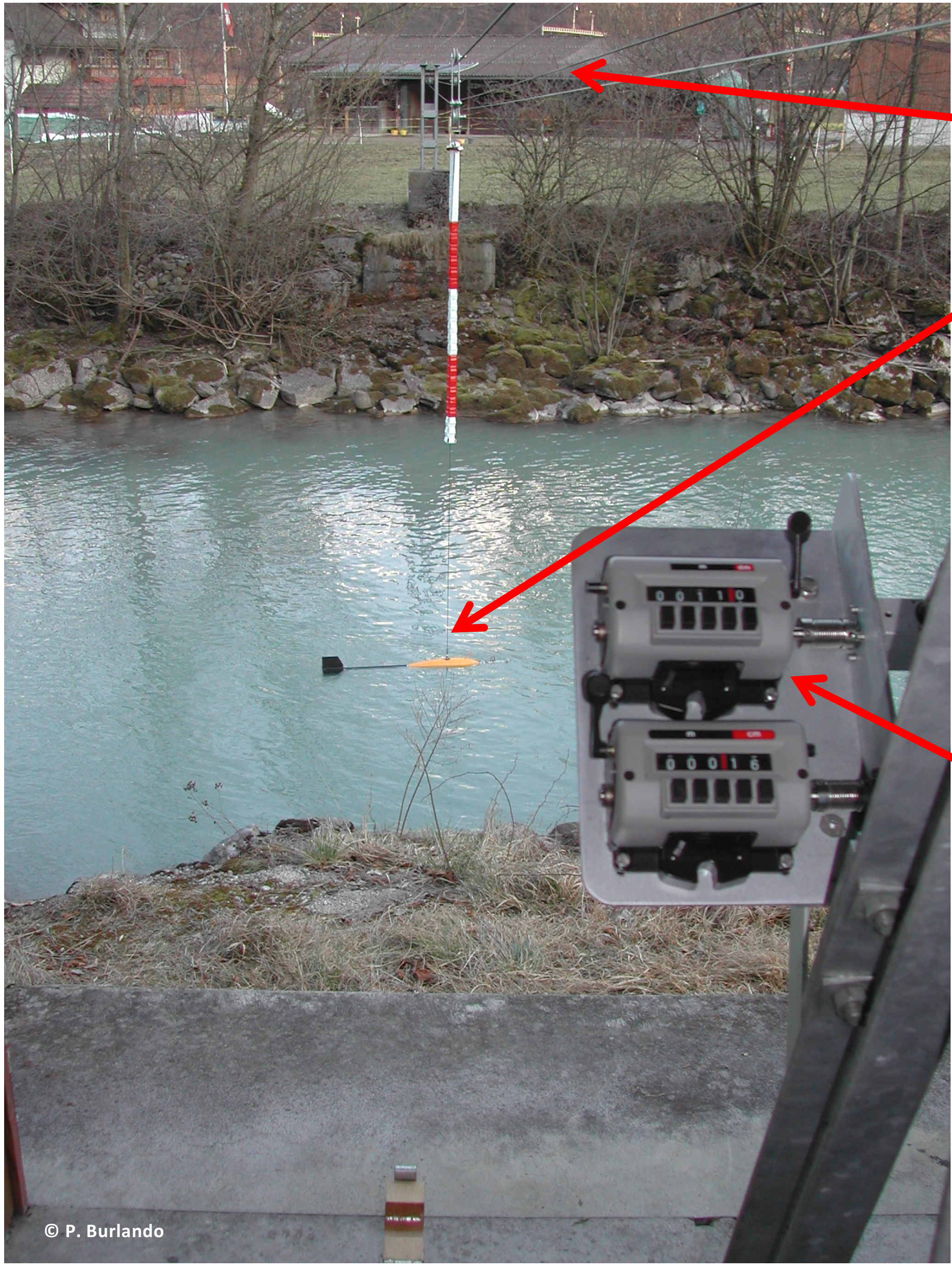
- periodical ***check*** of cross-section and ***update*** of the rating curve are necessary for high quality data
- measurements in flood conditions are difficult → ***extrapolation*** of the curve outside the calibration observation range is ***dangerous***

↳



Discharge measurement station (BAFU)

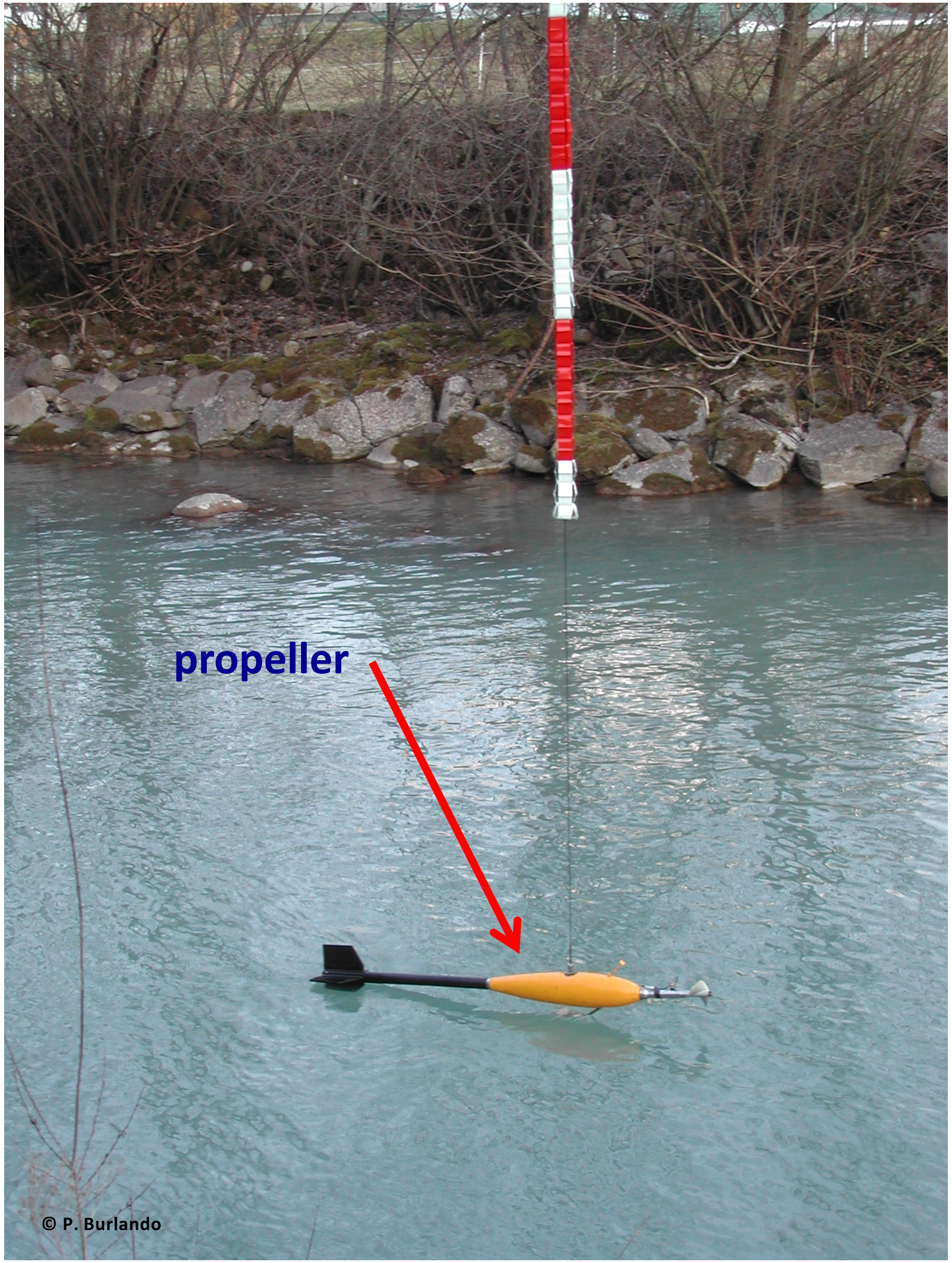
- **water level (pressure gauge)**
- **velocity (propeller)**
- **stable cross-section**



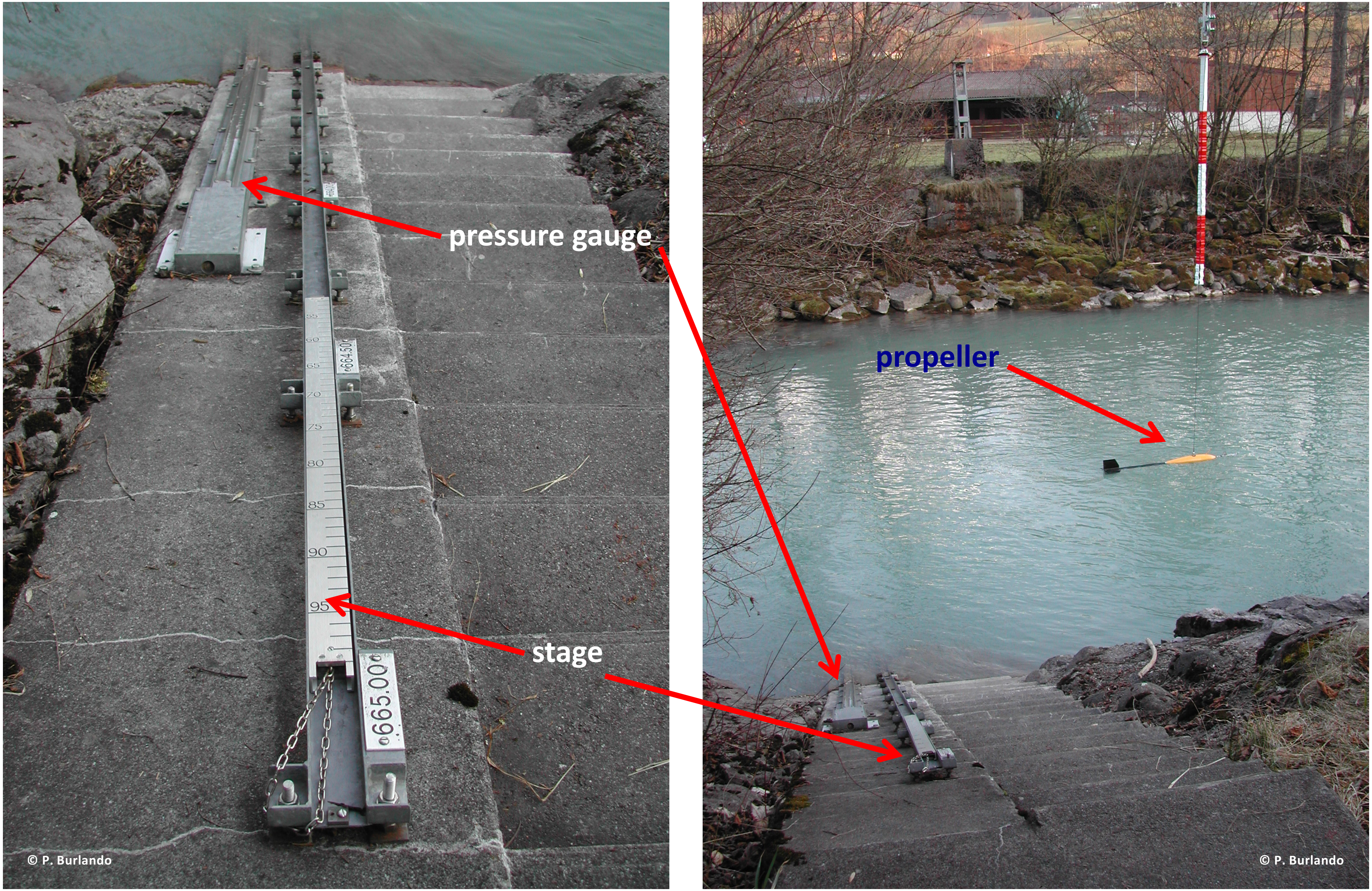
guiding cables

propeller

counter


propeller
© P. Burlando


propeller
operating
station
© P. Burlando


pressure gauge
stage
propeller
665.00
© P. Burlando
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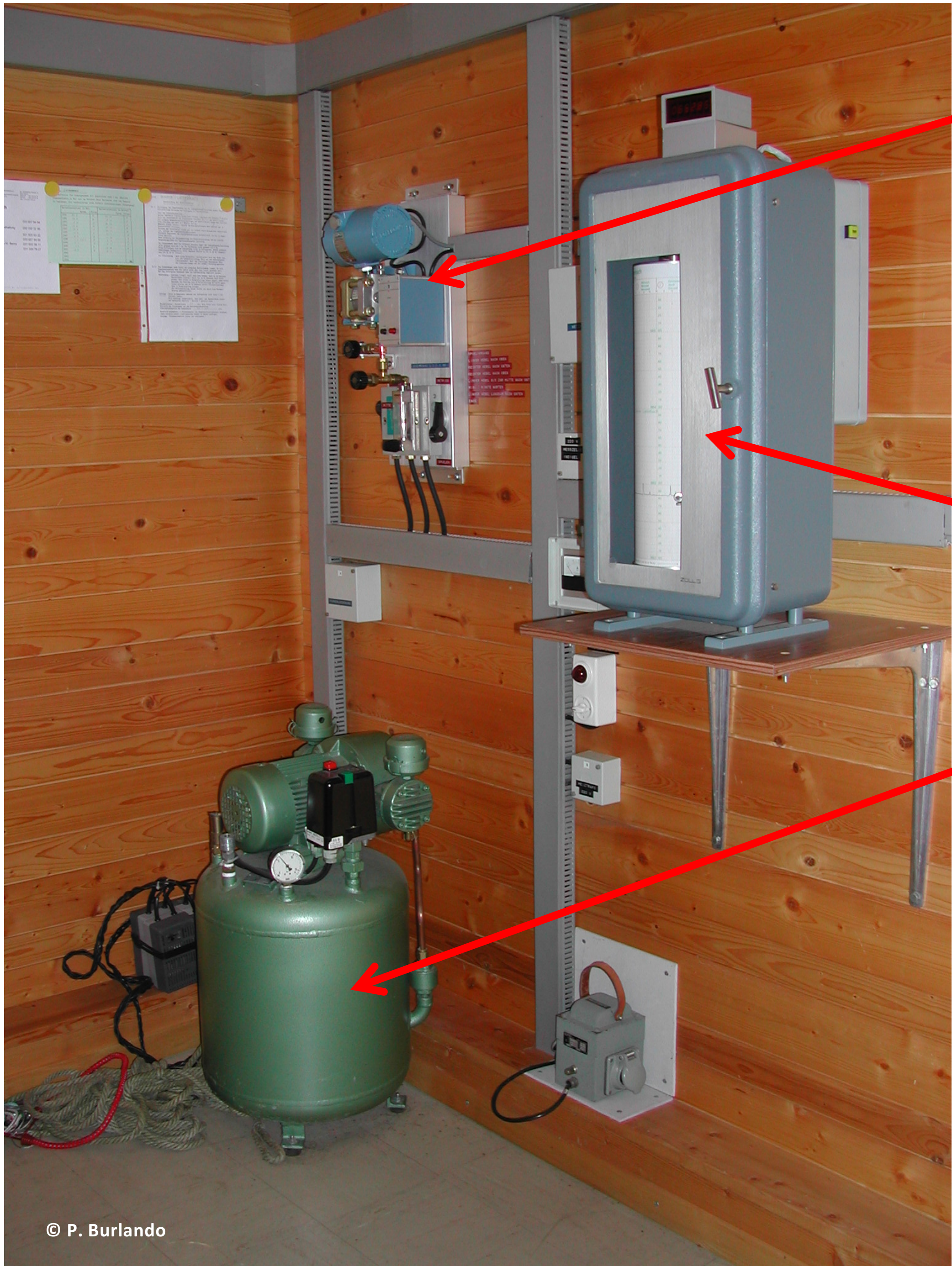


pressure gauge
electronic components

drum chart

compressor

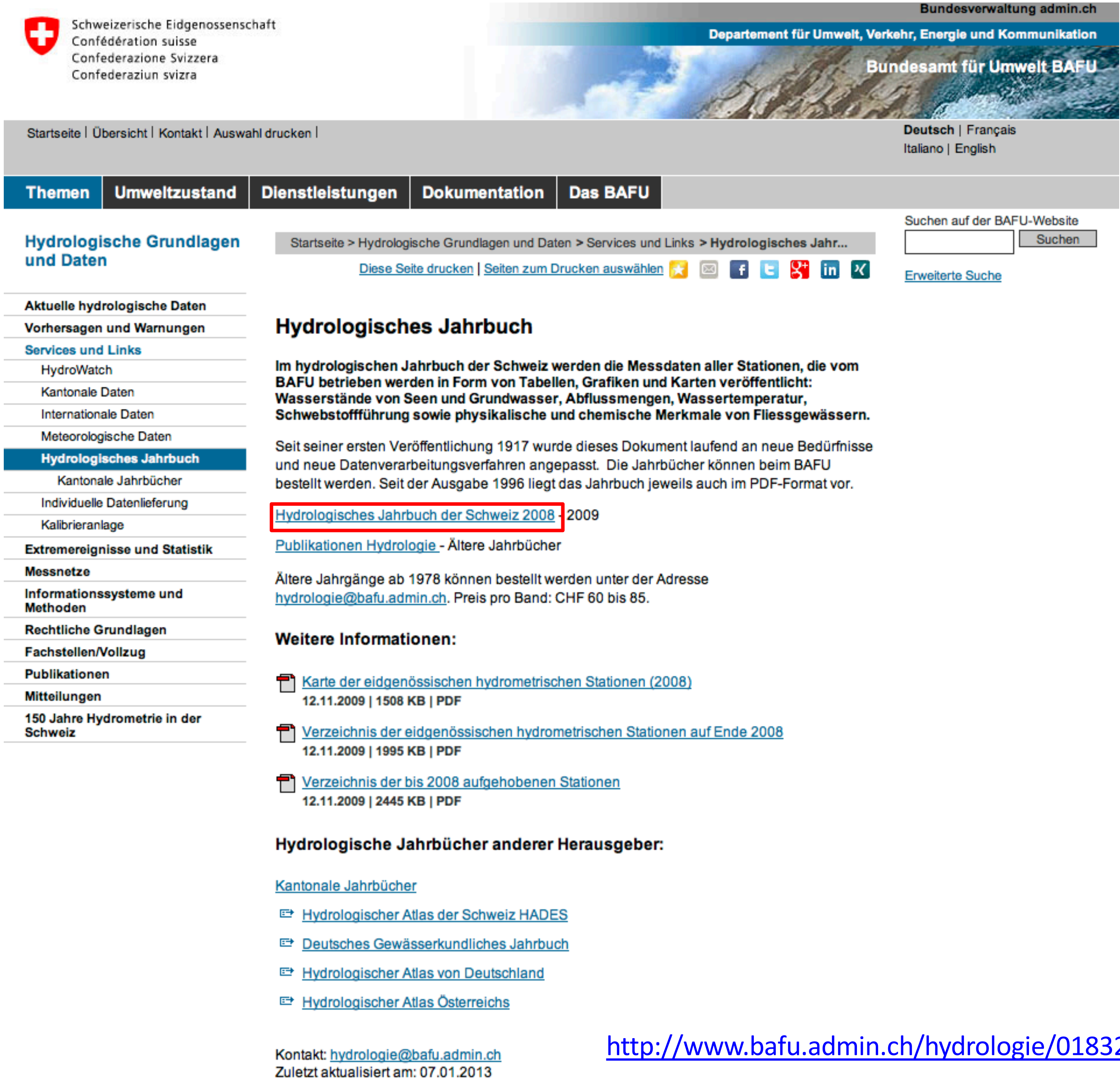
Streamflow data sources

Streamflow measurements are collected / elaborated by hydrologic agencies

- *in CH* → Hydrology Division of the Federal Office for the Environment

http://www.bafu.admin.ch/hydrologie/index.html?lang=de

Streamflow data sources: hydrological yearbook



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Hydrologisches Jahrbuch

Im hydrologischen Jahrbuch der Schweiz werden die Messdaten aller Stationen, die vom BAFU betrieben werden in Form von Tabellen, Grafiken und Karten veröffentlicht: Wasserstände von Seen und Grundwasser, Abflussmengen, Wassertemperatur, Schwebstofführung sowie physikalische und chemische Merkmale von Fliessgewässern.

Seit seiner ersten Veröffentlichung 1917 wurde dieses Dokument laufend an neue Bedürfnisse und neue Datenverarbeitungsverfahren angepasst. Die Jahrbücher können beim BAFU bestellt werden. Seit der Ausgabe 1996 liegt das Jahrbuch jeweils auch im PDF-Format vor.

Hydrologisches Jahrbuch der Schweiz 2008 - 2009

Publikationen Hydrologie - Ältere Jahrbücher

Ältere Jahrgänge ab 1978 können bestellt werden unter der Adresse hydrologie@bafu.admin.ch. Preis pro Band: CHF 60 bis 85.

Weitere Informationen:

Karte der eidgenössischen hydrometrischen Stationen (2008)
12.11.2009 | 1508 KB | PDF

Verzeichnis der eidgenössischen hydrometrischen Stationen auf Ende 2008
12.11.2009 | 1995 KB | PDF

Verzeichnis der bis 2008 aufgehobenen Stationen
12.11.2009 | 2445 KB | PDF

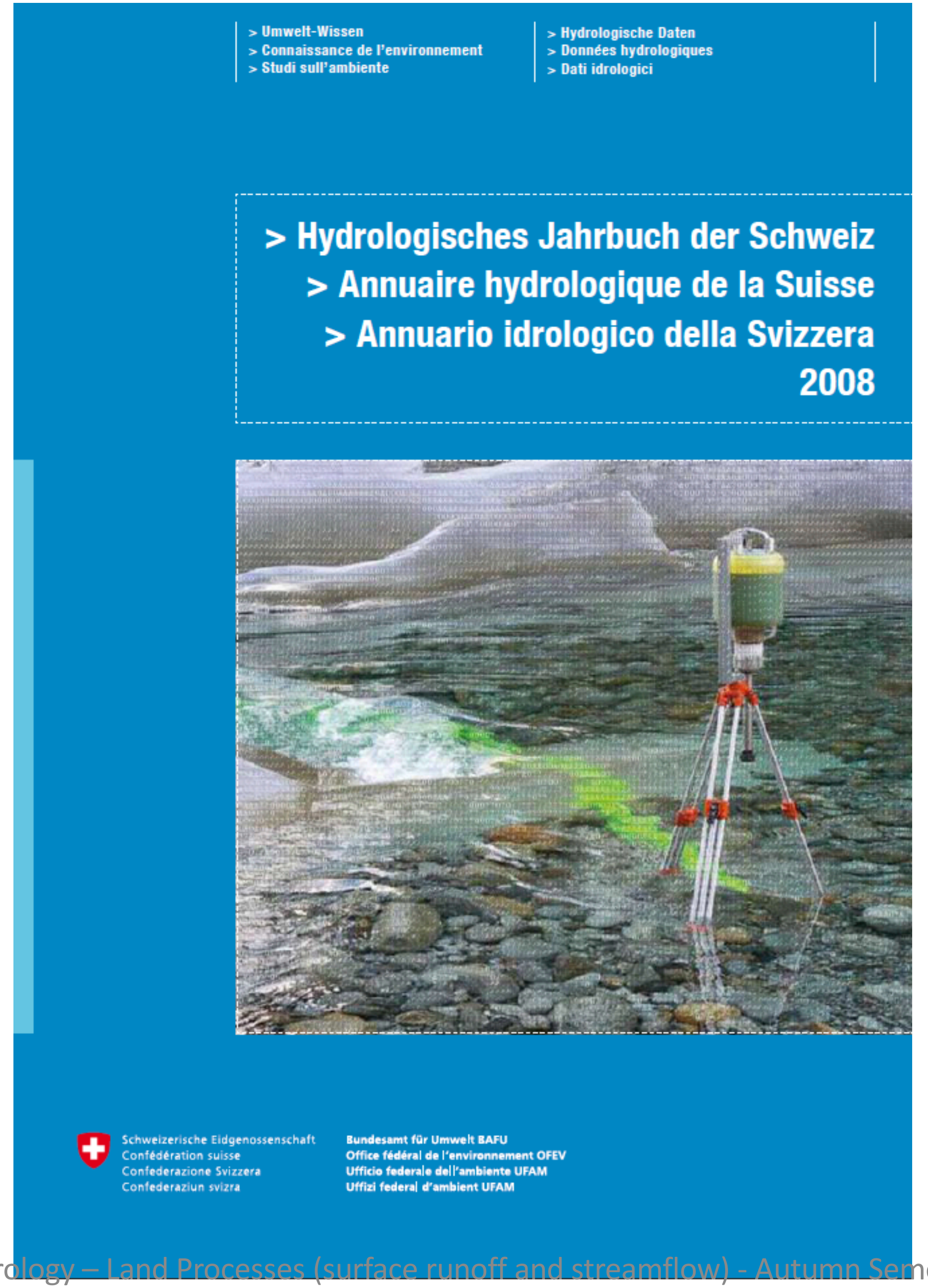
Hydrologische Jahrbücher anderer Herausgeber:

Kantonale Jahrbücher
- Hydrologischer Atlas der Schweiz HADES
- Deutsches Gewässerkundliches Jahrbuch
- Hydrologischer Atlas von Deutschland
- Hydrologischer Atlas Österreichs

Kontakt: hydrologie@bafu.admin.ch
Zuletzt aktualisiert am: 07.01.2013

http://www.bafu.admin.ch/hydrologie/01832/01852/index.html?lang=de

Streamflow data sources: hydrological yearbook



Streamflow data sources: hydrological yearbook

Dritter Teil

Abflüsse

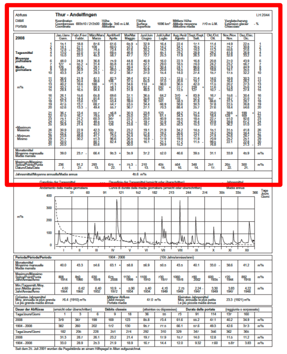
Troisième partie

Débits

Terza parte

Deflussi

Streamflow data sources: hydrological yearbook



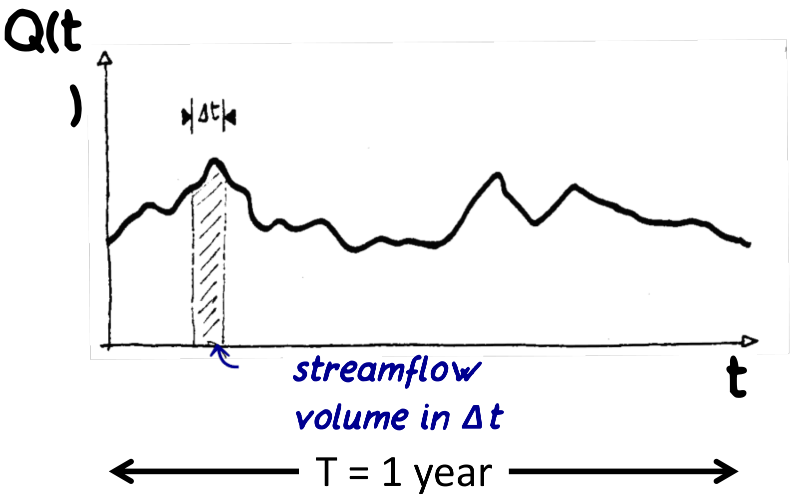
daily data

Abfluss	**Thur - Andelfingen**					LH 2044
Débit	Koordinaten	Höhe	Fläche	Mittlere Höhe	Vergletscherung	
Portata	Coordonnées 693510 / 272500	Altitude 356 m ü.M.	Surface 1696 km²	Altitude moyenne 770 m ü.M.	Extension glacier - %	
	Coordinate	Altitudine	Superficie	Altitudine media	Ghiacciaio	

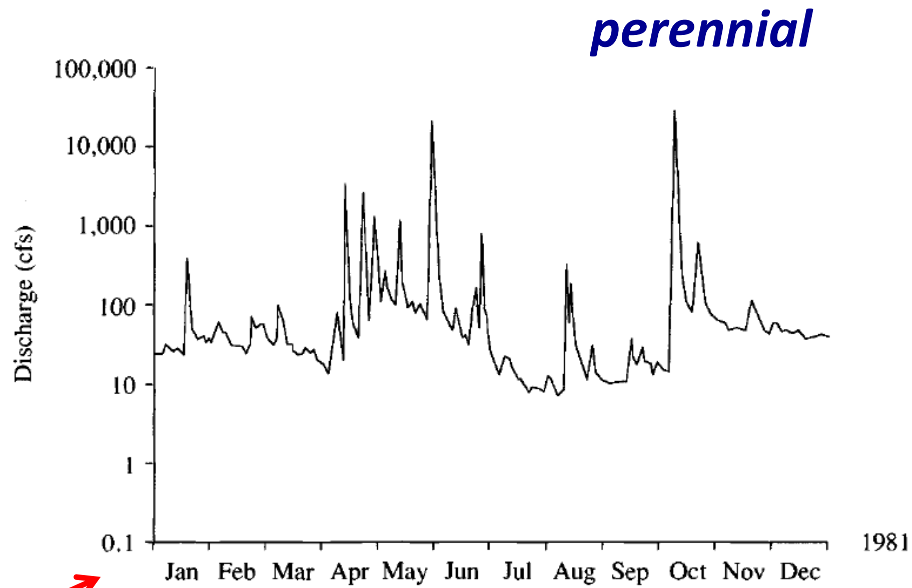
2008		Jan./Janv. Genn.	Febr./Févr. Febbr.	März/Mars Marzo	April/Avril Aprile	Mai/Mai Maggio	Juni/Juin Giugno	Juli/Juillet Luglio	Aug./Août Agosto	Sept./Sept. Sett.	Okt./Oct. Ott.	Nov./Nov. Nov.	Dez./Déc. Dic.	
	1	15.1	18.8	87.6	61.6	65.9 +	32.9	16.4	22.4	17.1	11.4	74.9	22.5	1
	2	14.1	27.1	108	60.0	52.3	23.7	14.2	34.1	16.5	11.2	75.7	30.8	2
	3	12.8 -	28.0	74.5	73.4	47.6	30.2	14.3	25.3	14.0	11.3	55.6	31.6	3
Tagesmittel	4	13.0	22.0	57.9	69.5	46.8	32.2	45.1	19.2	28.9	29.2	41.8	26.9	4
	5	15.0	22.3	45.3	58.7	47.7	72.7	25.3	17.8	26.3	27.6	32.8	33.2	5
Moyenne journalière	6	48.0	24.9	36.8	75.9	44.8	46.9	16.0	22.3	16.8	20.8	27.0	43.9	6
	7	127 +	55.2 +	31.4	85.8	41.6	52.1	29.0	18.5	74.0	24.2	23.2	56.7	7
Media giornaliera	8	126	40.2	28.1	62.1	39.4	37.2	30.4	24.1	86.6	28.0	21.9	44.9	8
	9	59.9	30.9	24.7 -	49.0 -	38.5	30.9	20.8	18.5	40.6	19.8	19.1	35.5	9
	10	43.3	24.7	29.3	67.2	38.7	27.0	15.4	14.0	27.4	15.7	17.5	32.2	10
	11	36.6	21.9	47.1	82.3	38.4	61.2	13.3 -	12.5 -	21.4	14.0	16.8	30.3	11
	12	33.4	20.4	98.6	106	37.5	65.0	31.0	20.8	19.7	12.8	16.4	28.2	12
	13	40.2	18.6	188 +	71.3	34.6	114 +	98.0	36.5	42.0	11.5	20.2	27.3	13
m³/s	14	33.2	17.1	90.3	58.1	31.8	82.2	242 +	27.7	239 +	11.6	21.8	25.6	14
	15	29.4	16.5	94.4	59.1	31.9	48.0	141	72.5	127	10.7 -	18.0	27.4	15
	16	26.1	15.6	65.8	69.6	37.1	36.5	64.2	370 +	83.9	16.7	15.6 -	30.4	16
	17	25.3	14.4	81.6	61.5	32.1	35.6	103	103	52.3	157 +	18.7	31.0	17
	18	31.3	13.6	120	53.4	39.0	36.7	141	58.3	41.8	66.6	31.3	28.7	18
	19	47.5	13.7	68.7	54.7	53.5	34.4	66.9	38.6	30.3	37.8	22.5	26.8	19
	20	52.6	13.3 -	49.4	55.7	36.7	27.1	70.3	88.4	25.7	27.6	18.4	54.6	20
	21	36.7	13.4	55.7	56.8	30.3	23.8	123	48.2	21.4	23.0	39.6	199 +	21
	22	47.0	16.7	79.5	379 +	25.0	20.7	61.1	34.3	19.5	18.4	128 +	169	22
	23	75.1	21.2	60.3	347	22.2	20.0	40.9	55.5	18.5	22.7	51.0	92.6	23
	24	42.2	19.2	48.5	175	21.3 -	19.7	31.9	78.2	16.4	20.9	39.8	67.2	24
	25	34.9	21.4	45.0	126	23.8	18.7	26.3	50.3	15.3	17.0	36.2	51.0	25
+Maximum Massimo	26	30.9	22.9	42.3	105	23.2	19.1	21.9	34.2	14.5	15.1	31.5	41.8	26
	27	25.2	33.4	43.2	82.2	23.6	21.4	19.2	26.6	13.2	14.2	29.6	34.4	27
- Minimum Minimo	28	23.8	48.8	41.7	73.5	25.4	16.8	21.0	22.3	12.1	21.4	25.6	28.7	28
	29	21.7	30.2	51.3	96.6	26.5	14.9 -	17.9	19.4	11.9	70.9	25.2	25.1	29
	30	20.0		80.1	82.4	26.8	16.1	21.1	17.2	11.5 -	99.5	22.1	22.8	30
	31	20.0		83.6		30.0		29.9	15.2		76.8		21.3 -	31
Monatsmittel Moyenne mensuelle Media mensile		39.0	23.7 -	66.4	95.3 +	35.9	37.2	52.0	46.6	39.5	31.1	33.9	45.9	m³/s
Maximum/Massimo Spitze/Pointe/Punta Datum/Date/Data		236 7.	91.2 27.	293 13.	675 + 22.	75.3 - 1.	210 13.	405 14.	564 16.	348 14.	251 17.	265 22.	300 21.	m³/s
Jahresmittel/Moyenne annuelle/Media annua						45.6 m³/s								

Streamflow regimes

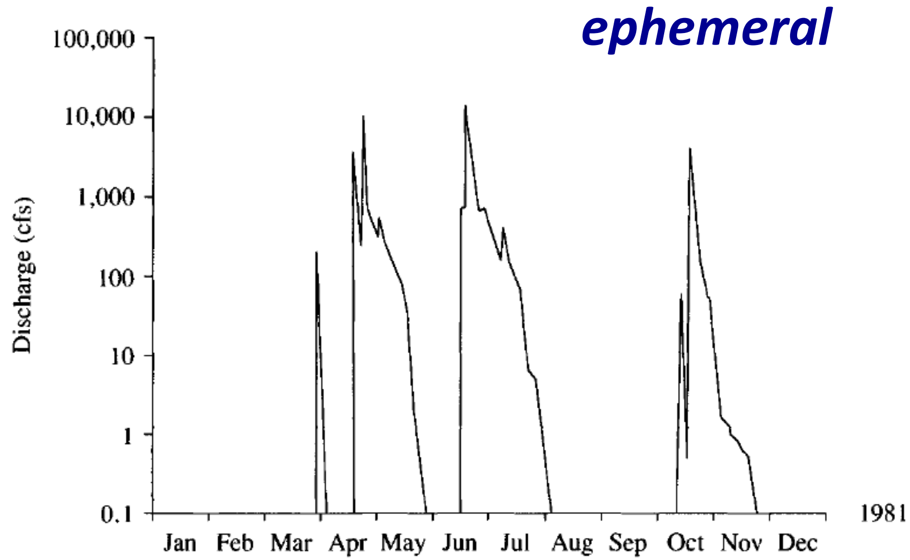
Annual hydrograph



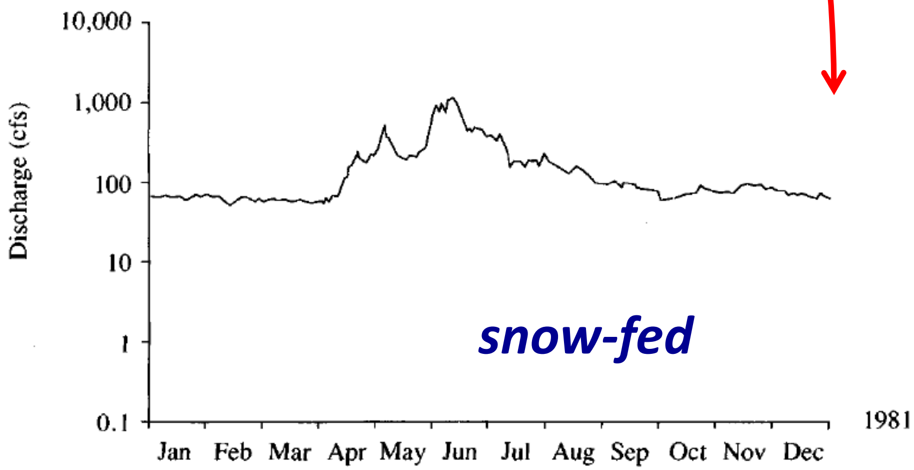
Examining the annual hydrograph allows to identify the ***streamflow regime***, e.g.



(*a*) Mill Creek near Belville, Texas (watershed area = 376 mi^2)

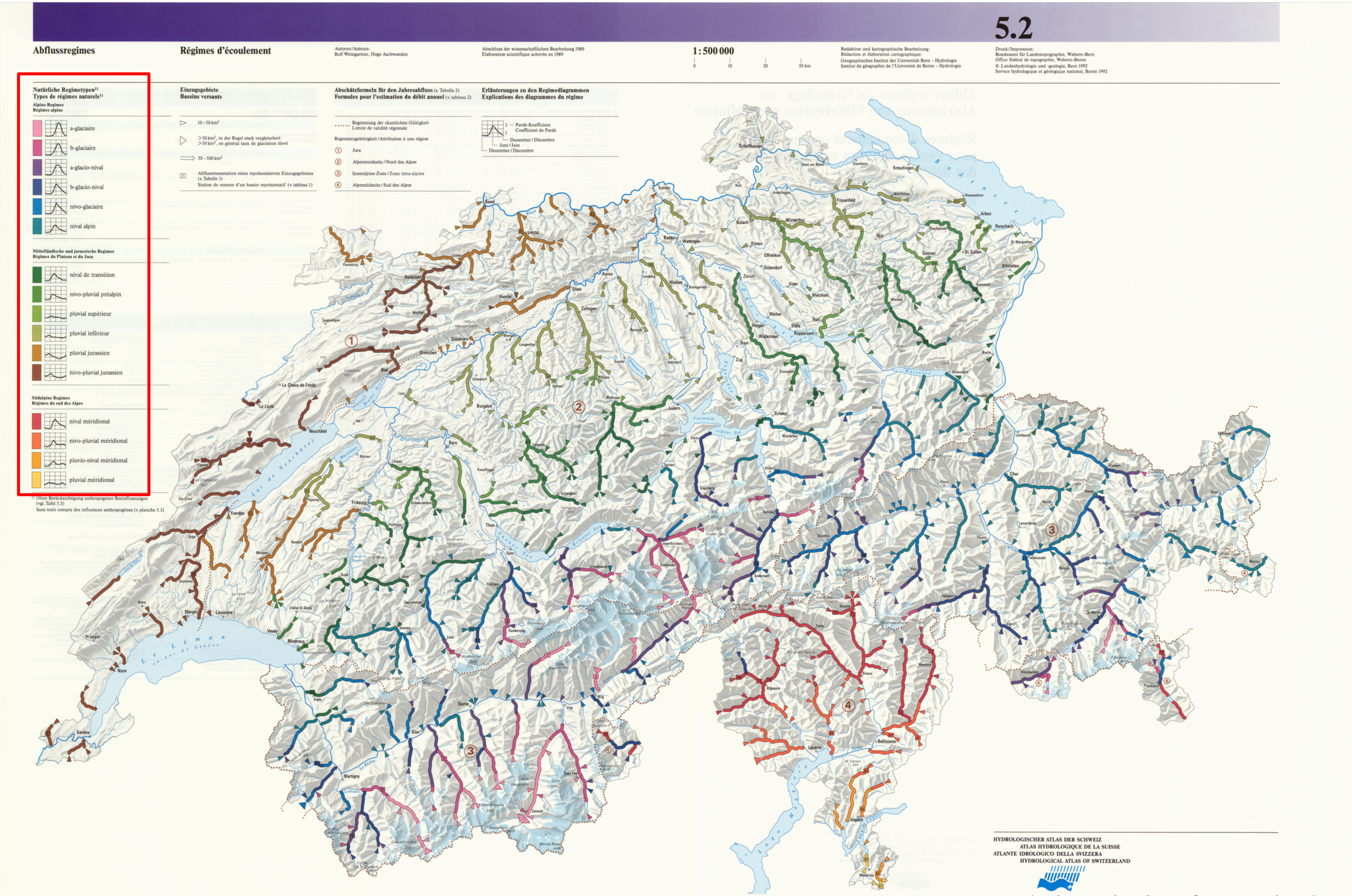


(*b*) Frio River near Uvalde, Texas (watershed area = 661 mi^2)



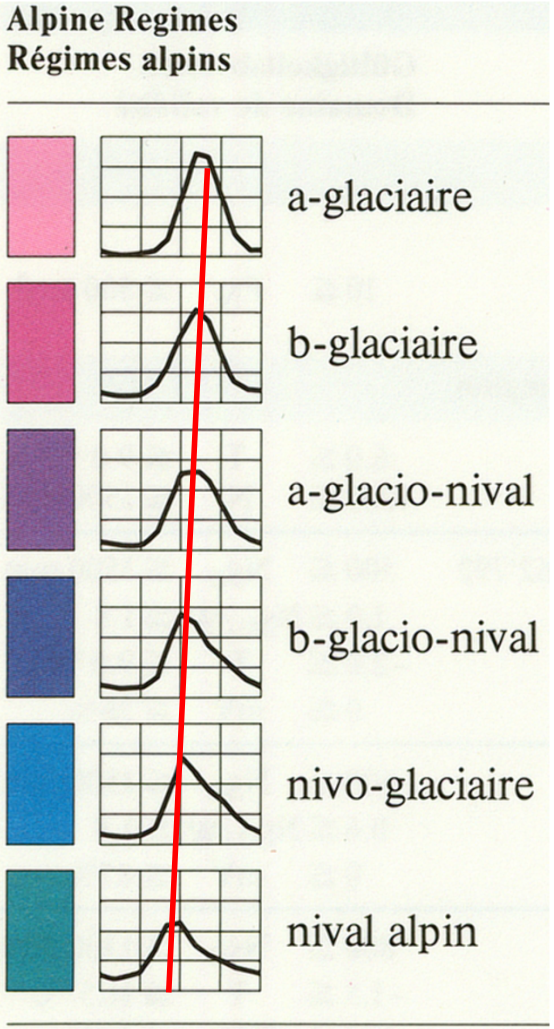
(*c*) East River at Almont, Colorado (watershed area = 289 mi^2)

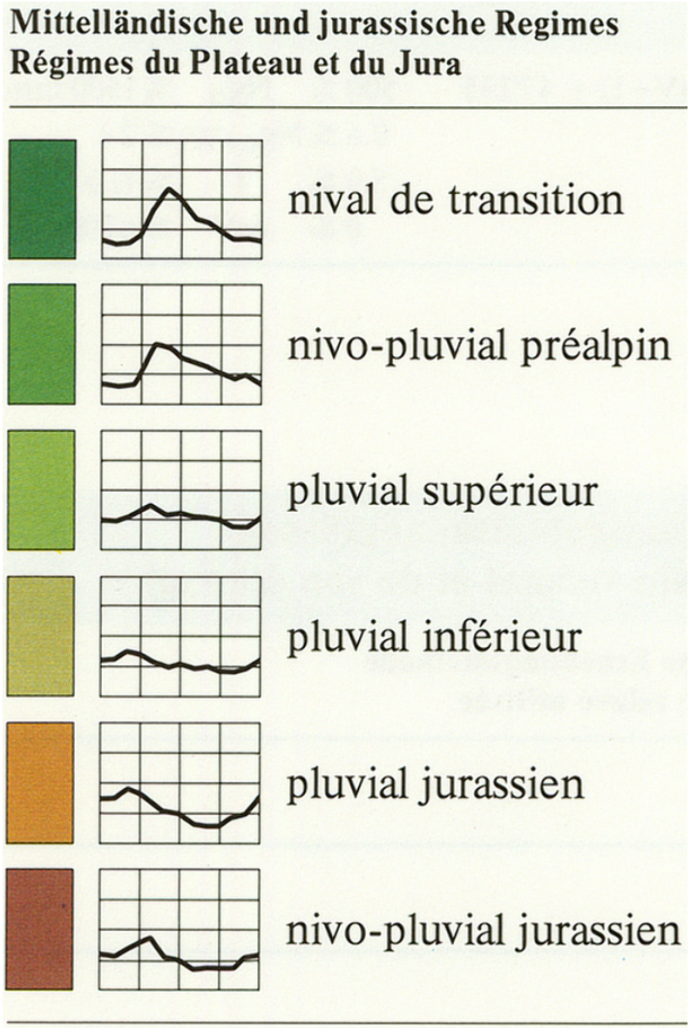
Streamflow regimes in Switzerland

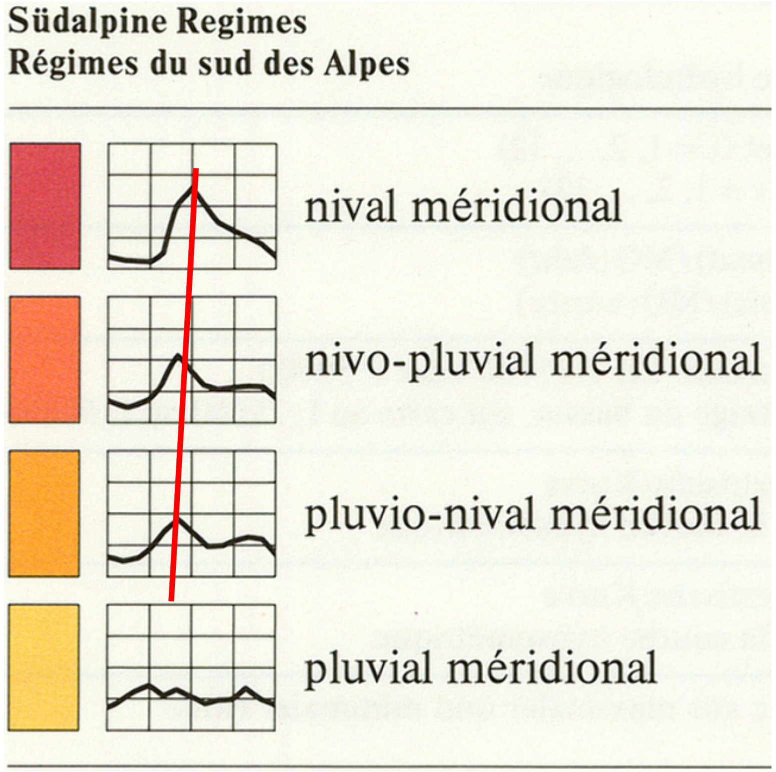


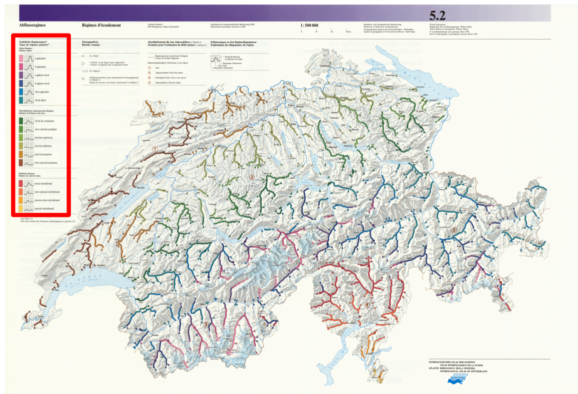
source: Hydrological Atlas of Switzerland

Streamflow regimes in Switzerland



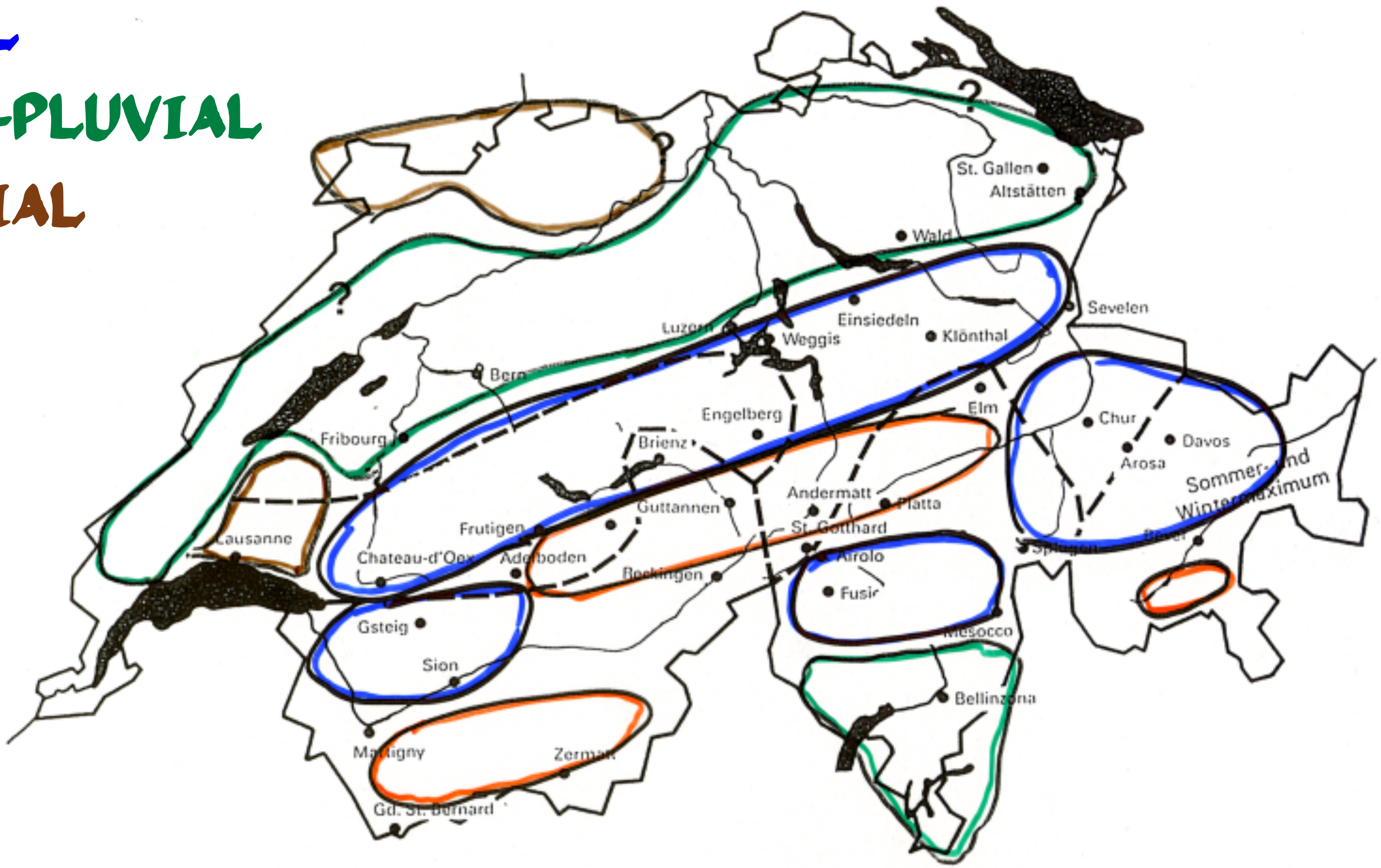






Streamflow (macro)regimes in Switzerland

- GLAZIAL
- NIVAL
- NIVO-PLUVIAL
- PLUVIAL

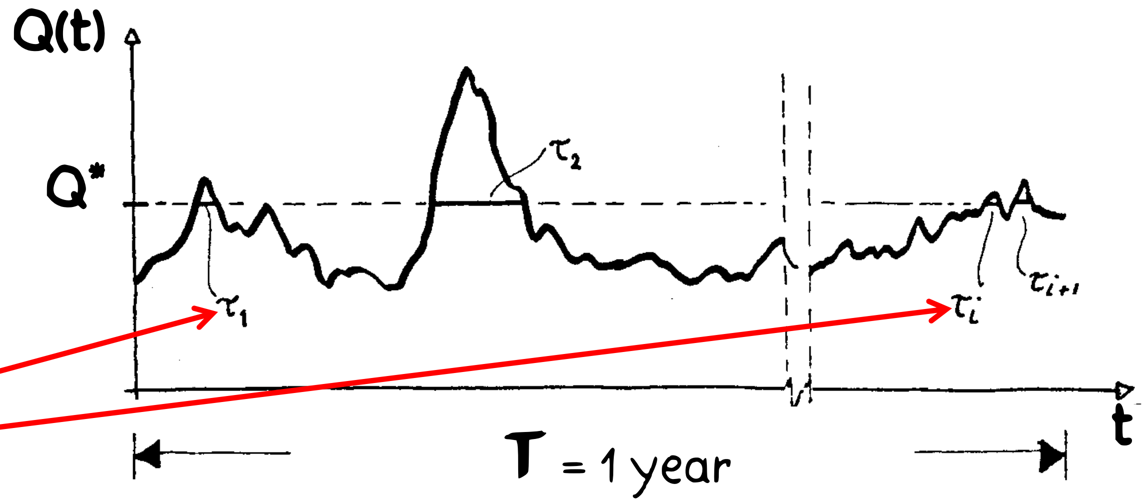


Flow duration curve

It provides the ***percentage of time that the flow in a stream is likely to equal or exceed some specified value of interest***.

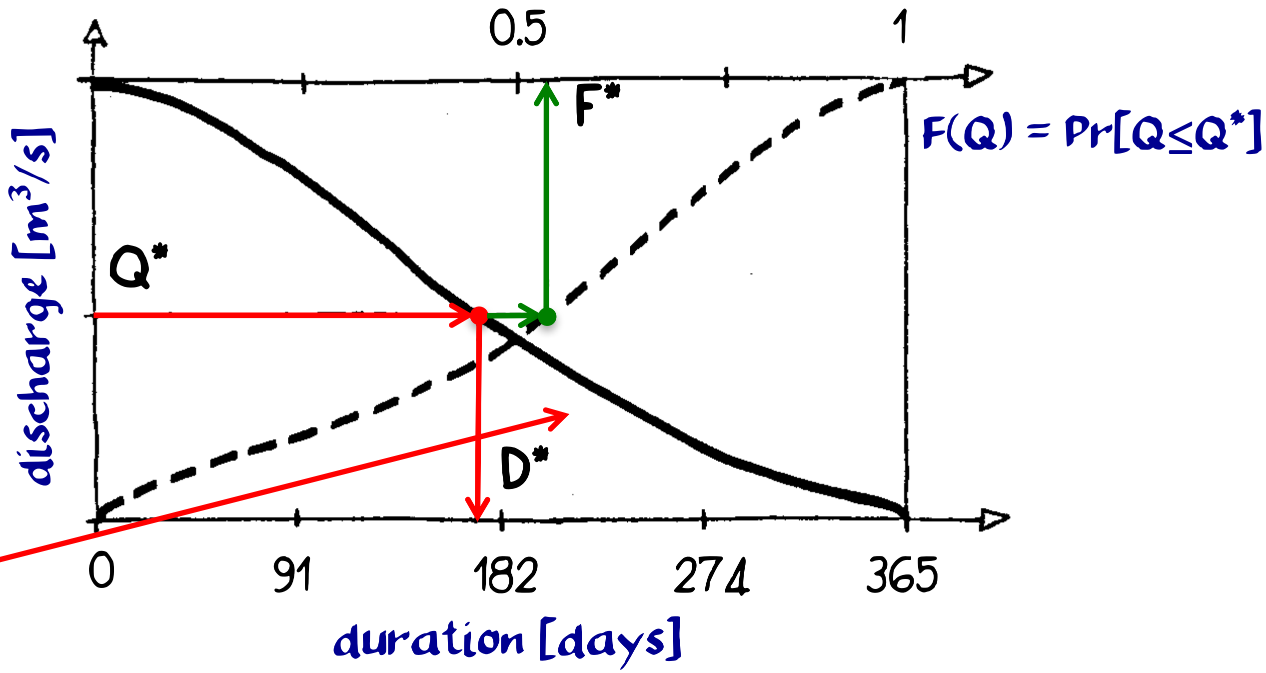
↳ frequency information

Duration of Q* → $\sum_i \tau_i$



The ***construction of the curve*** is frequently done using daily data:

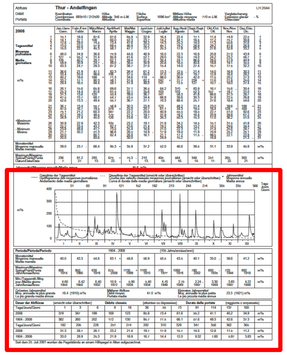
1. *for each year* **sort** *the* **daily data** *in descending order*
   ↳ highest flow exceeded for 1 day, 2nd highest for 2 days, …, lowest for 365 days.
2. *compute the* **average** *of ranked flows for each ranking position*
3. *plot the* **flow duration curve** *using the averaged flow for each ranking position*

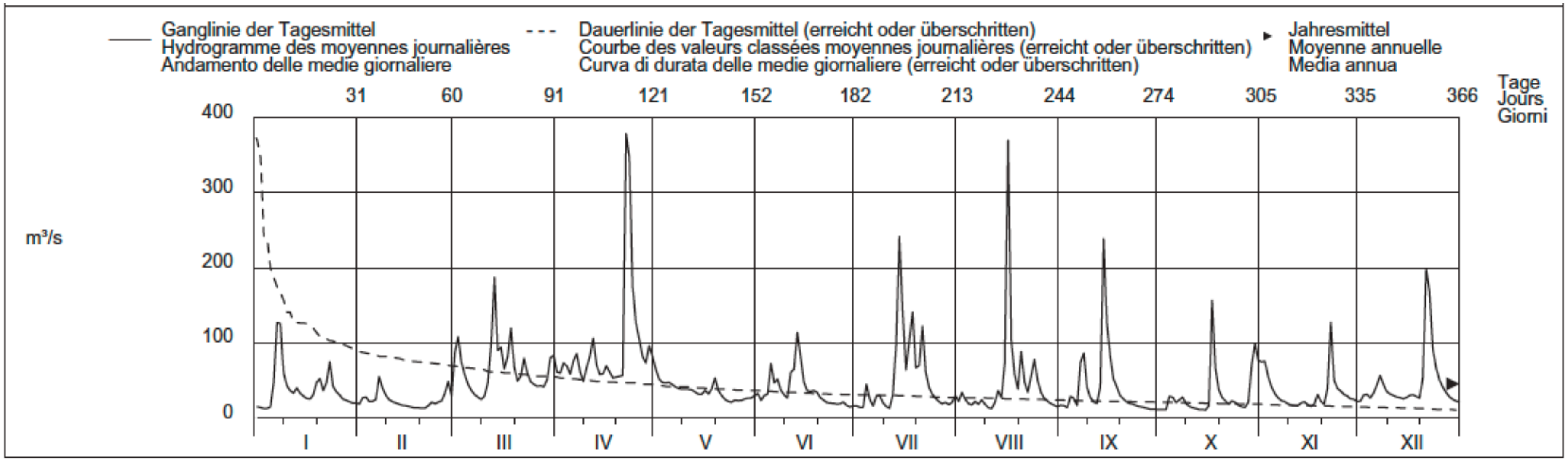


$Pr[Q \geq Q^*] = D(Q^*)/T = D^*/T; \quad Pr[Q \leq Q^*] = F(Q) = 1 - D^*/T$

Streamflow data sources: hydrological yearbook

daily data – flow duration curve





Periode/Période/Periodo				1904 - 2008			(105 Jahre/années/anni)						
Monatsmittel Moyenne mensuelle Media mensile	40.0	43.3	54.6	63.1 +	58.8	56.9	50.5	43.5	40.1	33.0 -	38.6	41.2	m³/s
Maximum/Massimo Spitze/Point/Punta Jahr/Année/Anno	808 1914	850 1990	630 1978	675 2008	1130 + 1999	1100 1910	730 1977	1060 1978	780 2002	600 - 1935	720 1944	892 1918	m³/s
Min./Tagesmitt./Moy. jour./Media giorno Jahr/Année/Anno	4.60 1954	6.42 1950	6.40 1932	10.9 + 1972	5.90 1934	5.40 1934	4.70 1949	2.75 1949	2.24 - 1947	3.30 1949	3.83 1947	4.22 1948	m³/s
Grösstes Jahresmittel Moy. annuelle la plus grande La più grande media annua	76.4 (1910) m³/s			Mittlerer Abfluss Débit moyen Portata media		47.0 m³/s		Kleinstes Jahresmittel Moy. annuelle la plus petite La più piccola media annua			23.3 (1921) m³/s		

Dauer der Abflüsse	(erreicht oder überschritten)		Débits classés		(atteintes ou dépassées)			Durata delle portate		(raggiunte o sorpassate)			
Tage/Jours/Giorni	1	3	6	9	18	36	55	73	91	114	137	160	
2008	379	347	199	169	123	85.8	73.4	61.6	55.2	47.1	40.2	34.9	m³/s
1904 - 2008	382	260	202	172	130	95.7	77.5	66.1	57.6	49.3	42.6	37.3	m³/s
Tage/Jours/Giorni	182	205	228	251	274	292	310	329	347	356	362	365	
2008	31.3	28.7	26.1	23.2	21.4	19.7	17.9	15.7	14.0	12.8	11.5	11.2	m³/s
1904 - 2008	33.0	28.9	25.3	21.9	18.9	16.7	14.4	12.0	9.32	7.60	5.87	3.83	m³/s

Seit dem 25. Juli 2001 wurden die Pegelstände an einem Hilfspegel in Alten aufgezeichnet.

Infiltration
example of application of knowledge

Engineering Problem:

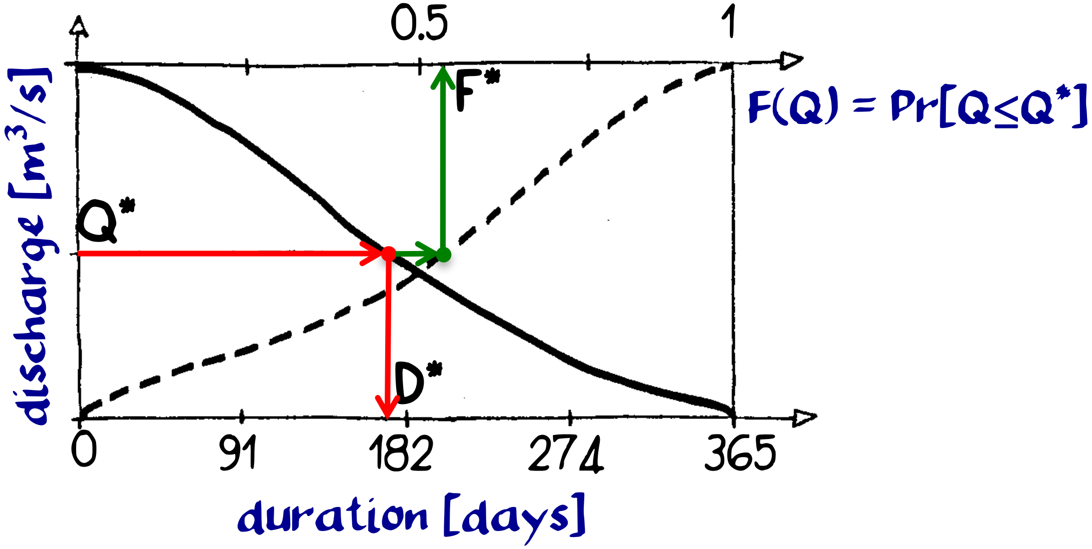
↳ *Estimate the amount of time (duration) for which water can be abstracted from a river to satisfy the demand of a water supply system*

Solution

↳ *Compute the flow duration curve from daily historical streamflow observations and read on the plot the duration corresponding to the water demand*

Method

↳ *flow duration curve*



Infiltration
example of application of knowledge

Engineering Problem:

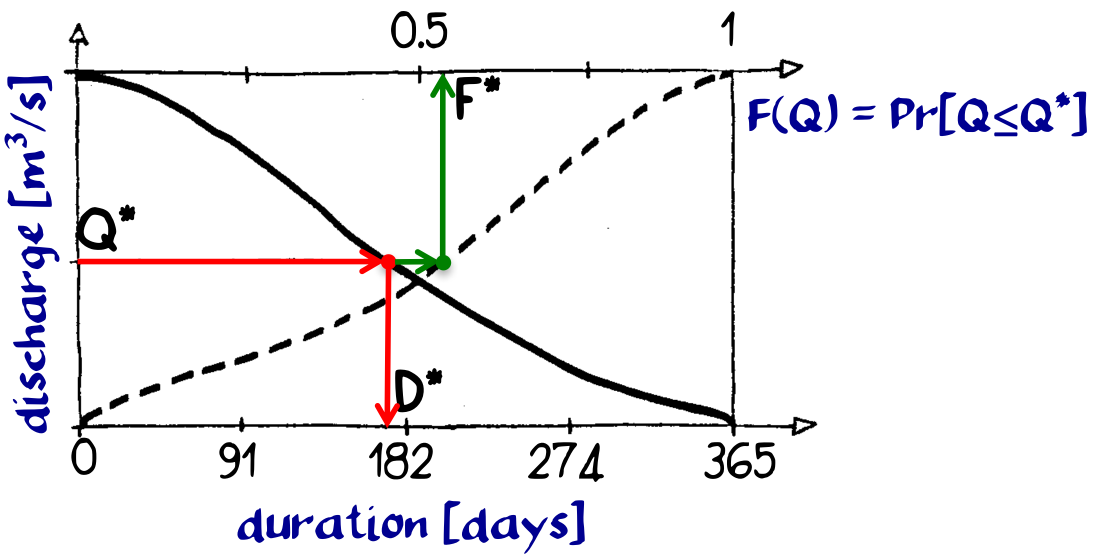
↳ *Estimate the amount of time (duration) for which water can be abstracted from a river to satisfy the demand of a run-of-river hydropower system*

Solution

↳ *Compute the flow duration curve from daily historical streamflow observations and read on the plot the duration corresponding to minimum flow required by the hydropwer system*

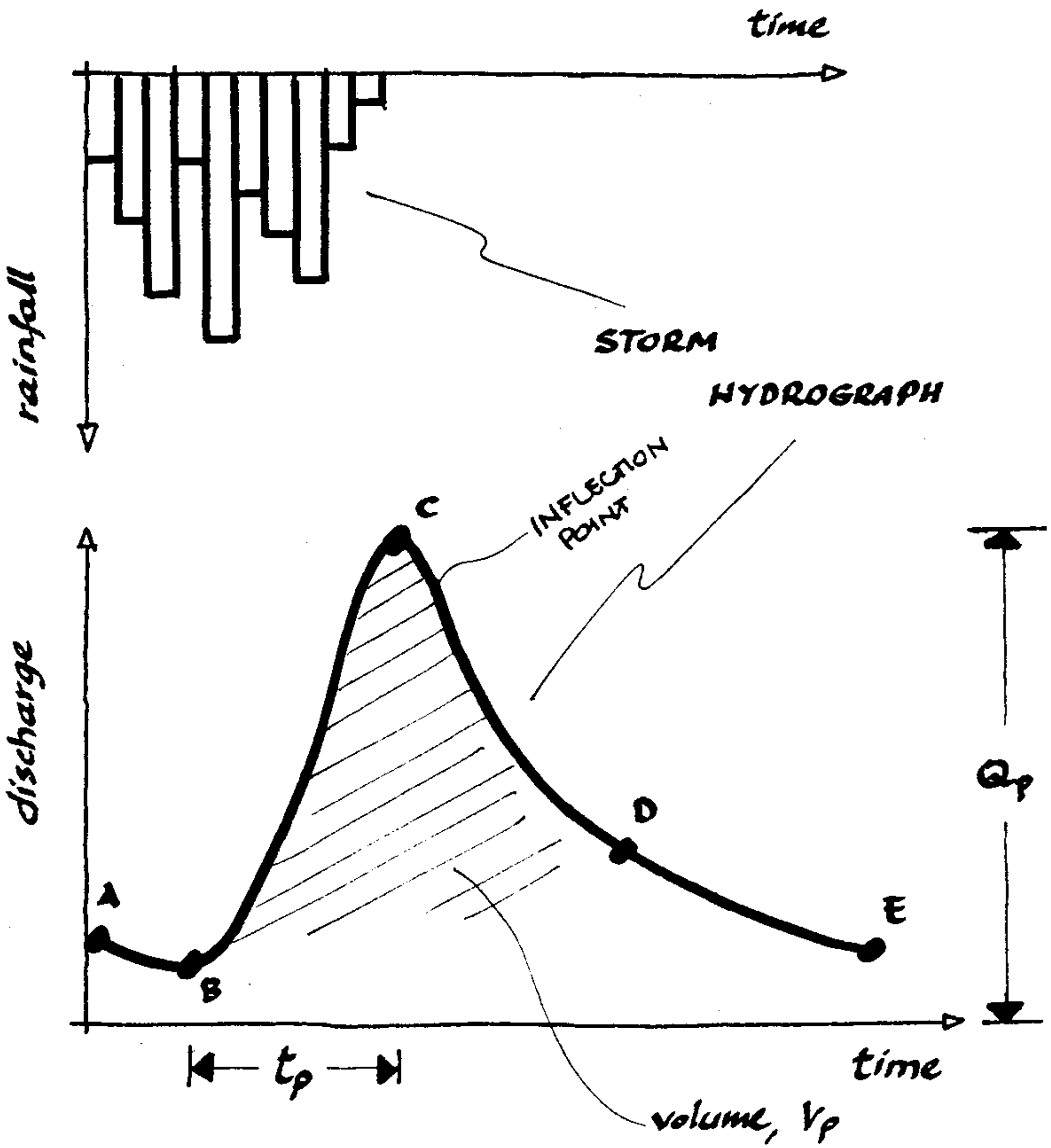
Method

↳ *flow duration curve*



Flood hydrograph analysis

Flood hydrograph analysis - nomenclature



hydrograph components

- AB → baseflow recession
- BC → rising limb
- CD → falling limb
- DE → baseflow recession
- t_p → rime to peak
- V_p → flood volume
- Q_p → flood peak

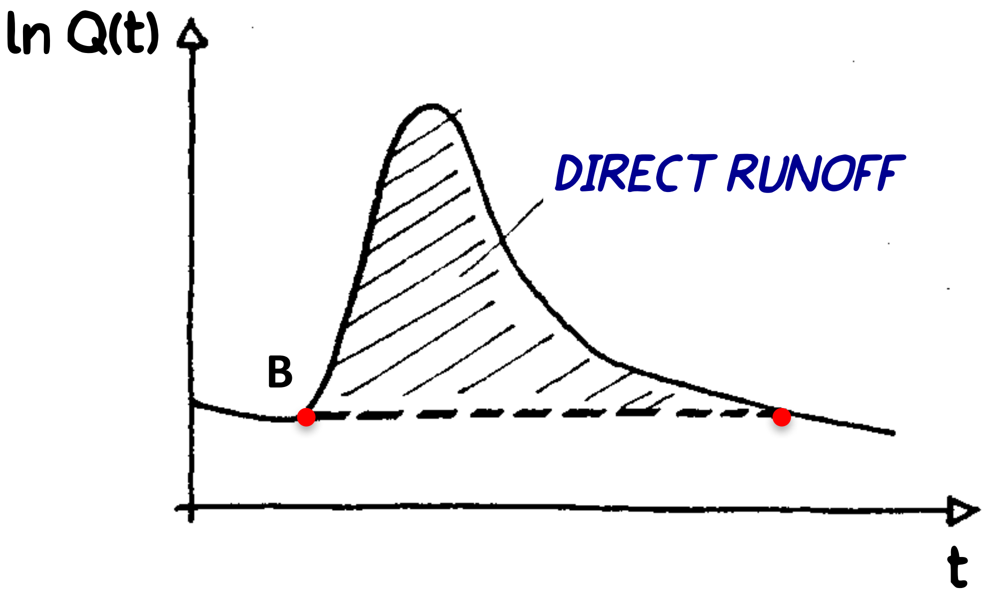
The analysis is conveniently carried out in a semi-log plane (lnQ-t), where the baseflow recession shows a linear behaviour

Flood hydrograph analysis: baseflow separation (1)

- Observed streamflow in rivers is composed of three components: *surface runoff, interflow and baseflow*
- to quantify the contribution of surface runoff to the streamflow it is necessary to separate the baseflow and interflow

↳ ***baseflow separation methods → empirical methods***

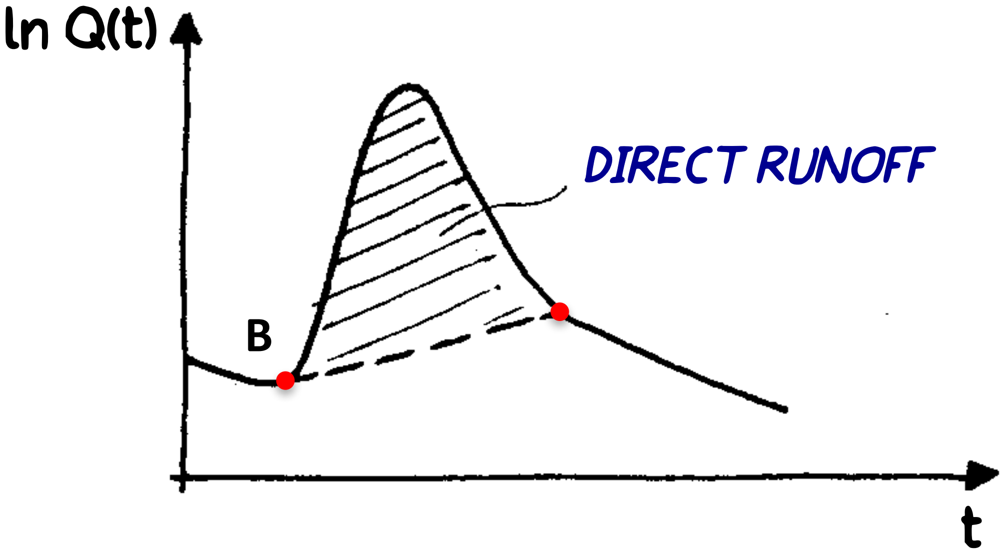
NB 1 these methods consider **baseflow and interflow as one single component**
NB 2 surface runoff computed from baseflow separation can be used for calibration/verification of runoff generation models (e.g. Φ-index)

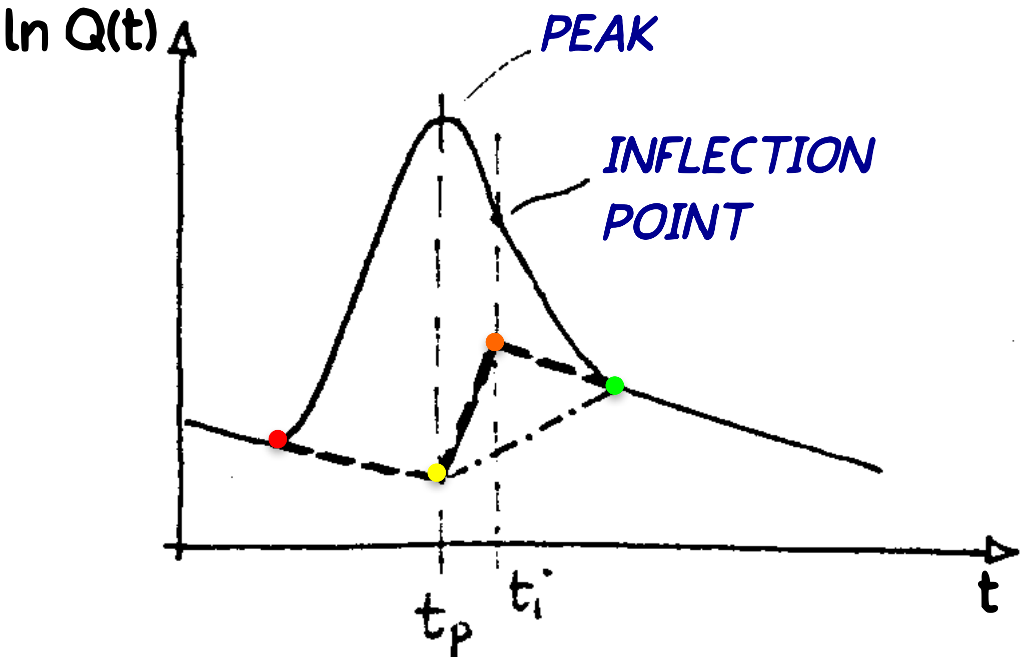


STRAIGHT LINE METHOD

- *a* **horizontal line** *is* **drawn from** *the point at which surface runoff begins,* **B,** *to the intersection with the recession limb.*
- *does not account for* **interflow**
- *applicable to* **ephemeral streams**

Baseflow separation (2)





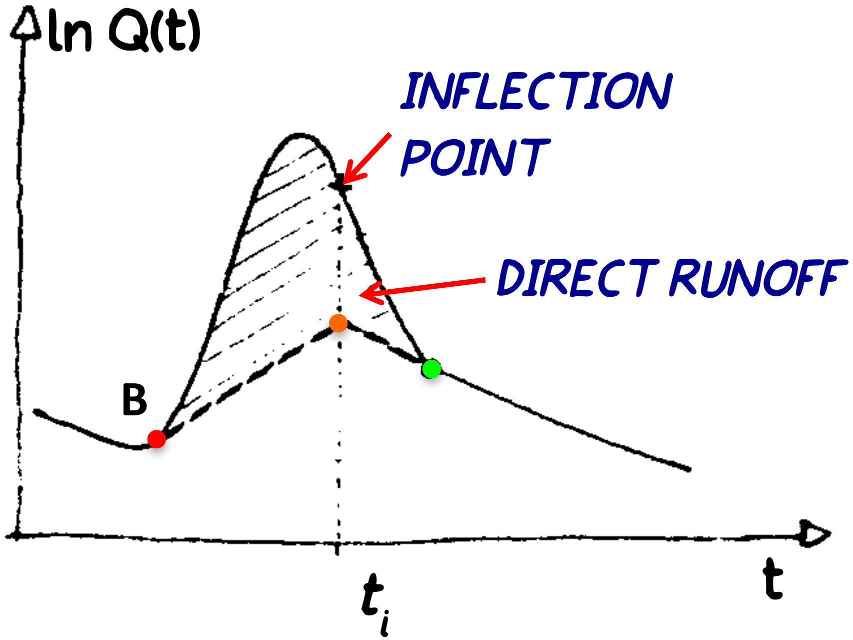
STRAIGHT (INCLINED) LINE METHOD

- *an* **inclined line** *is* **drawn from** *the beginning point of the surface runoff,* **B***, with the point on the recession limb of the hydrograph where normal baseflow resumes.*
- *accounts implicitely for* **interflow** *(inclined straight line)*
- *applicable to* **(small) forested watersheds in humid regions**

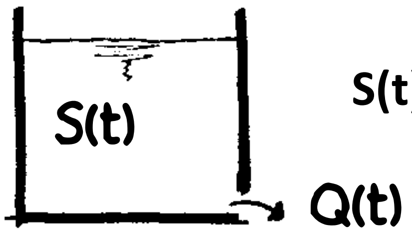
VARIABLE SLOPE METHOD

- **extraplolation (forward)** *of the baseflow recession curve up to t_p* →
- **extrapolation (backward)** *of the baseflow recession curve up to t_i* →
- **connection** *of the extrapolated curves* →
- *accounts implicitely for* **interflow**
- *applicable to systems with* **threshold driven interflow**

Baseflow separation: normal depletion curve



linear reservoir analogue



S(t) = k Q(t)   (••)

combining (••) with the continuity equation -Q(t)=dS(t)/dt we obtain (•)

- *it is based on the evidence of the* **exponential decay** *of the recession limb*
  - ↳ **linear reservoir analogue**

$$Q(t) = Q_0 \cdot e^{-(t-t_0)/k} \qquad (\bullet)$$

  where Q_0 is the flow at time t_0 a nd k is an exponential decay constant having the dimensions of time.

- *the* **equation is linearized in a semi-log** (ln Q(t) – t) **plane**
- *two* **inclined lines** *can be* **drawn**
  - ↳ **forward from** *the beginning point of the surface runoff,* **B,** *to the time of the inflection point, and*
  - ↳ **backward from** *the point on the recession limb of the hydrograph where normal baseflow resumes to the time of the inflection point.*
- *the estimation of k is obtained by fitting the linearized form of (•) to the flow values of the recession limb*
- *accounts implicitly for* **interflow** *(inclined straight line)*
- *applicable to* **watersheds where interflow is controlled by soil storage**