Introduction to Hydrology

Lecture content

1) ***Definition*** and ***scope*** of Hydrology
2) ***Examples*** of water resources and engineering problems to which Hydrology provides answers
3) ***Methodological approach*** to hydrological sciences

4) ***Water balance*** and the ***hydrological cycle***
5) ***Hydrological processes*** overview
6) ***Hydrological data*** and space and time ***scales***

Goal: ***to understand the philosophy of representing the functioning of hydrological/natural systems through an engineering (quantitative) description***

Definition and scope

Hydrology - Definition

*“***Hydrology***, which* **treats all phases of the earth's water***, is a subject of great importance for people and their environment.* **Practical applications** *of hydrology are found in such tasks as the* **design and operation** *of hydraulic structures, water supply, wastewater treatment and disposal, irrigation, drainage, hydropower generation, flood control, navigation, erosion and sediment control, salinity control, pollution abatement, recreational use of water, and fish and wildlife protection. The* **role of applied hydrology is to help analyze the problems involved in these tasks and to provide guidance for the planning and management of water resources***”.*

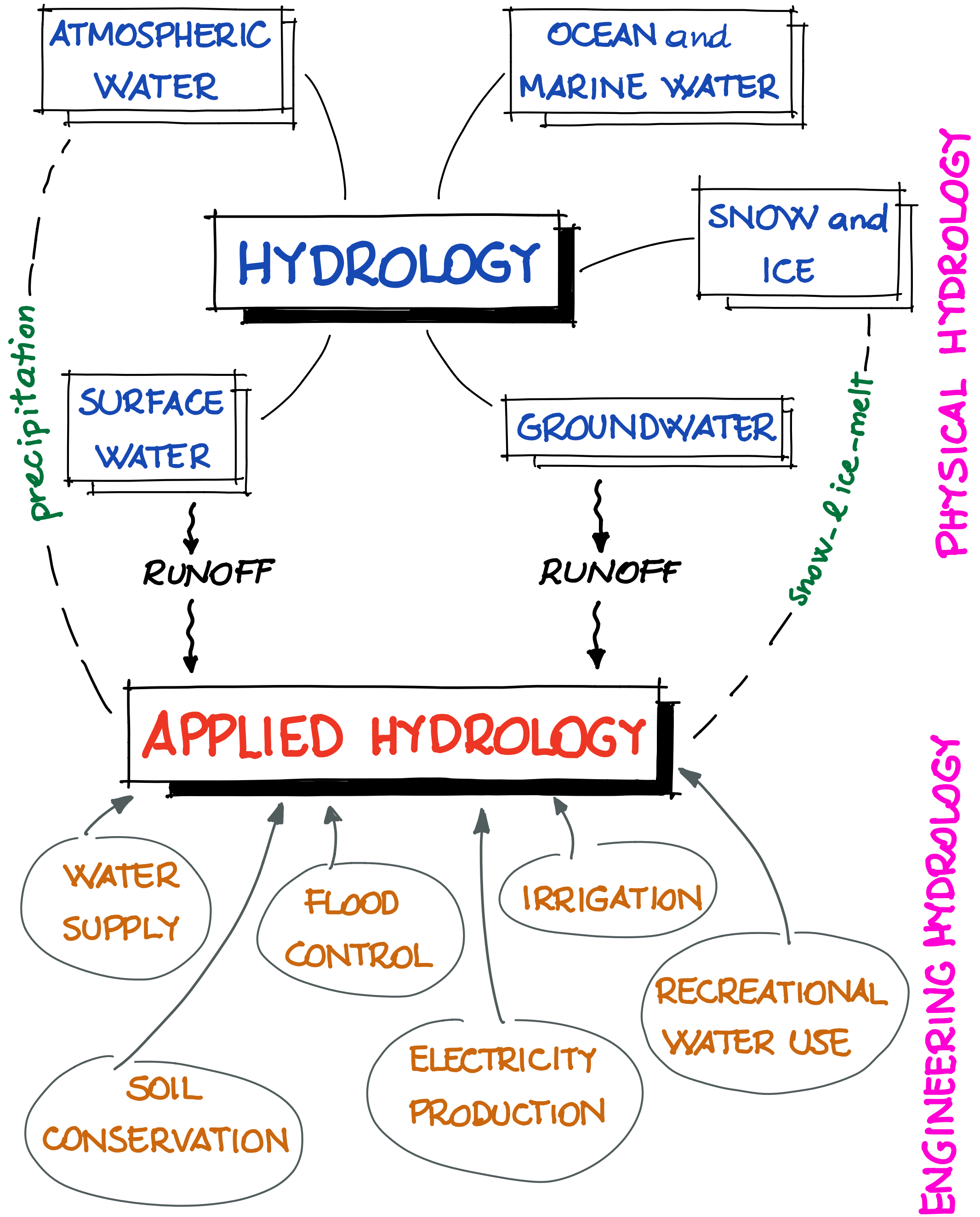
[Chow et al. 1998]

WATER USE vs WATER CONSERVATION

↓

SUSTAINABLE WATER RESOURCES MANAGEMENT

Elements of Hydrology and other geosciences



Hydrology as science behind water resources problems

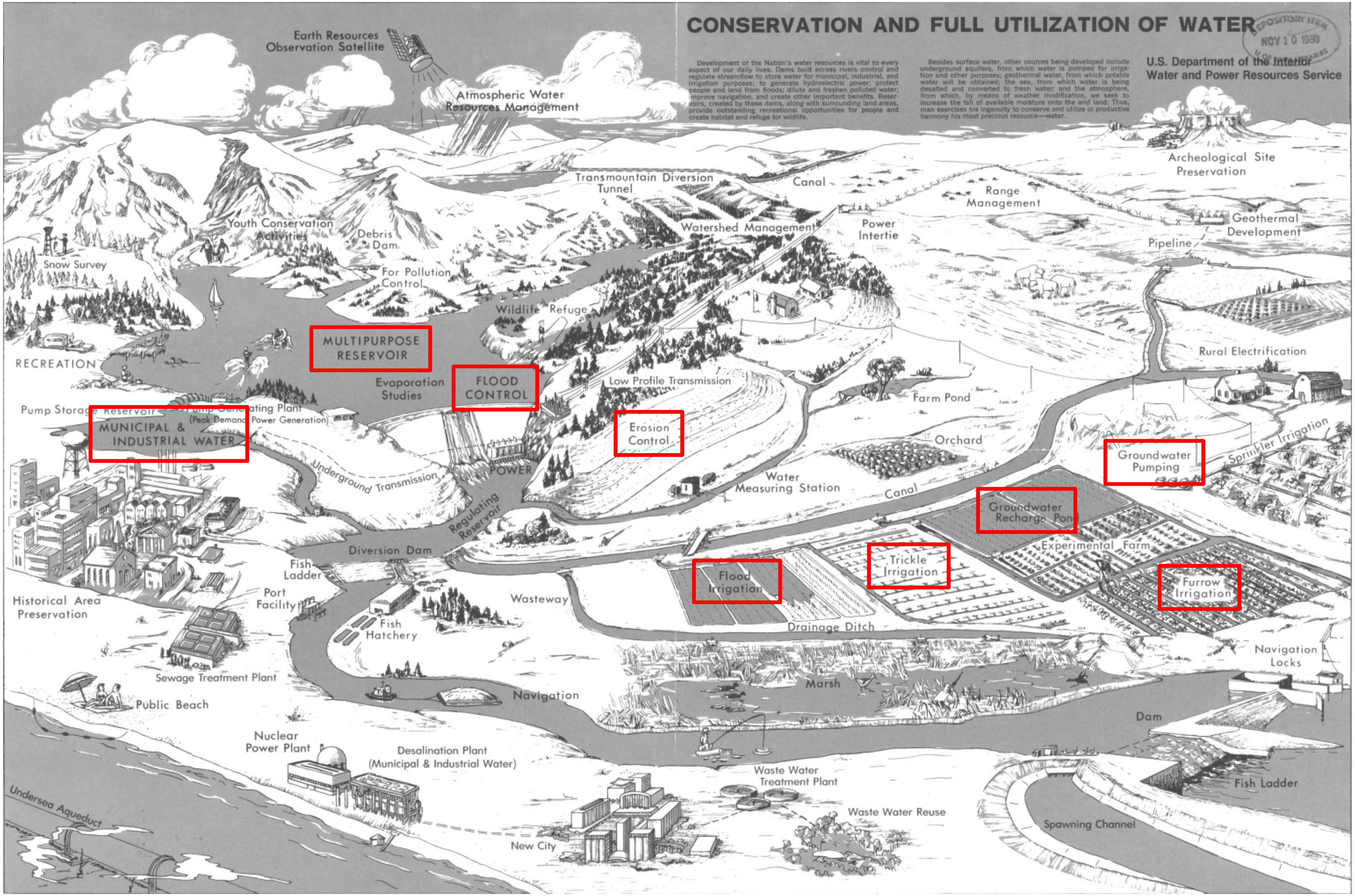
Examples of water engineering problems

Examples of water resources engineering problems to which Hydrology can provide answers

	Control of excess of water				Conservation (quantity)				Conservation (quality)
Studies and facilities required	Flood storm mitigation	Storm drainage	Bridges, culverts	Sewerage	Water supply	Irrigation	Hydropower	Navigation	Pollution control
How much water is needed?	-	-	-	-	x	x	x	x	x
How much water can be expected?									
Min. flow	-	-	-	x	x	x	x	x	x
Annual yield	-	-	-	x	x	x	x	x	x
Flood peaks	x	x	x	-	x	x	x	x	
Flood volume	x	x	-	-	-	-	-	-	x
Groundwater	-	x	-	x	x	x	-	-	x

Hydrology for Water Resources Management

How much water is needed?
How much water can be expected?



CONSERVATION AND FULL UTILIZATION OF WATER

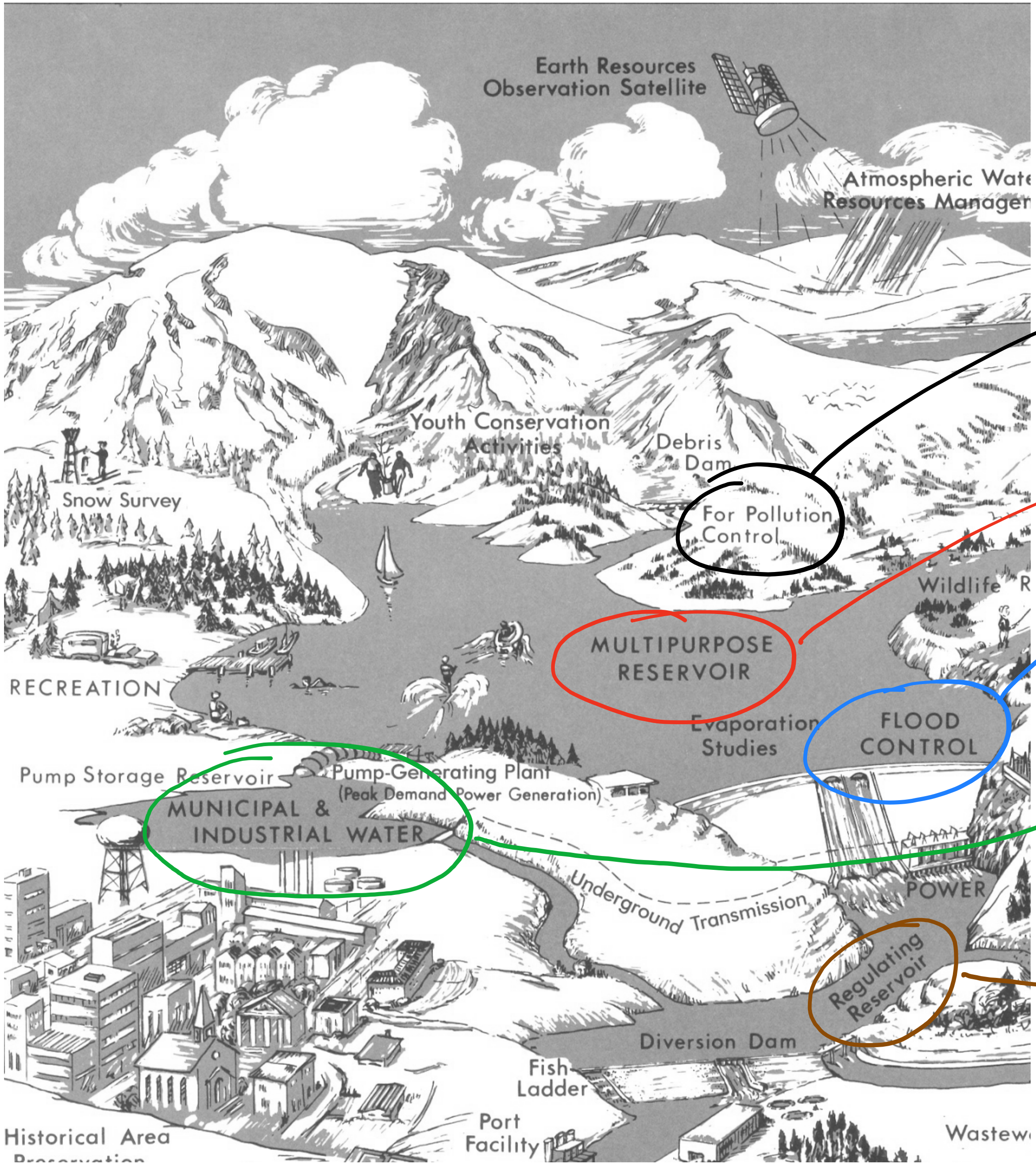
Development of the Nation's water resources is vital to every aspect of our daily lives. Dams built across rivers control and regulate streamflow to store water for municipal, industrial, and irrigation purposes; to generate hydroelectric power; protect people and land from floods; dilute and freshen polluted water; improve navigation, and create other important benefits. Reservoirs, created by these dams, along with surrounding land areas, provide outstanding recreational opportunities for people and create habitat and refuge for wildlife.

Besides surface water, other sources being developed include underground aquifers, from which water is pumped for irrigation and other purposes; geothermal water, from which potable water will be obtained; the sea, from which water is being desalted and converted to fresh water; and the atmosphere, from which, by means of weather modification, we seek to increase the fall of available moisture onto the arid land. Thus, man exercises his ingenuity to conserve and utilize in productive harmony his most precious resource—water.

U.S. Department of the Interior
Water and Power Resources Service

digital.lib.uiowa.edu/gpc

How much water is needed?
How much water can be expected?



water quality requirements

annual water yield

flood peak, volume & duration

how much water will be used ? and when ?

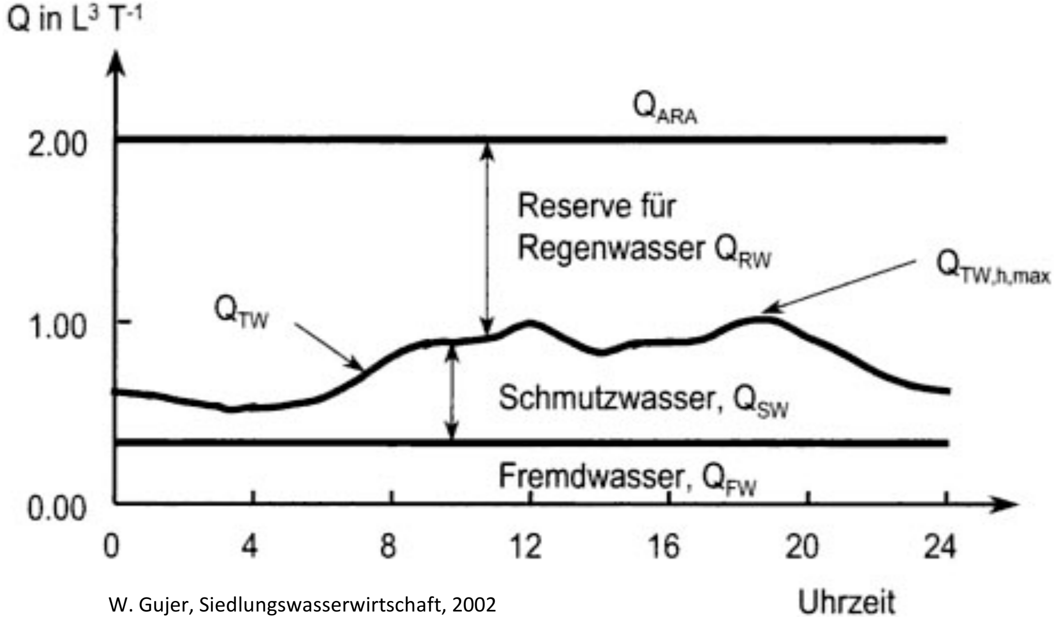
environmental flow release

image provided by electrical-engineering-portal.com

Saltina, Brig – flood (1993)

Debris flow Brig, Roberto Loat BAFU 1993

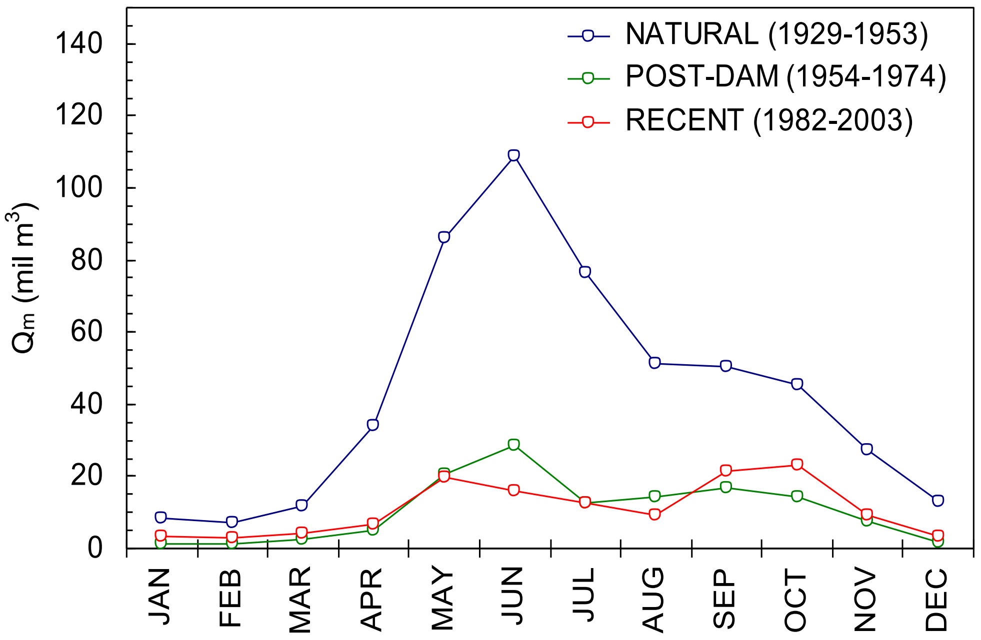
Debris flow Brig, Jean-Pierre Jordan 1993

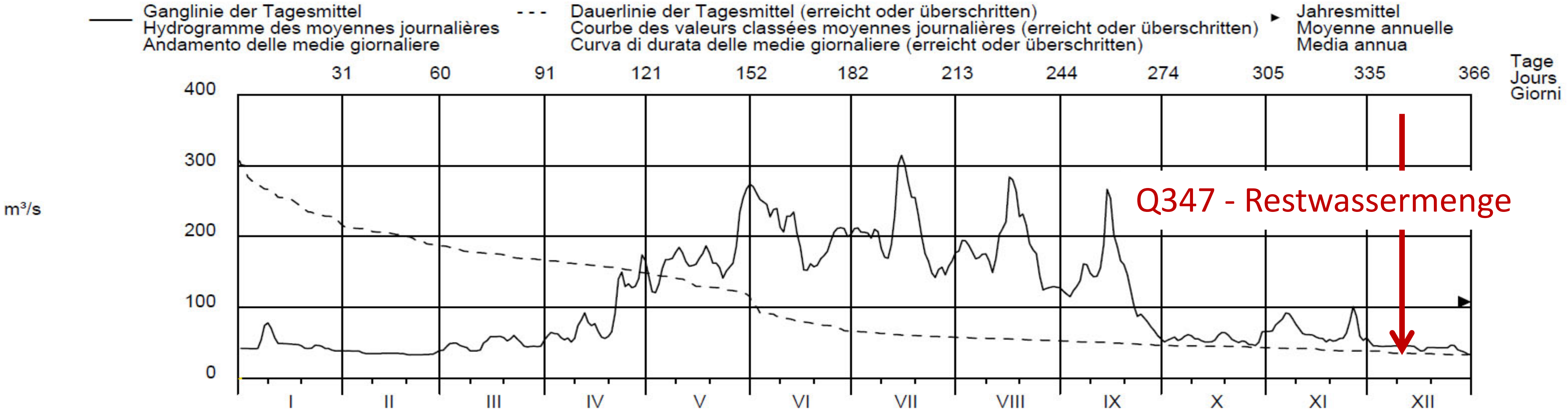


W. Gujer, Siedlungswasserwirtschaft, 2002

Frankfort Municipal Utilities

[http://water.usgs.gov/outreach/Posters/water_quality/images/WaterQuality_BW.jpg]

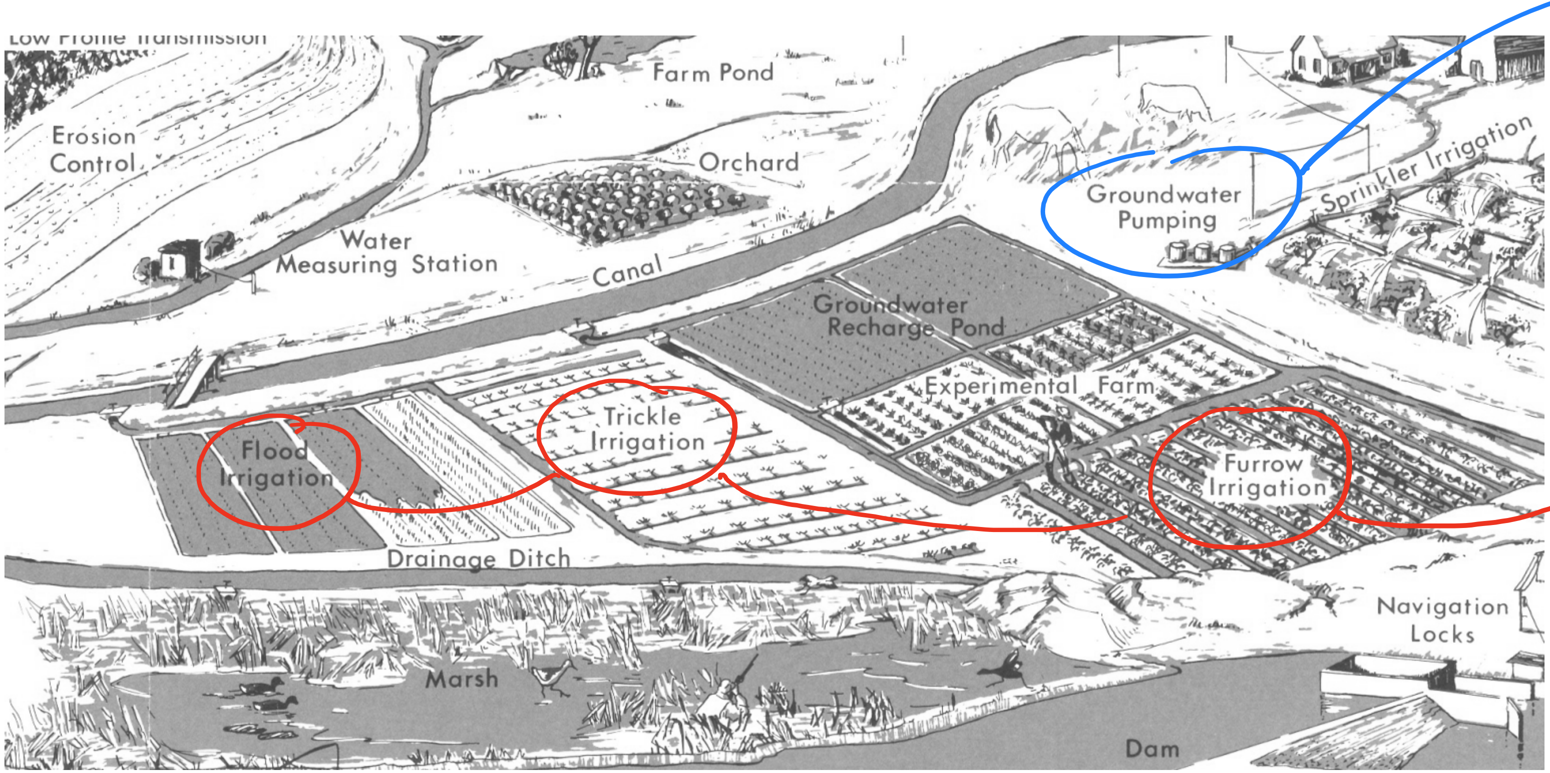




Q347 - Restwassermenge

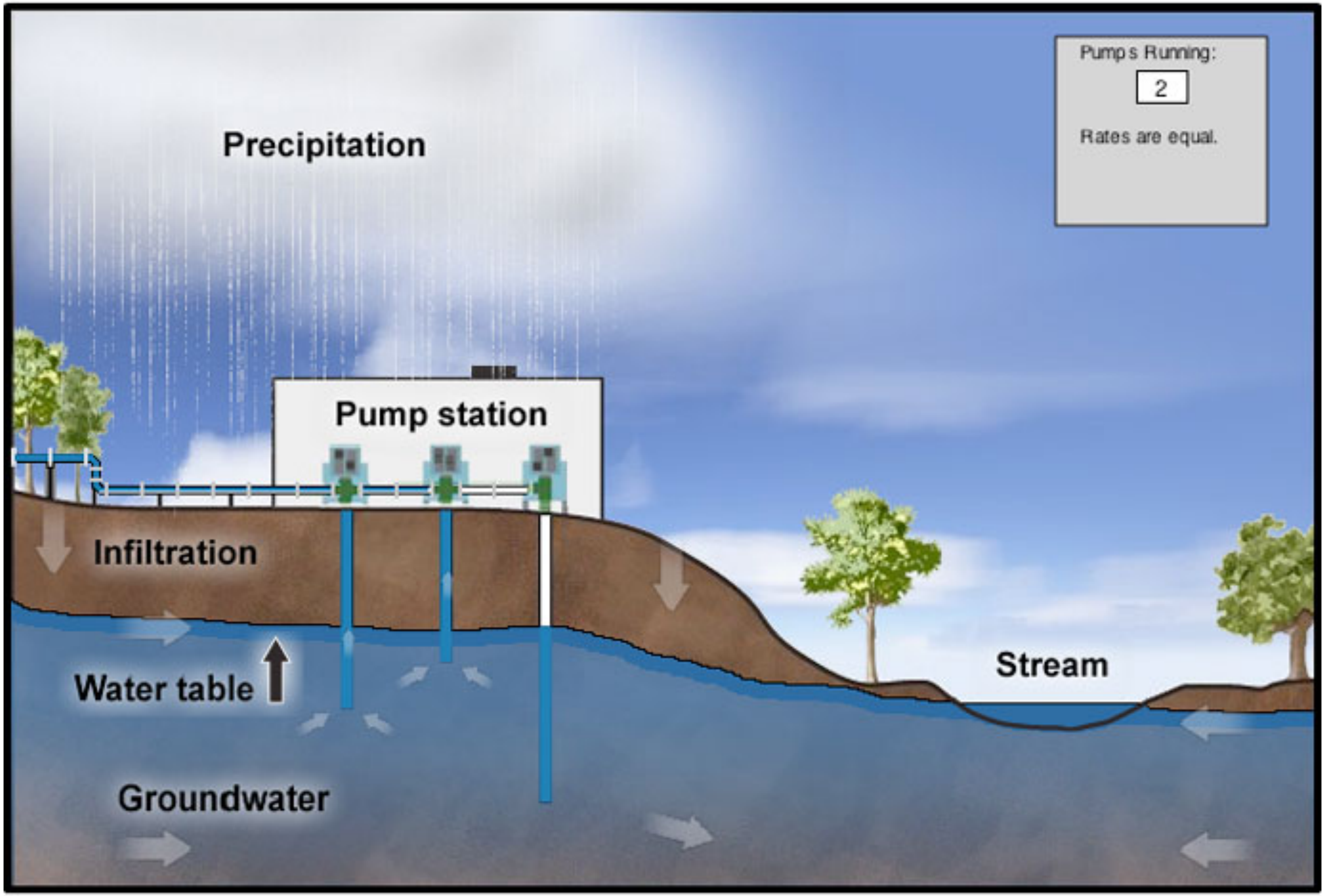
Bundesamt für Umwelt BAFU

How much water is needed?
How much water can be expected?



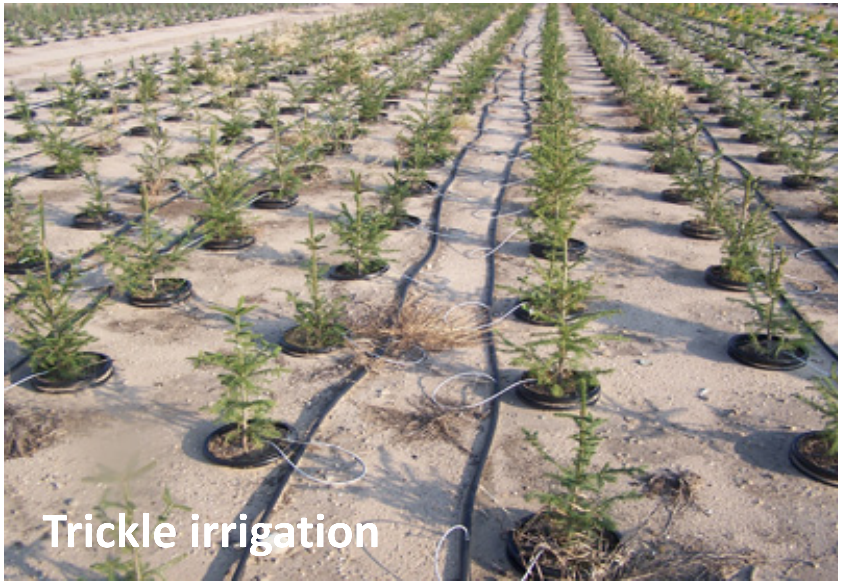
water balance
& groundwater
recharge

water demand
vs
water availability



[http://oceanexplorer.noaa.gov/edu/learning/7_water_cycle/activities/groundwater.html#activity]

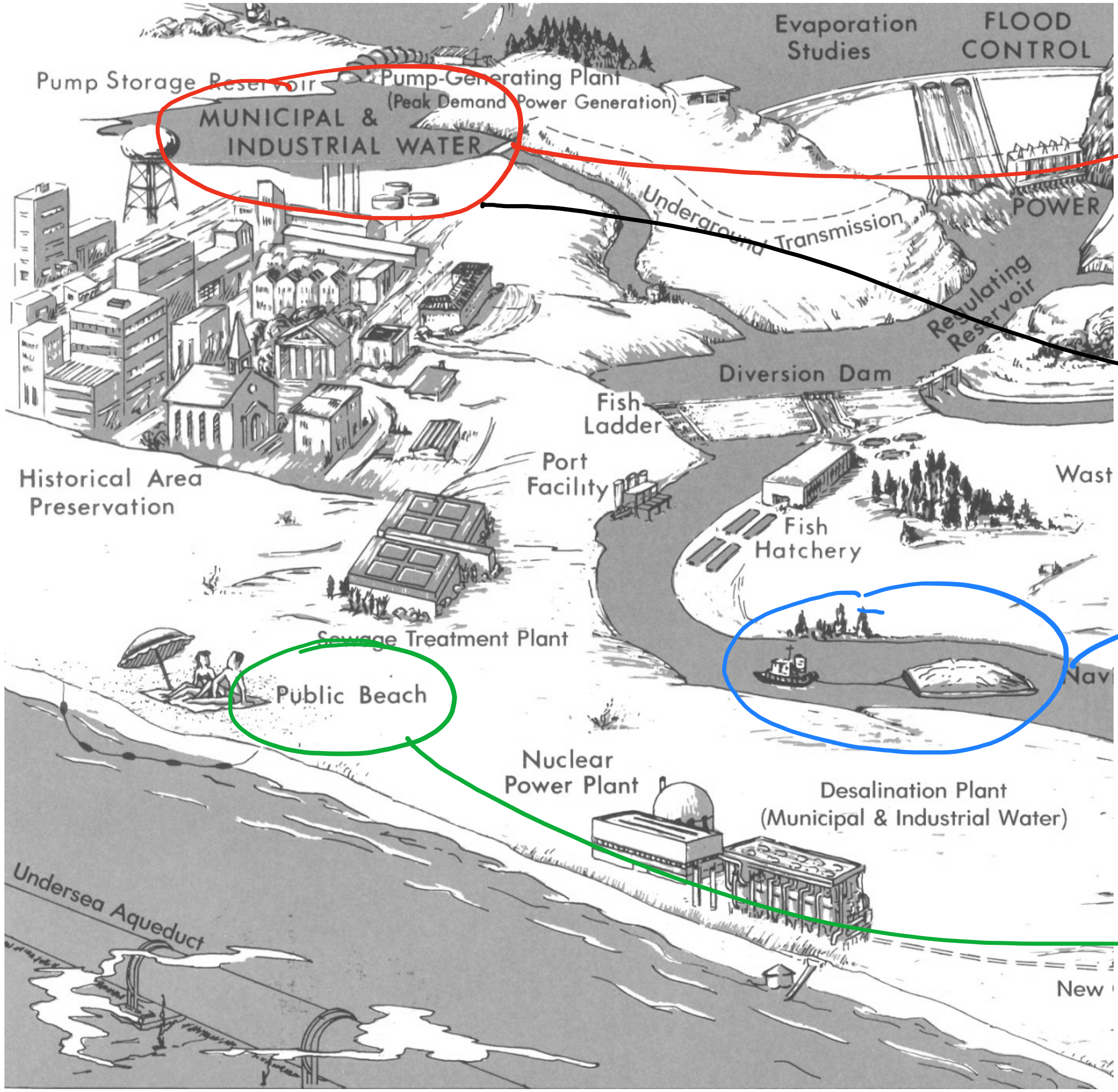
http://photogallery.nrcs.usda.gov/Index.asp



Wordpress.com

USDA Natural Resources Conservation Service

How much water is needed?
How much water can be expected?

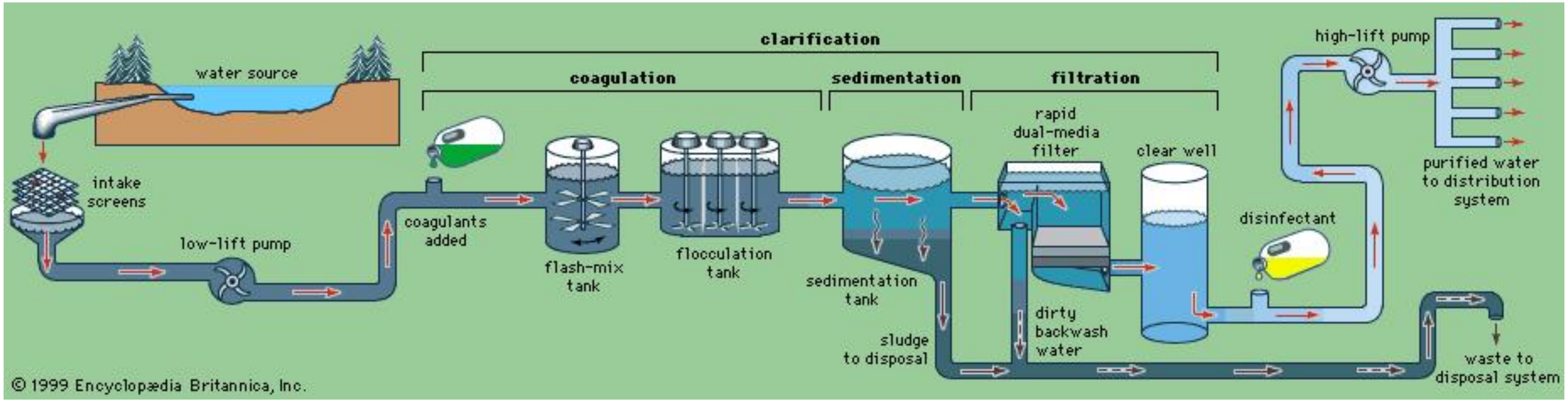


surface and groundwater availability to satisfy the demand

how much rainwater should be drained from roads and the urban catchment

how much water should be released for navigation & environment conservation

sediment load from rivers to avoid coastal erosion



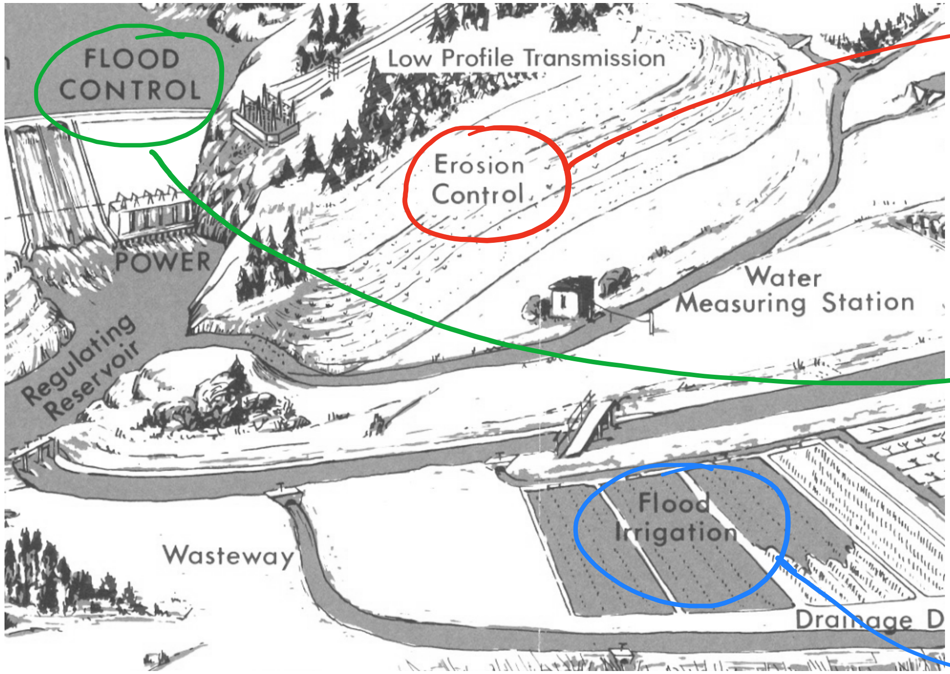
http://www.britannica.com/technology/water-supply-system/Water-treatment

Fischabstieg am WKW Elz; Quelle: Archiv Wasserkraft Volk AG

Auengebiet *Gérine* im Kanton Freiburg (Foto J.Cl. Bersier, Freiburg)

http://www.power-technology.com

How much water is needed?
How much water can be expected?



extreme rainfall events
estimation to quantify erosion

estimation of flood peak,
volume and duration

water demand vs
water availability

Flood Wallis, 2000

Unwetter 2000 im Wallis (1), PLANAT 16.10.2000

Unwetter 2000 im Wallis (2), PLANAT 16.10.2000

Unwetter 2000 im Wallis (3), PLANAT 16.10.2000

Ufererosion in Wolfenschiessen, Kanton NW 27.08.2005

Methodological approach

The reference geographical unit: the river basin

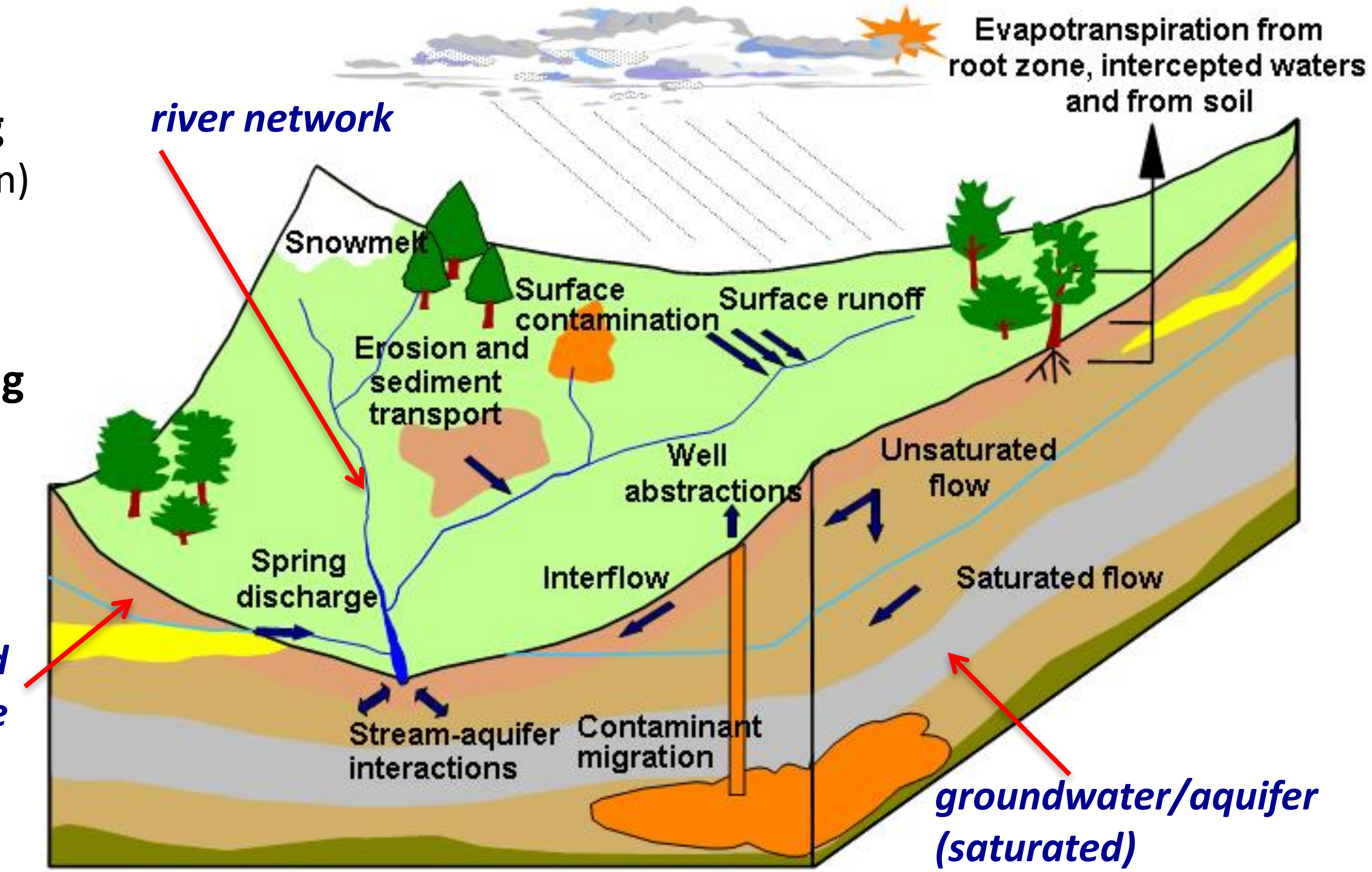
terms used as synonymous of "river basin":

- *watershed*
- *catchment*

Process understanding
(measurement, observation)

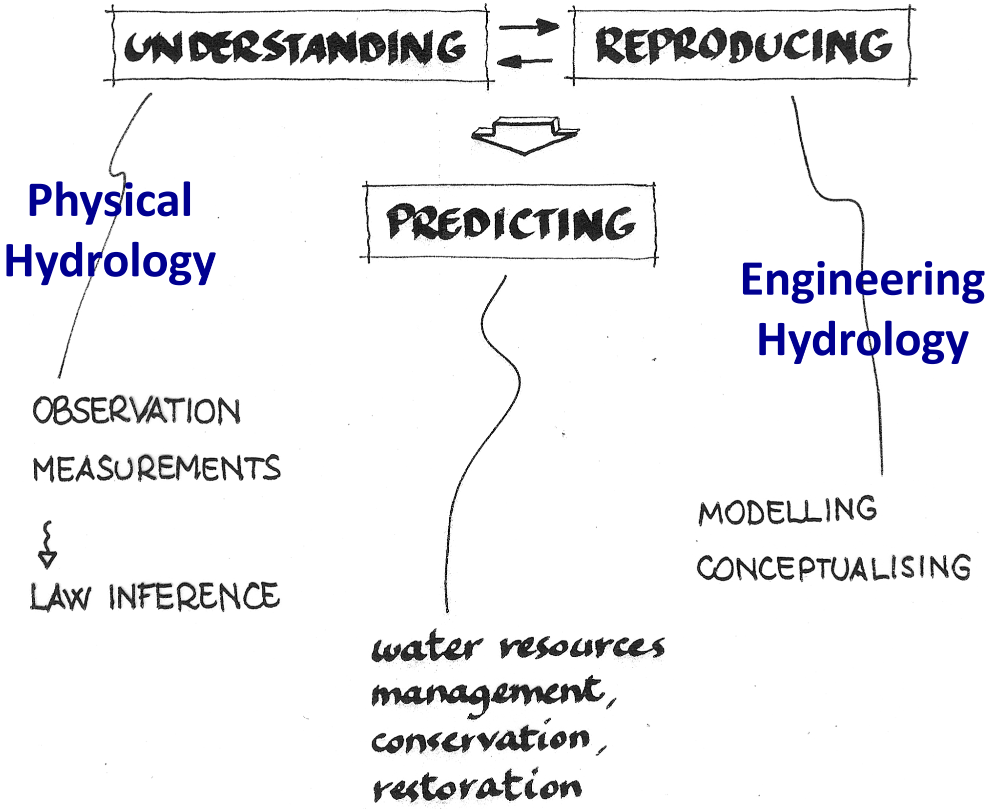
🡻

Mathematical Modelling
(simulation, prediction)



http://research.ncl.ac.uk/shetran/images/ShetranProcesses.jpg

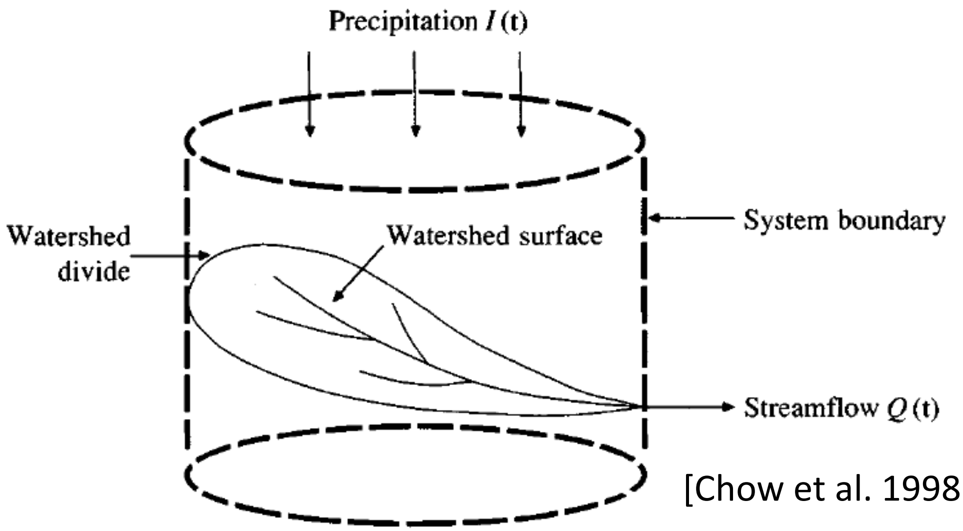
Methodological approach



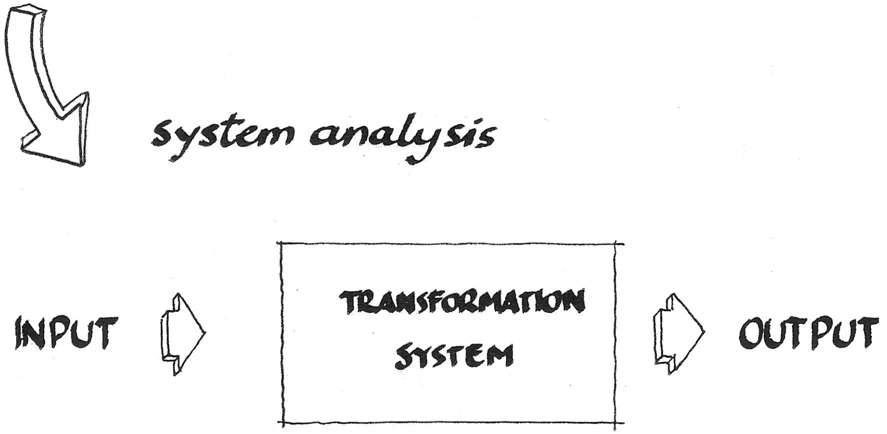
Physical Hydrology

Engineering Hydrology

The watershed as hydrologic system



[Chow et al. 1998]

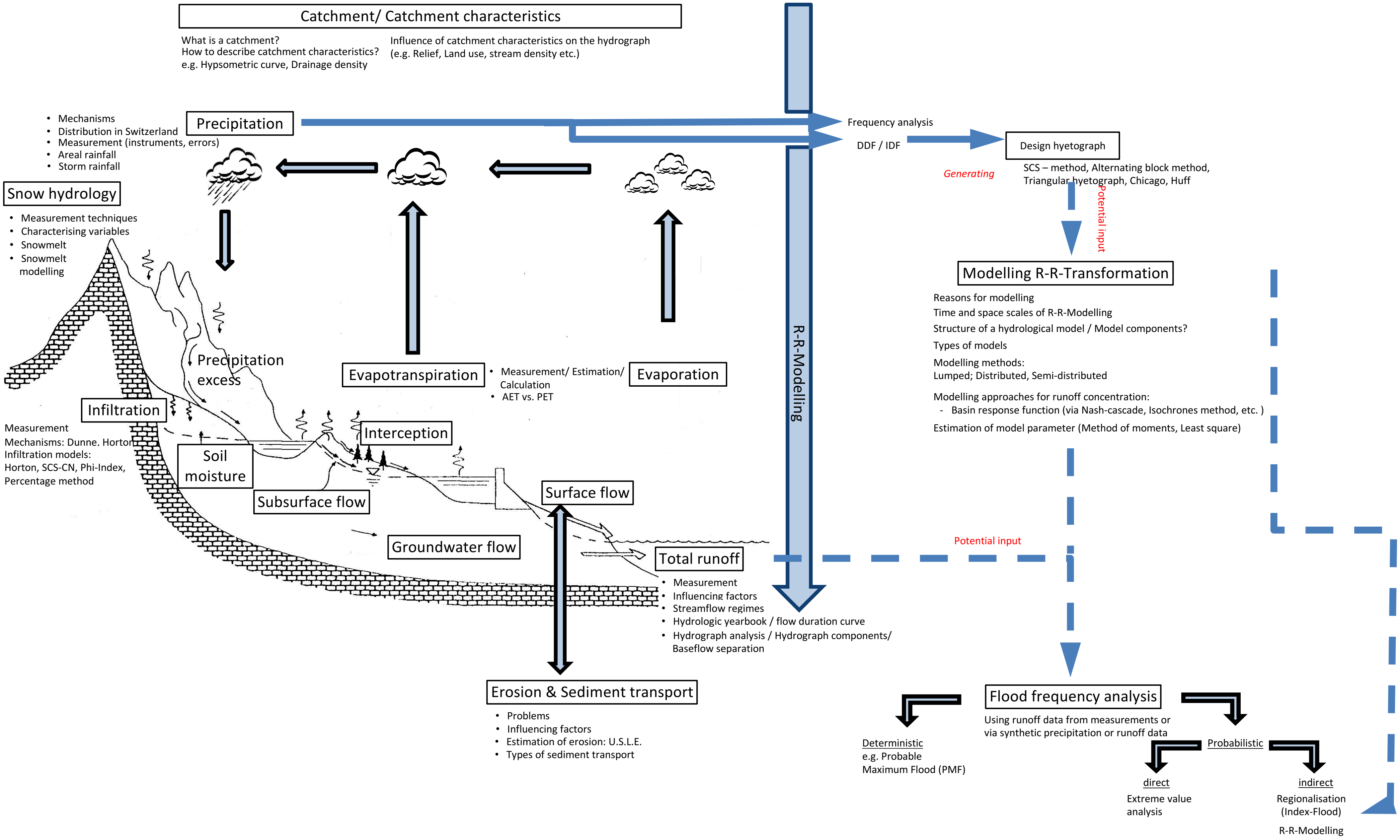


Physical Hydrology / System

= Process understanding, Monitoring, Measuring …

Engineering Hydrology / System

= Modelling, Conceptualisation, Reproducing processes…



Catchment/ Catchment characteristics

What is a catchment?
How to describe catchment characteristics?
e.g. Hypsometric curve, Drainage density

Influence of catchment characteristics on the hydrograph
(e.g. Relief, Land use, stream density etc.)

Precipitation

- Mechanisms
- Distribution in Switzerland
- Measurement (instruments, errors)
- Areal rainfall
- Storm rainfall

Snow hydrology

- Measurement techniques
- Characterising variables
- Snowmelt
- Snowmelt modelling

Precipitation excess

Infiltration

- Measurement
- Mechanisms: Dunne. Horton
- Infiltration models: Horton, SCS-CN, Phi-Index, Percentage method

Soil moisture

Subsurface flow

Groundwater flow

Interception

Evapotranspiration

- Measurement/ Estimation/ Calculation
- AET vs. PET

Evaporation

Surface flow

Total runoff

- Measurement
- Influencing factors
- Streamflow regimes
- Hydrologic yearbook / flow duration curve
- Hydrograph analysis / Hydrograph components/ Baseflow separation

Erosion & Sediment transport

- Problems
- Influencing factors
- Estimation of erosion: U.S.L.E.
- Types of sediment transport

R-R-Modelling

Frequency analysis

DDF / IDF

Design hyetograph

Generating

SCS – method, Alternating block method, Triangular hyetograph, Chicago, Huff

Potential input

Modelling R-R-Transformation

Reasons for modelling
Time and space scales of R-R-Modelling
Structure of a hydrological model / Model components?
Types of models
Modelling methods:
Lumped; Distributed, Semi-distributed

Modelling approaches for runoff concentration:
- Basin response function (via Nash-cascade, Isochrones method, etc.)

Estimation of model parameter (Method of moments, Least square)

Potential input

Flood frequency analysis

Using runoff data from measurements or via synthetic precipitation or runoff data

Deterministic
e.g. Probable Maximum Flood (PMF)

Probabilistic

direct
Extreme value analysis

indirect
Regionalisation (Index-Flood)
R-R-Modelling

Water balance

How much water is available on our planet?

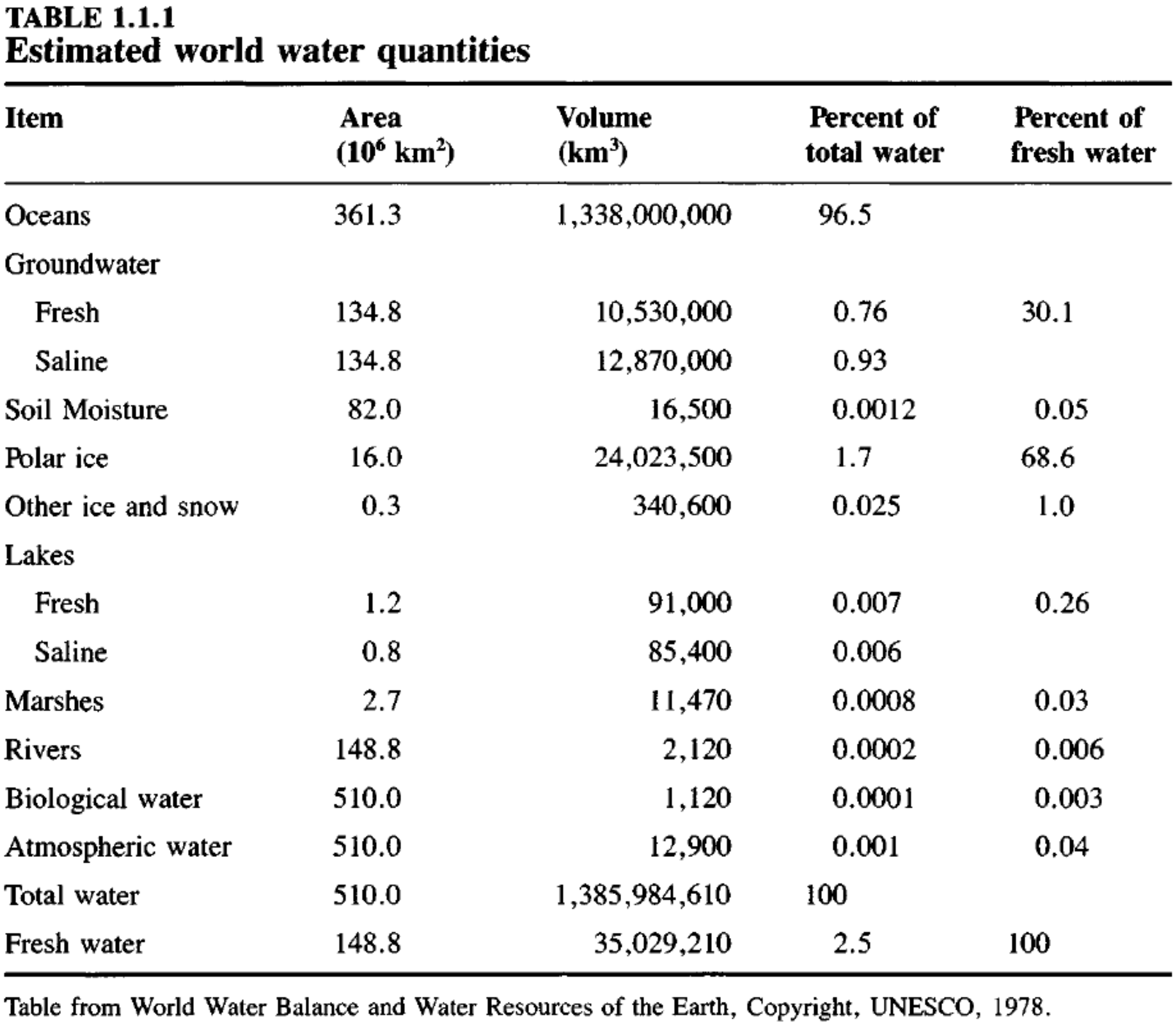


TABLE 1.1.1
Estimated world water quantities

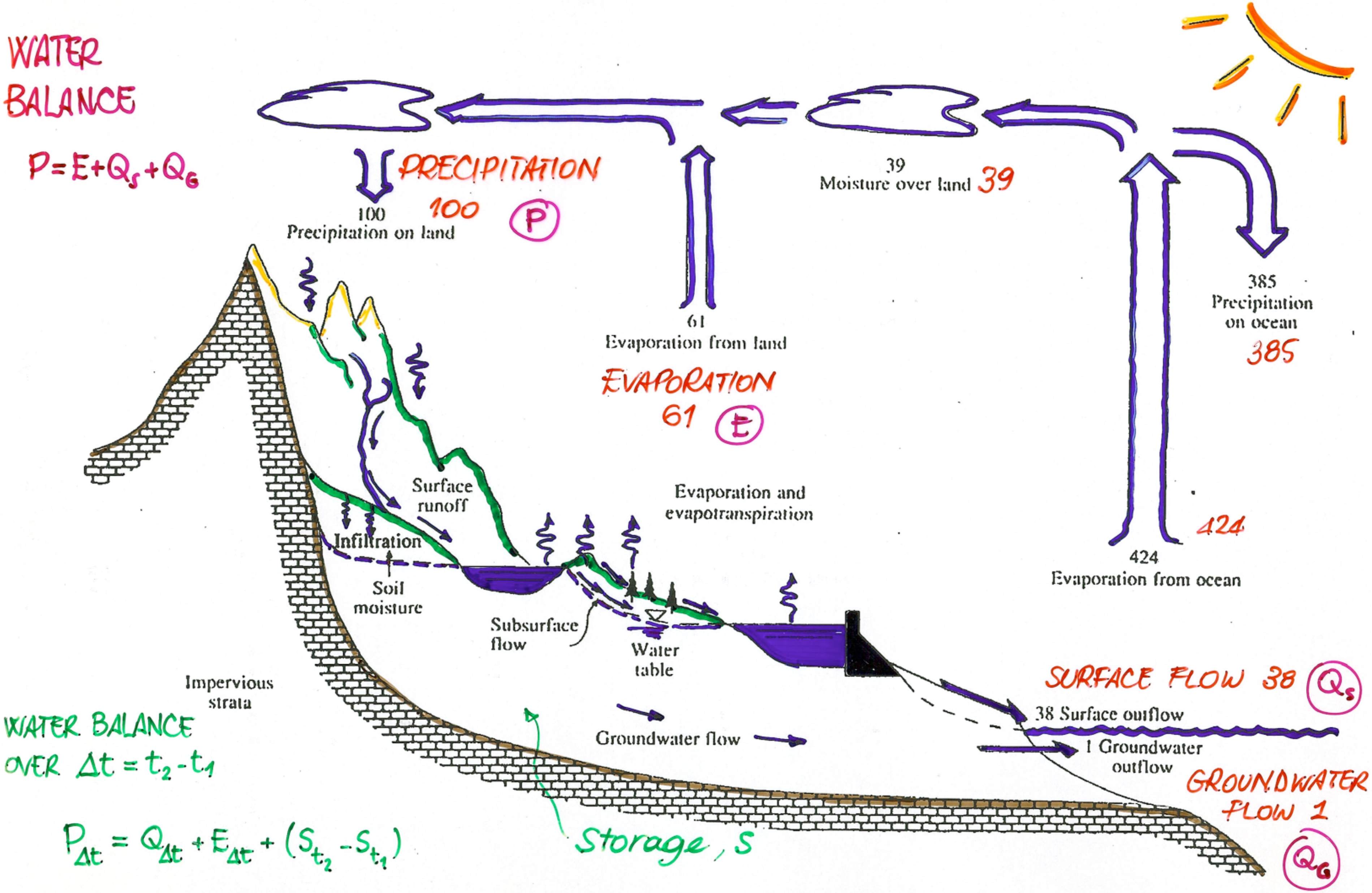
Item	**Area (10^6 km^2)**	**Volume (km^3)**	**Percent of total water**	**Percent of fresh water**
Oceans	361.3	1,338,000,000	96.5	
Groundwater				
Fresh	134.8	10,530,000	0.76	30.1
Saline	134.8	12,870,000	0.93	
Soil Moisture	82.0	16,500	0.0012	0.05
Polar ice	16.0	24,023,500	1.7	68.6
Other ice and snow	0.3	340,600	0.025	1.0
Lakes				
Fresh	1.2	91,000	0.007	0.26
Saline	0.8	85,400	0.006	
Marshes	2.7	11,470	0.0008	0.03
Rivers	148.8	2,120	0.0002	0.006
Biological water	510.0	1,120	0.0001	0.003
Atmospheric water	510.0	12,900	0.001	0.04
Total water	510.0	1,385,984,610	100	
Fresh water	148.8	35,029,210	2.5	100

Table from World Water Balance and Water Resources of the Earth, Copyright, UNESCO, 1978.

Water balance

- The water balance defines the ***conservation of mass*** across the different compartments of the ***hydrological cycle*** (atmosphere, water bodies, soil and ground, vegetation, snowpack and ice, …)
  - *it is computed with regard to a reference geographical unit / scale*
    - *Earth*
    - *continent*
    - *region*
    - *river basin*
    - *soil column*
    - *…*
- The concept of conservation of mass implies the identification of an ***incoming*** and an ***outgoing*** flux, and of a ***storage variation*** over a given unit of time.

The hydrological cycle



WATER BALANCE

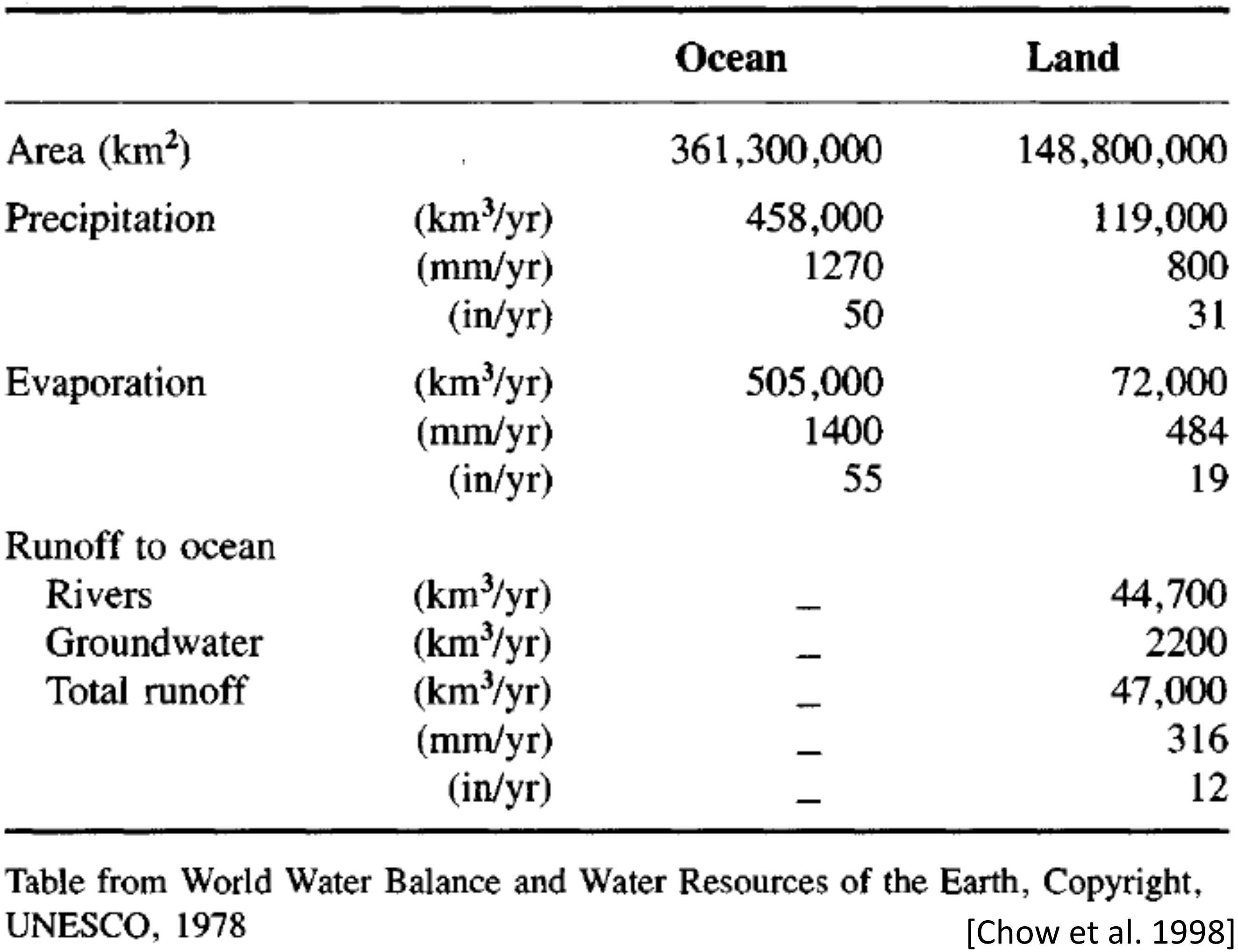
$$P = E + Q_S + Q_G$$

WATER BALANCE OVER $\Delta t = t_2 - t_1$

$$P_{\Delta t} = Q_{\Delta t} + E_{\Delta t} + (S_{t_2} - S_{t_1})$$

Hydrologic cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land. [Chow et al. 1998]

Global annual water balance



		Ocean	Land
Area (km^2)		361,300,000	148,800,000
Precipitation	(km^3/yr)	458,000	119,000
	(mm/yr)	1270	800
	(in/yr)	50	31
Evaporation	(km^3/yr)	505,000	72,000
	(mm/yr)	1400	484
	(in/yr)	55	19
Runoff to ocean			
Rivers	(km^3/yr)	–	44,700
Groundwater	(km^3/yr)	–	2200
Total runoff	(km^3/yr)	–	47,000
	(mm/yr)	–	316
	(in/yr)	–	12

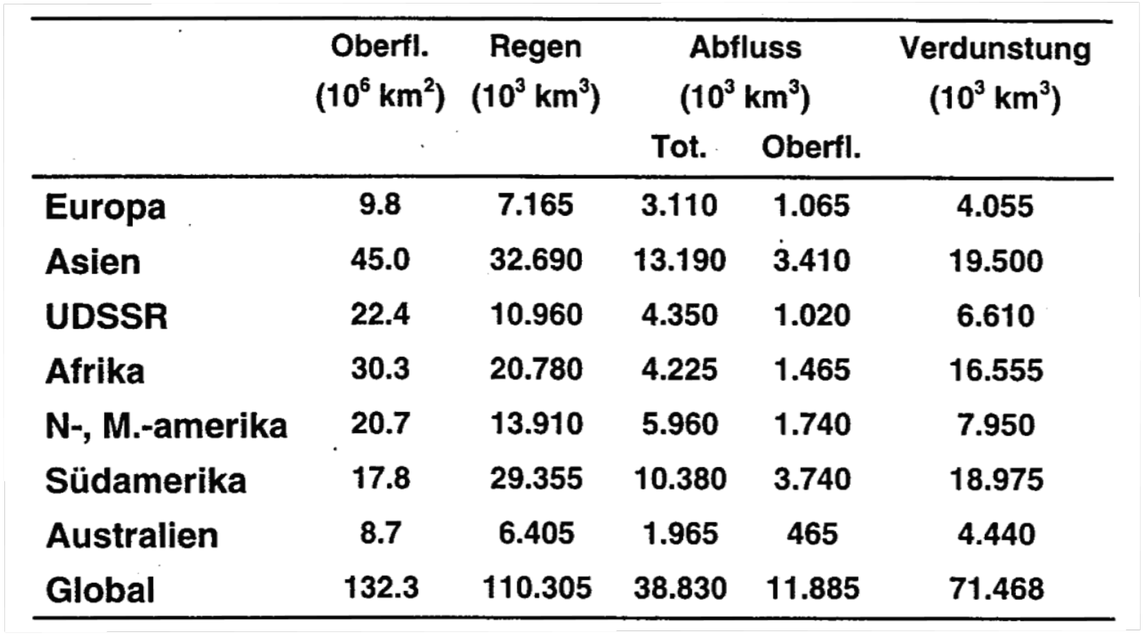
Table from World Water Balance and Water Resources of the Earth, Copyright, UNESCO, 1978

[Chow et al. 1998]

estimates and not measurements

Water balance – continental scale

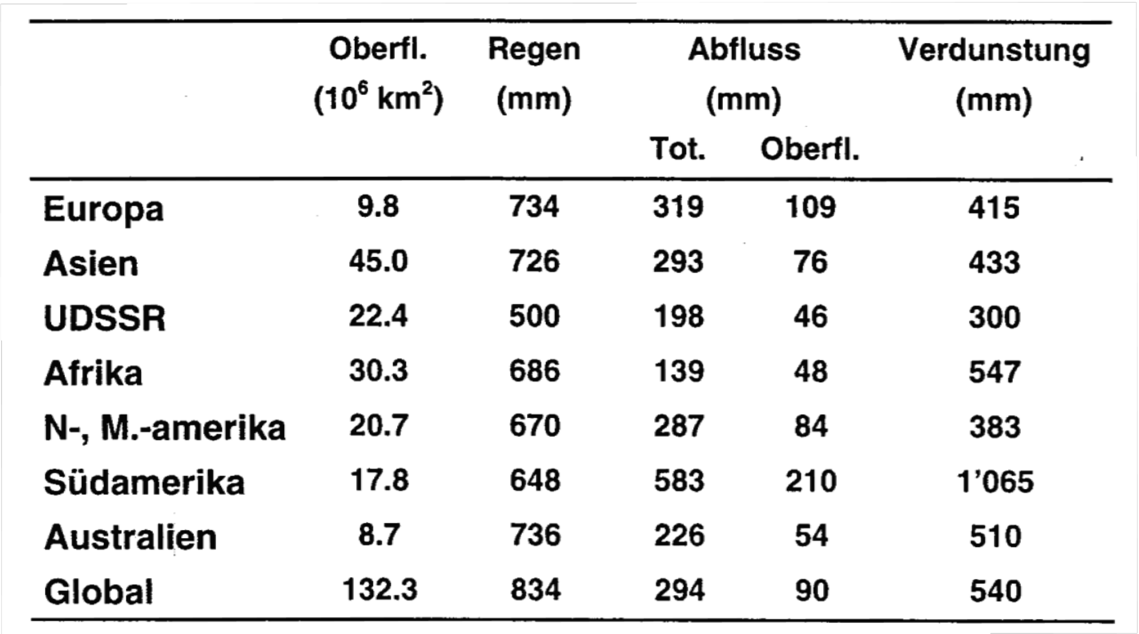
average annual volumes



	Oberfl. (10^6 km^2)	Regen (10^3 km^3)	Abfluss (10^3 km^3)		Verdunstung (10^3 km^3)
			Tot.	Oberfl.	
Europa	9.8	7.165	3.110	1.065	4.055
Asien	45.0	32.690	13.190	3.410	19.500
UDSSR	22.4	10.960	4.350	1.020	6.610
Afrika	30.3	20.780	4.225	1.465	16.555
N-, M.-amerika	20.7	13.910	5.960	1.740	7.950
Südamerika	17.8	29.355	10.380	3.740	18.975
Australien	8.7	6.405	1.965	465	4.440
Global	132.3	110.305	38.830	11.885	71.468

estimates
and not
measurements

average annual volumes per area

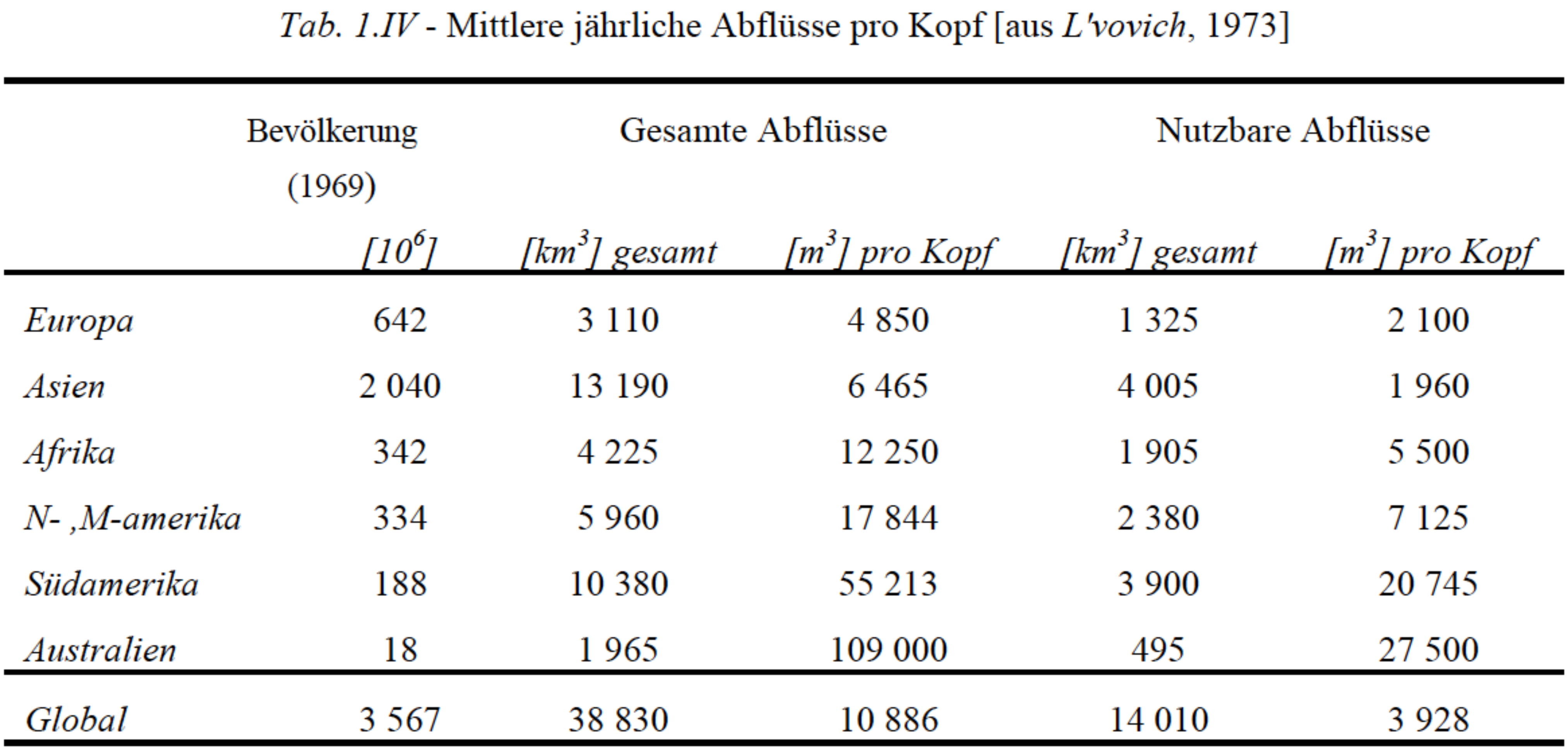


	Oberfl. (10^6 km^2)	Regen (mm)	Abfluss (mm)		Verdunstung (mm)
			Tot.	Oberfl.	
Europa	9.8	734	319	109	415
Asien	45.0	726	293	76	433
UDSSR	22.4	500	198	46	300
Afrika	30.3	686	139	48	547
N-, M.-amerika	20.7	670	287	84	383
Südamerika	17.8	648	583	210	1’065
Australien	8.7	736	226	54	510
Global	132.3	834	294	90	540

[L'vovich, 1973]

Water availability – continental scale

estimates
and not
measurements

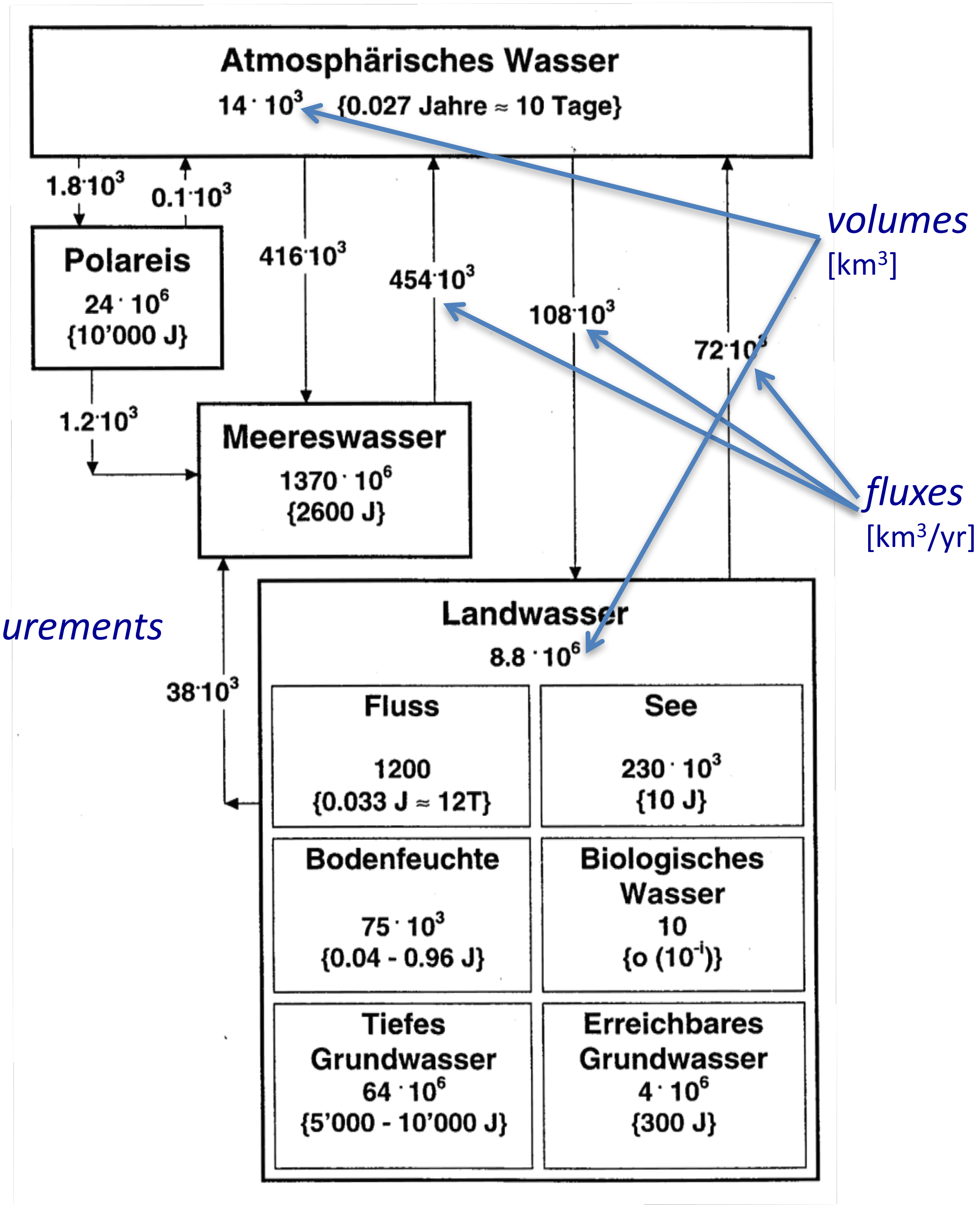


Tab. 1.IV - Mittlere jährliche Abflüsse pro Kopf [aus *L'vovich*, 1973]

	Bevölkerung (1969)	Gesamte Abflüsse		Nutzbare Abflüsse	
	[10^6]	*[km^3] gesamt*	*[m^3] pro Kopf*	*[km^3] gesamt*	*[m^3] pro Kopf*
Europa	642	3 110	4 850	1 325	2 100
Asien	2 040	13 190	6 465	4 005	1 960
Afrika	342	4 225	12 250	1 905	5 500
N- ,M-amerika	334	5 960	17 844	2 380	7 125
Südamerika	188	10 380	55 213	3 900	20 745
Australien	18	1 965	109 000	495	27 500
Global	3 567	38 830	10 886	14 010	3 928

Water balance – fluxes

Volumes
and
average residence time
of water in the different
compartments of the
hydrological cycle



volumes
[km^3]

fluxes
[km^3/yr]

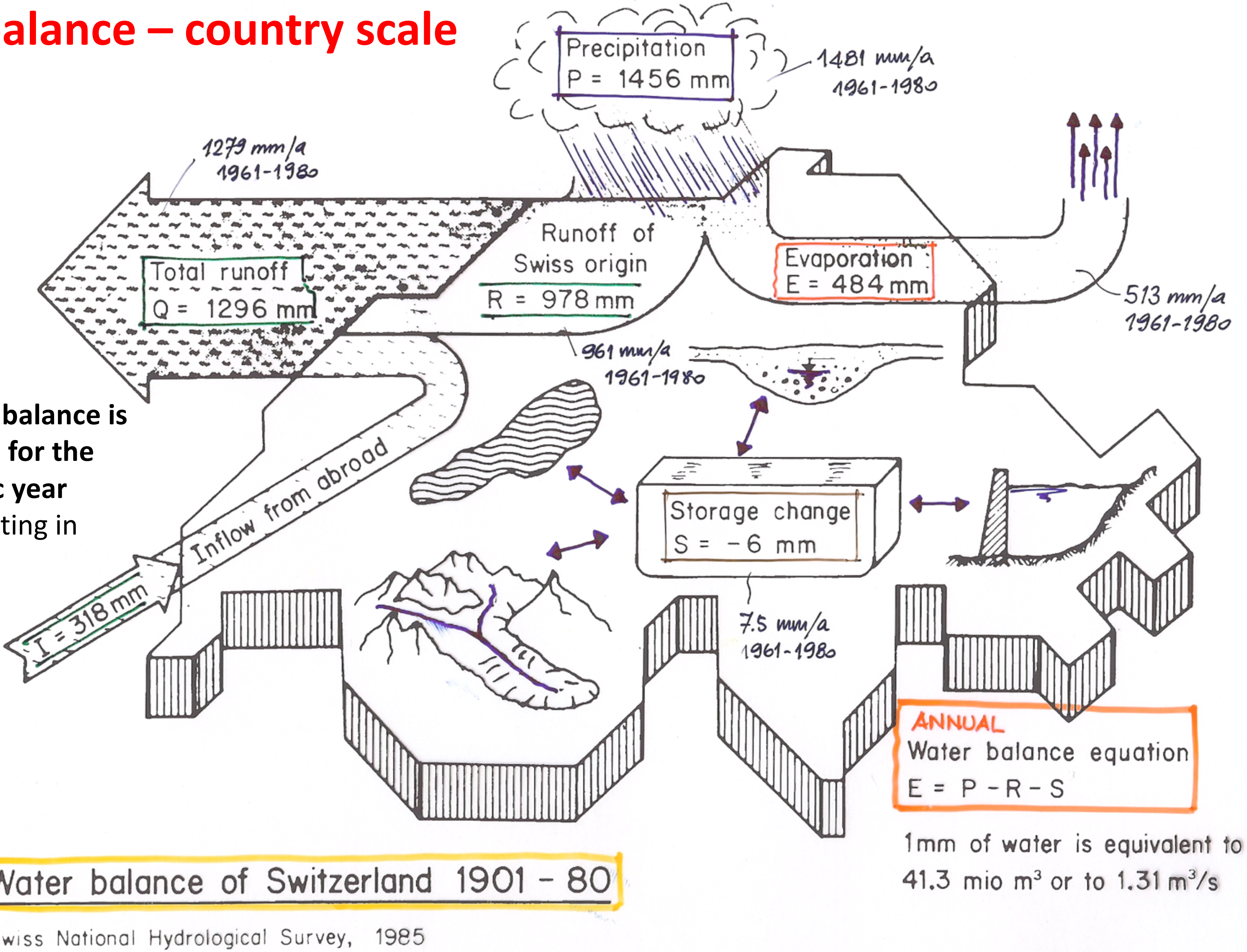
estimates and not measurements

residence time in the atmosphere:
T = V / Q

V = 14 · 10^3 km^3
Q = (416 + 108) · 10^3 = 524 · 10^3 km^3/yr
T = 14/524 ≃ 0.027 yr ≃ 9.75 days

Water balance – country scale

the water balance is computed for the hydrologic year (in CH starting in October)

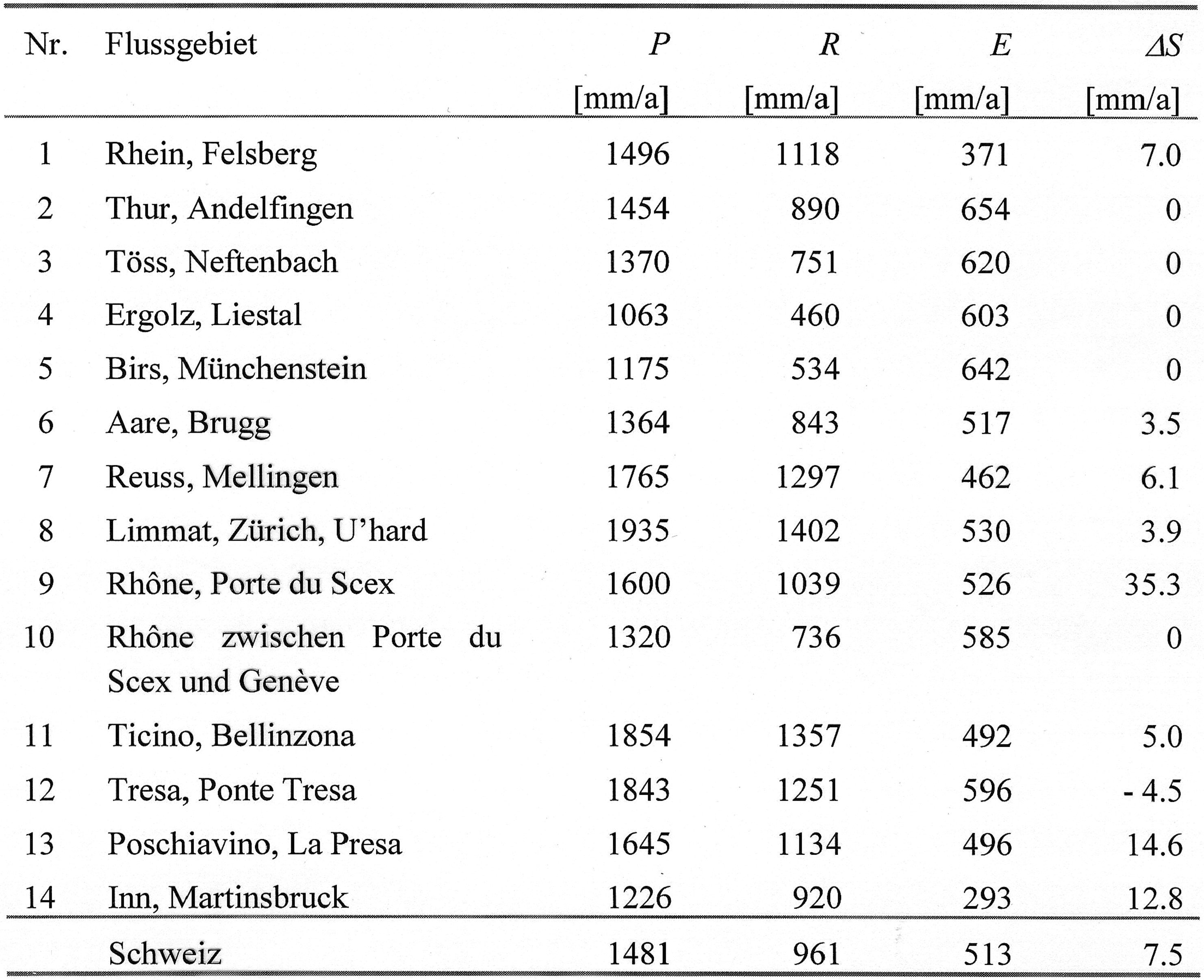


Water balance of Switzerland 1901 - 80

Swiss National Hydrological Survey, 1985

Water balance – river basin scale

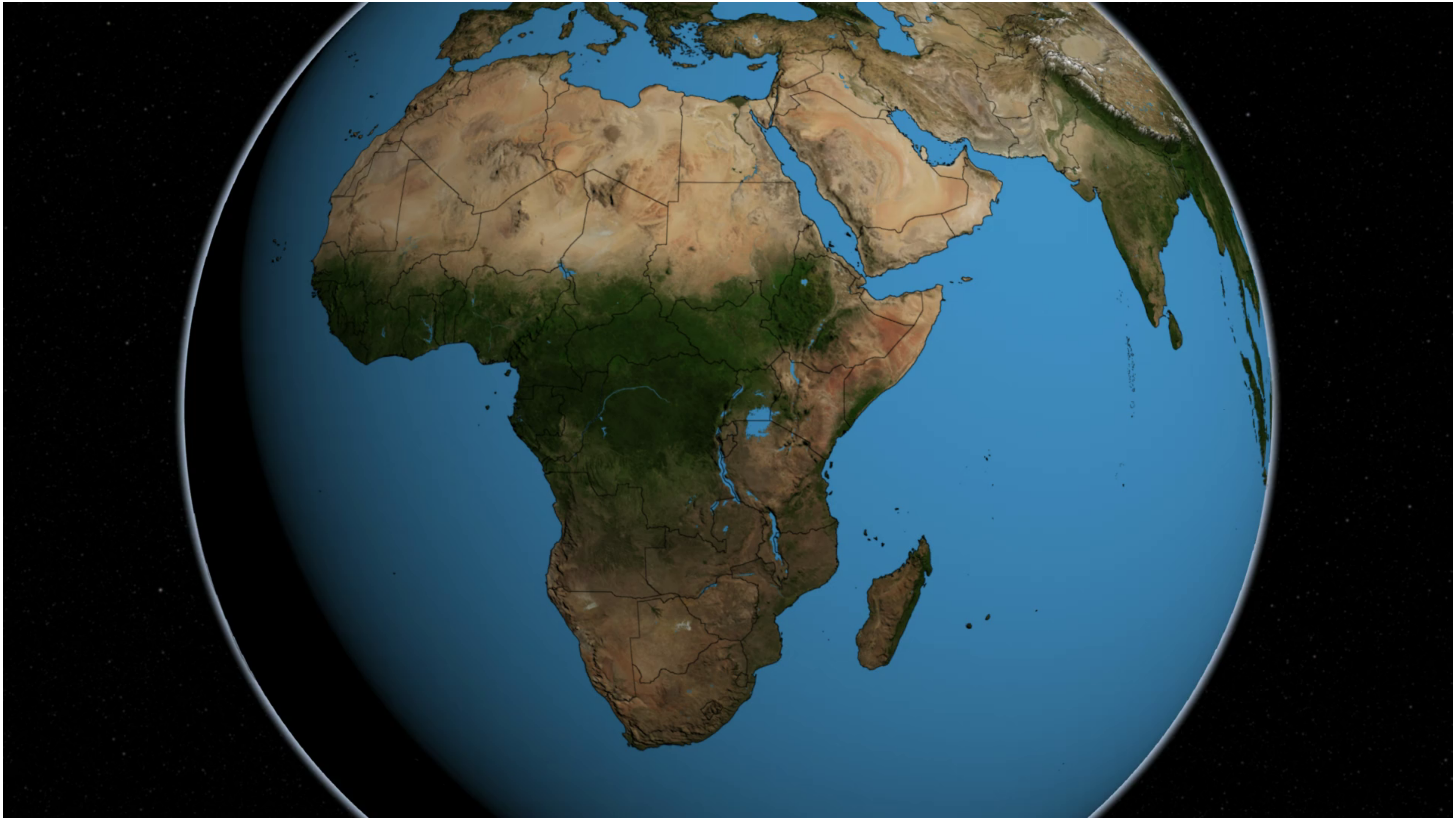
P = R + E + ΔS



Nr.	Flussgebiet	P [mm/a]	R [mm/a]	E [mm/a]	ΔS [mm/a]
1	Rhein, Felsberg	1496	1118	371	7.0
2	Thur, Andelfingen	1454	890	654	0
3	Töss, Neftenbach	1370	751	620	0
4	Ergolz, Liestal	1063	460	603	0
5	Birs, Münchenstein	1175	534	642	0
6	Aare, Brugg	1364	843	517	3.5
7	Reuss, Mellingen	1765	1297	462	6.1
8	Limmat, Zürich, U'hard	1935	1402	530	3.9
9	Rhône, Porte du Scex	1600	1039	526	35.3
10	Rhône zwischen Porte du Scex und Genève	1320	736	585	0
11	Ticino, Bellinzona	1854	1357	492	5.0
12	Tresa, Ponte Tresa	1843	1251	596	- 4.5
13	Poschiavino, La Presa	1645	1134	496	14.6
14	Inn, Martinsbruck	1226	920	293	12.8
	Schweiz	1481	961	513	7.5

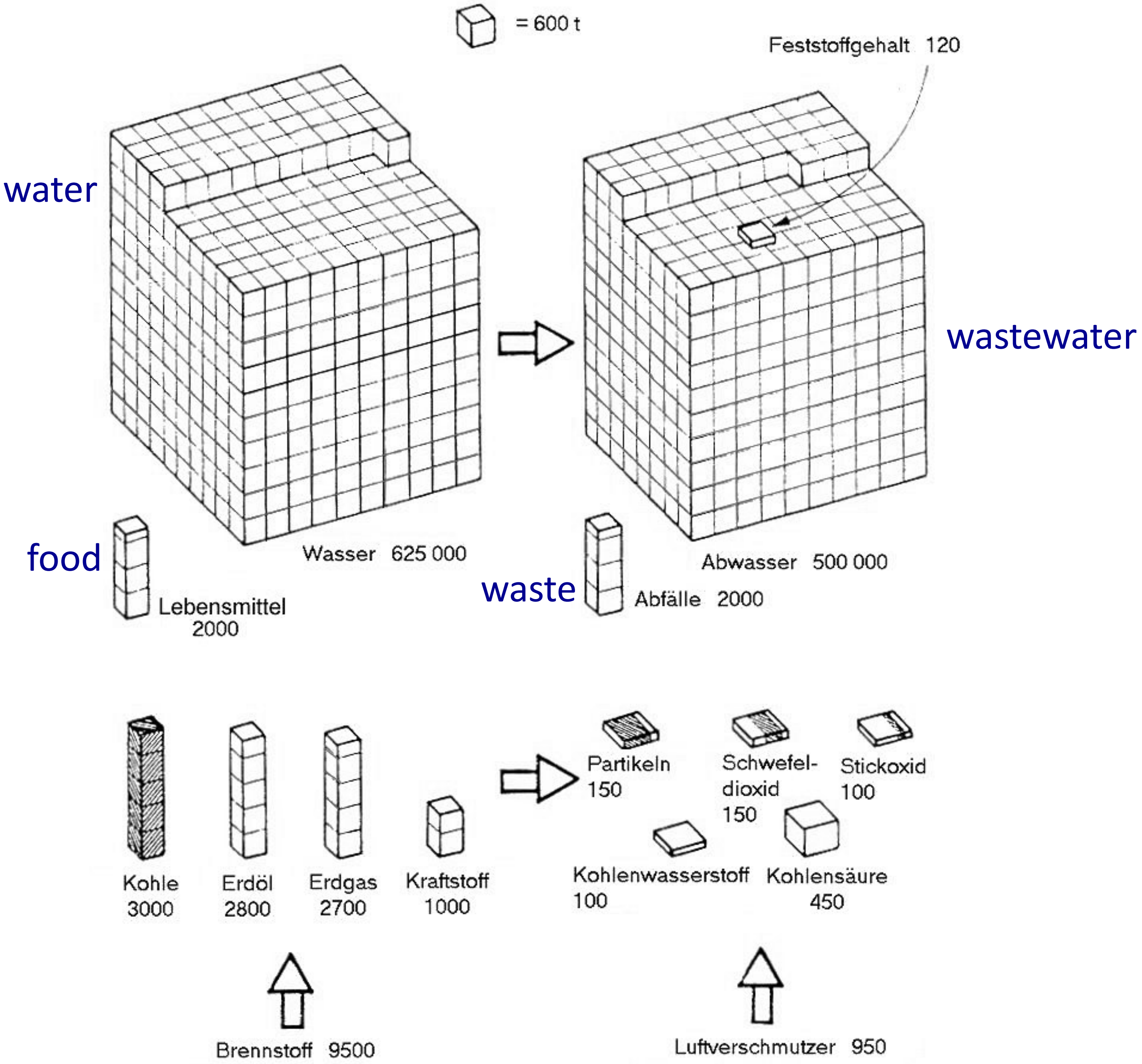
[Hydrologie Skript]

Water balance of the Nile river (process variability in space and time)



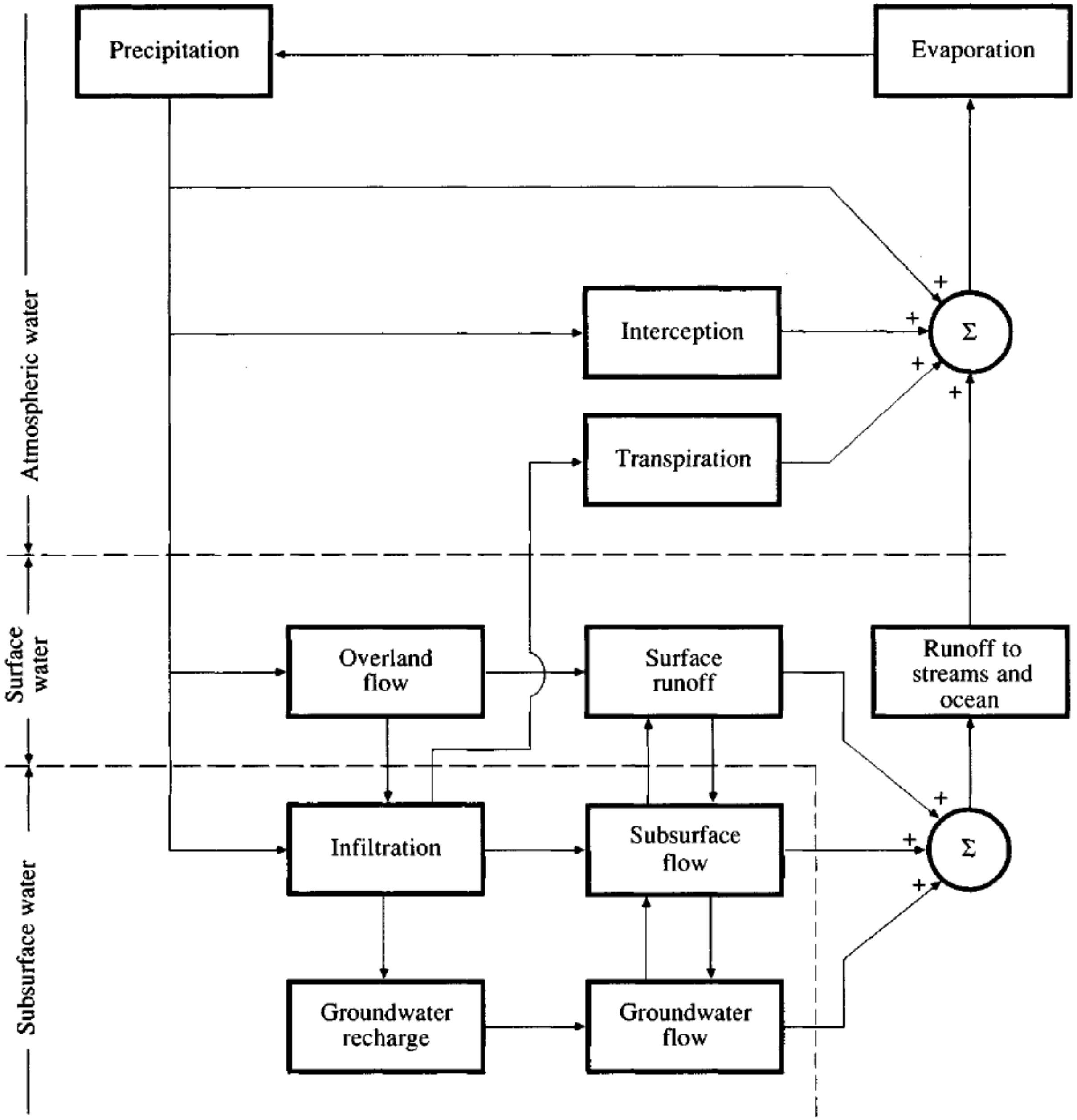
http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4044

Water balance – urban scale



The hydrological cycle at the event scale

Flowchart representation of the hydrological cycle

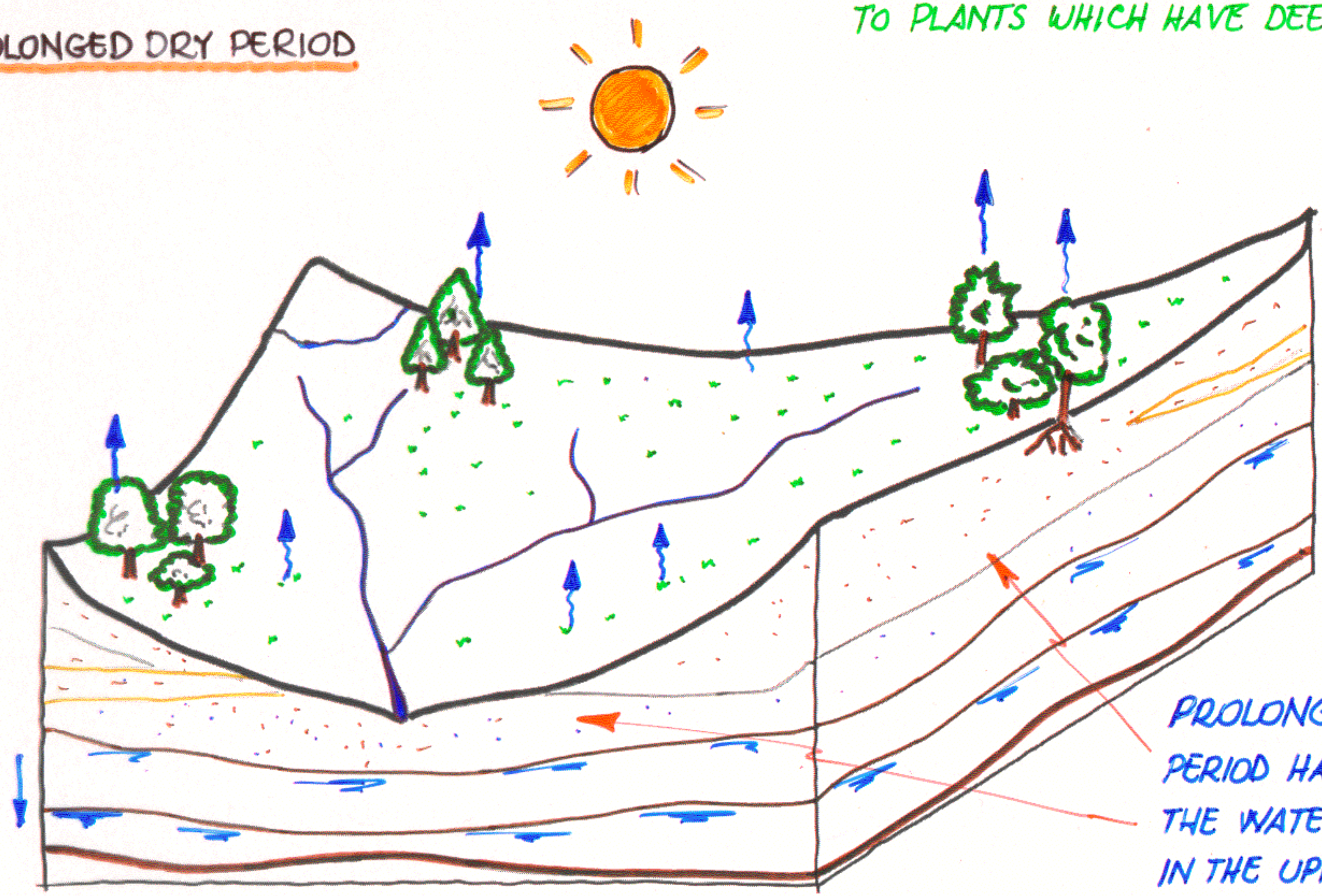


[Chow et al. 1998]

THE CATCHMENT

AFTER PROLONGED DRY PERIOD

EVAPOTRANSPIRATION IS LIMITED TO PLANTS WHICH HAVE DEEP ROOTS

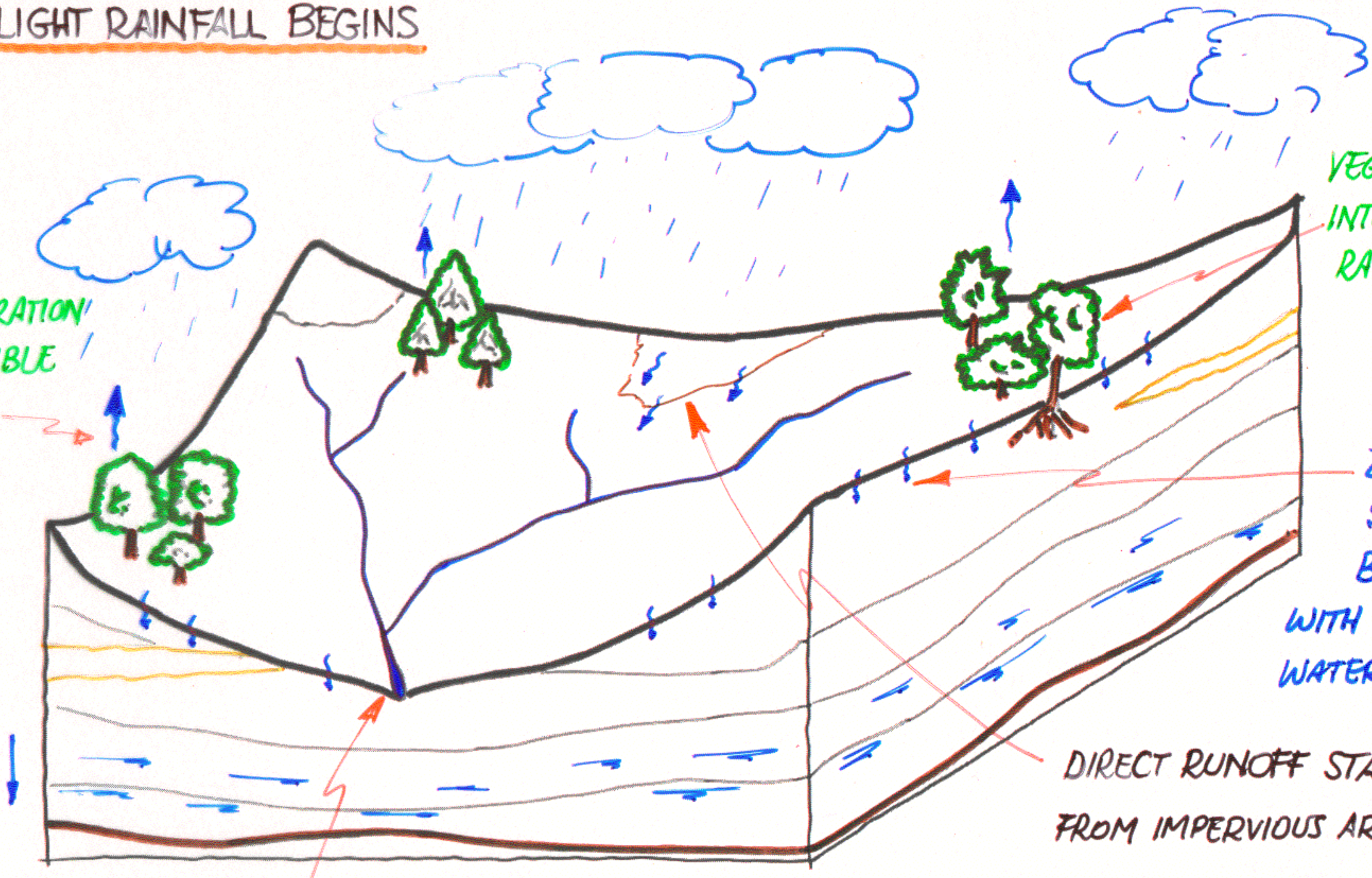


PROLONGED DRYING PERIOD HAS EMPTIED THE WATER STORED IN THE UPPER LAYER OF THE SOIL

RIVER FLOWS ARE LIMITED TO BASEFLOW,

THE CATCHMENT

WHEN LIGHT RAINFALL BEGINS



EVAPOTRANSPIRATION IS STILL POSSIBLE (EVENTUALLY INCREASES)

VEGETATION INTERCEPTS RAIN WATER

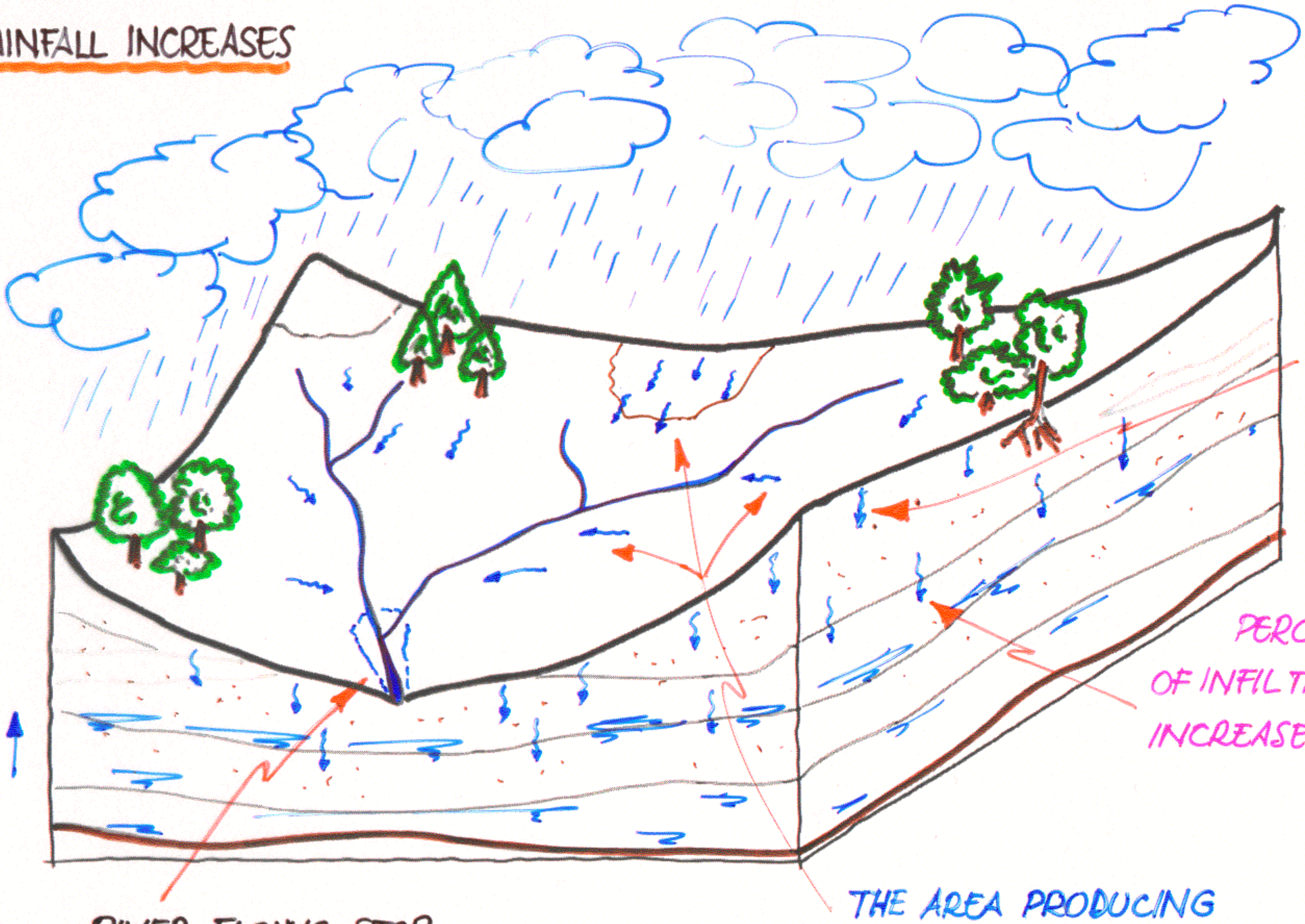
UPPER SOIL ZONES START TO BE SUPPLIED WITH INFILTRATING WATER

RIVER FLOWS CONTINUE TO BE LIMITED TO BASEFLOW, EXCEPT FOR

DIRECT RUNOFF STARTS FROM IMPERVIOUS AREAS

THE CATCHMENT

WHEN RAINFALL INCREASES



UPPER LAYERS OF THE SOIL RECEIVE MORE WATER

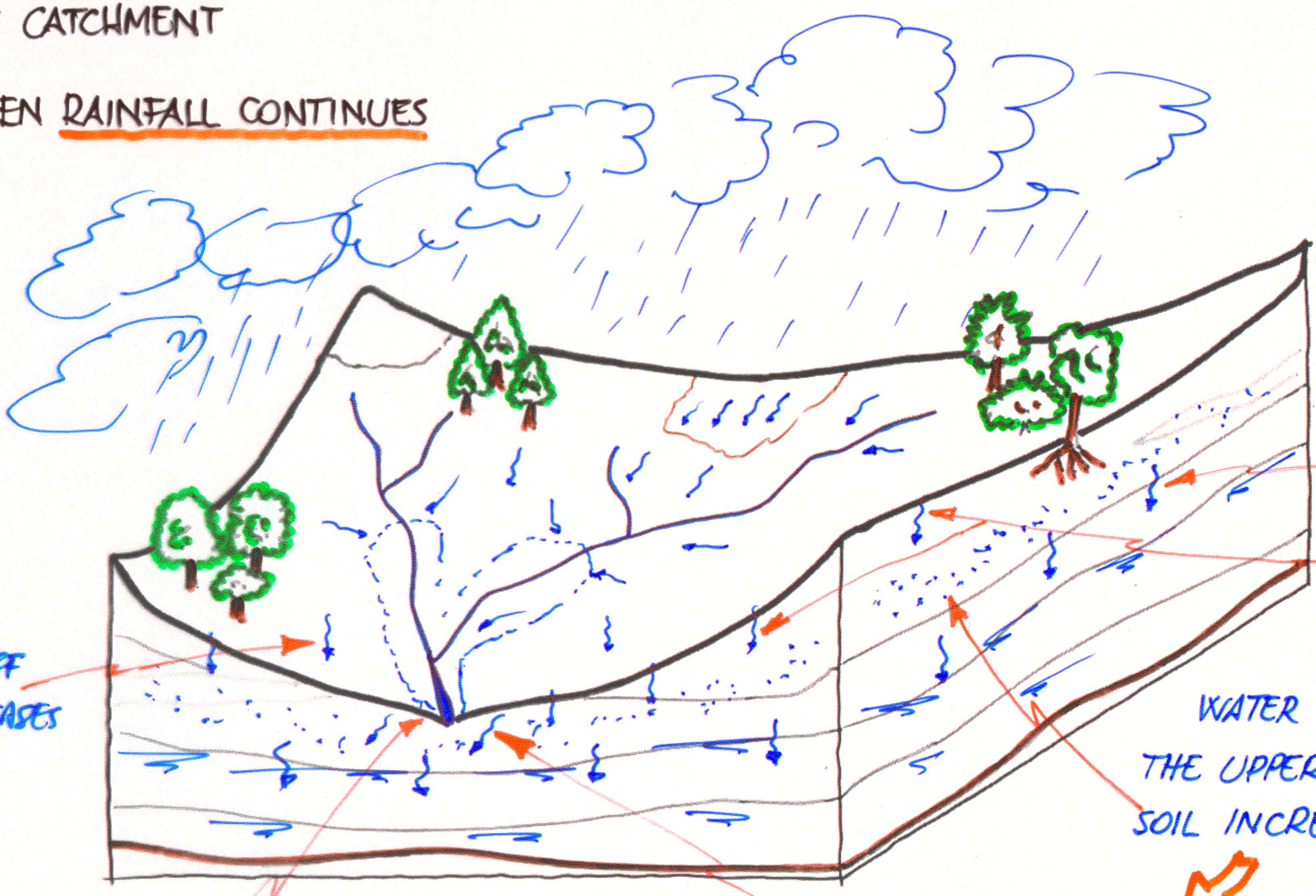
PERCOLATION OF INFILTRATED WATER INCREASES

RIVER FLOWS STOP THE DECREASING PHASE (RECESSION)

THE AREA PRODUCING DIRECT RUNOFF INCREASES

THE CATCHMENT

WHEN RAINFALL CONTINUES



DIRECT RUNOFF INCREASES

RAINFALL RATE EXCEEDS PERCOLATION AND INFILTRATION CAPABILITY

WATER CONTENT IN THE UPPER ZONES OF SOIL INCREASES

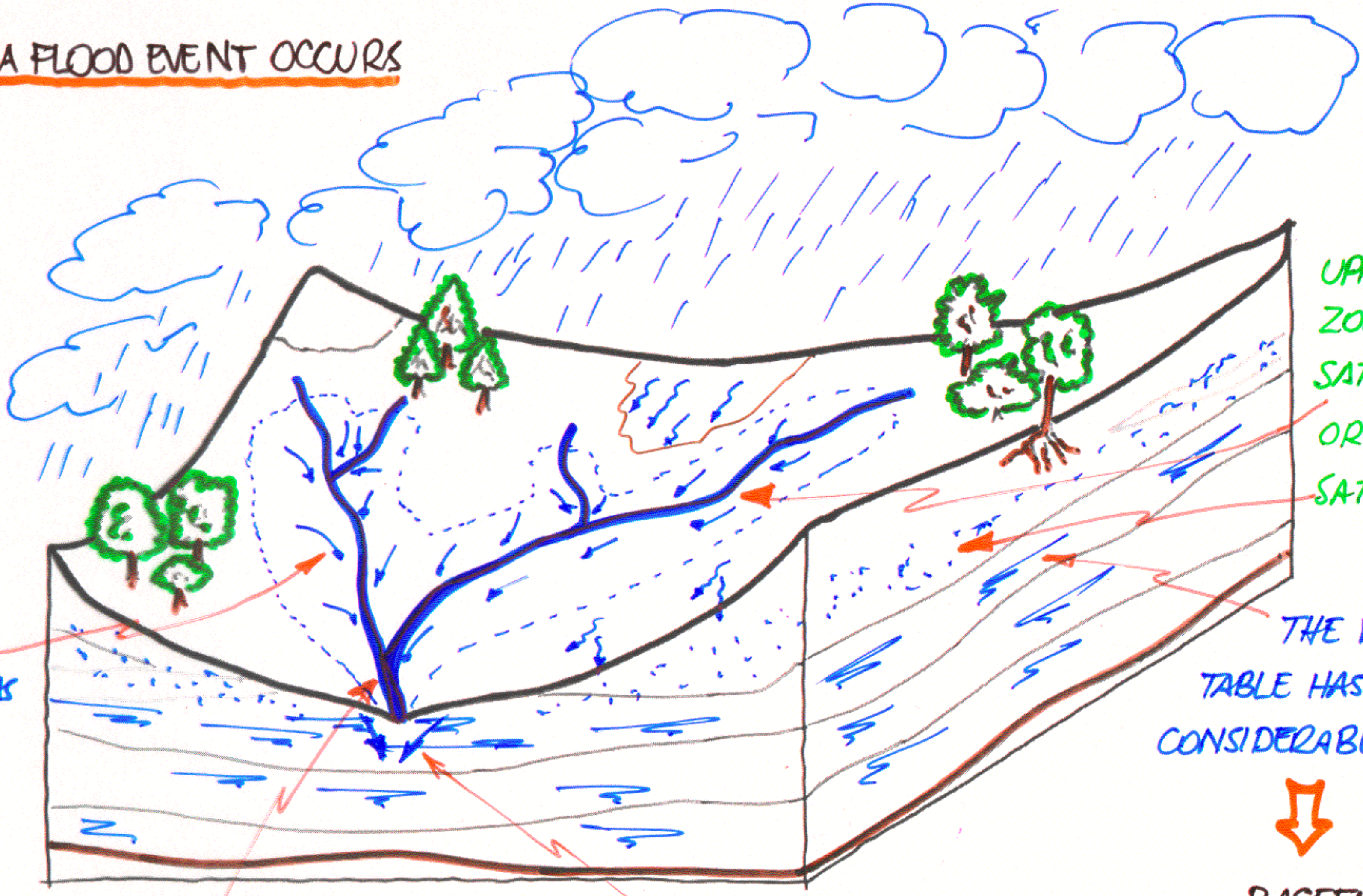
INTERFLOW PROCESSES BEGIN AND ....

... SUPPLY WATER TO THE RIVER NETWORK

RIVER FLOWS INCREASE

THE CATCHMENT

WHEN A FLOOD EVENT OCCURS



DIRECT RUNOFF HAS REACHED A MAXIMUM

UPPER SOIL ZONES ARE SATURATED OR ALMOST SATURATED

THE WATER TABLE HAS INCREASED CONSIDERABLY

⇩

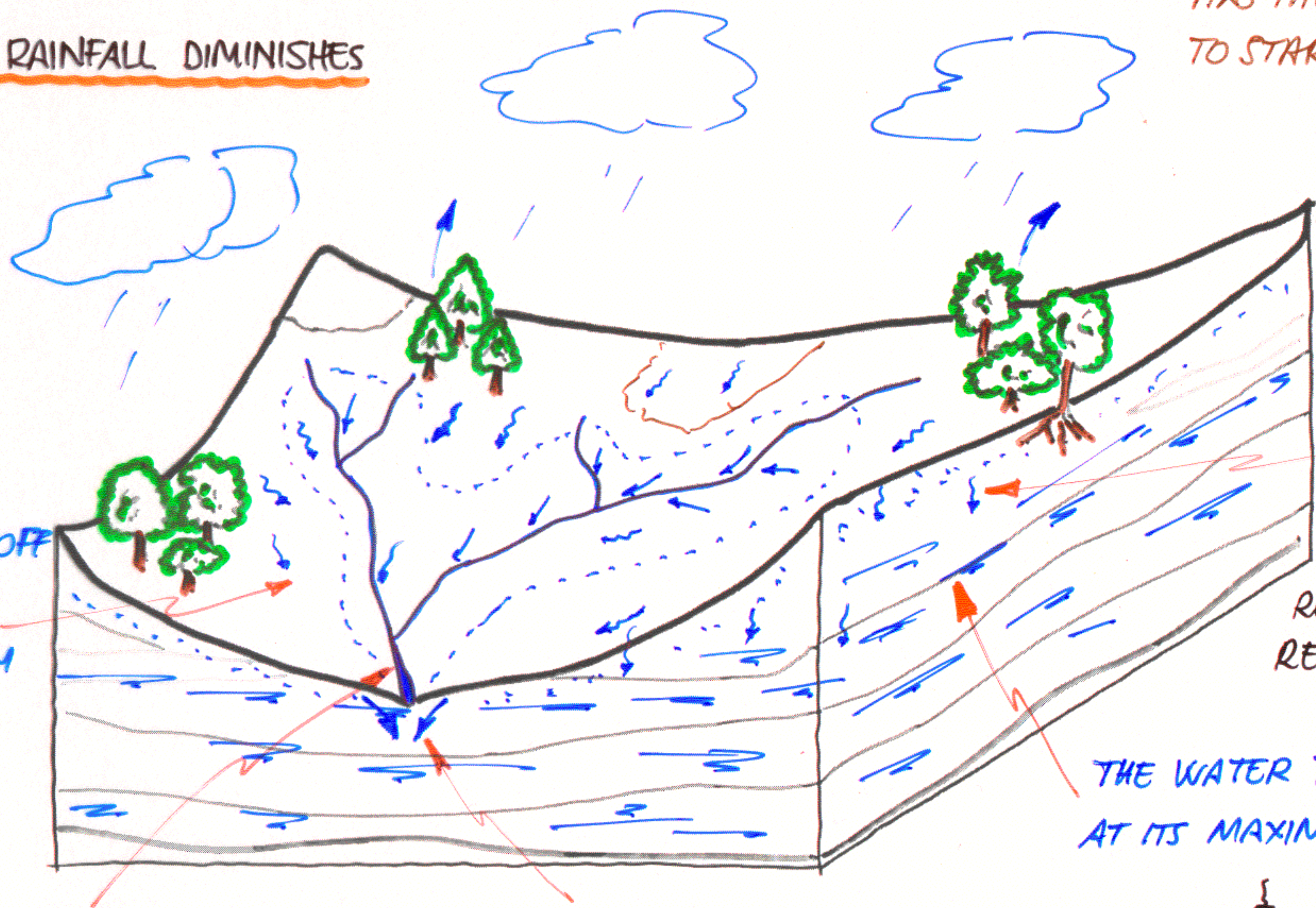
BASEFLOW CONTRIBUTES SIGNIFICANTLY TO RIVER FLOWS

THE RIVER FLOWS ARE AT THEIR MAXIMUM

INTERFLOW PROCESSES REACH THEIR MAXIMUM AND CONTRIBUTE SIGNIFICANTLY TO RIVER FLOWS

THE CATCHMENT

WHEN RAINFALL DIMINISHES



EVAPORATION HAS THE CHANCE TO START...

RAINFALL RATE DOES NOT EXCEED PERCOLATION

↓

SURFACE RUNOFF IS REDUCING

DIRECT RUNOFF STILL NEAR TO MAXIMUM

THE WATER TABLE IS AT ITS MAXIMUM

↓

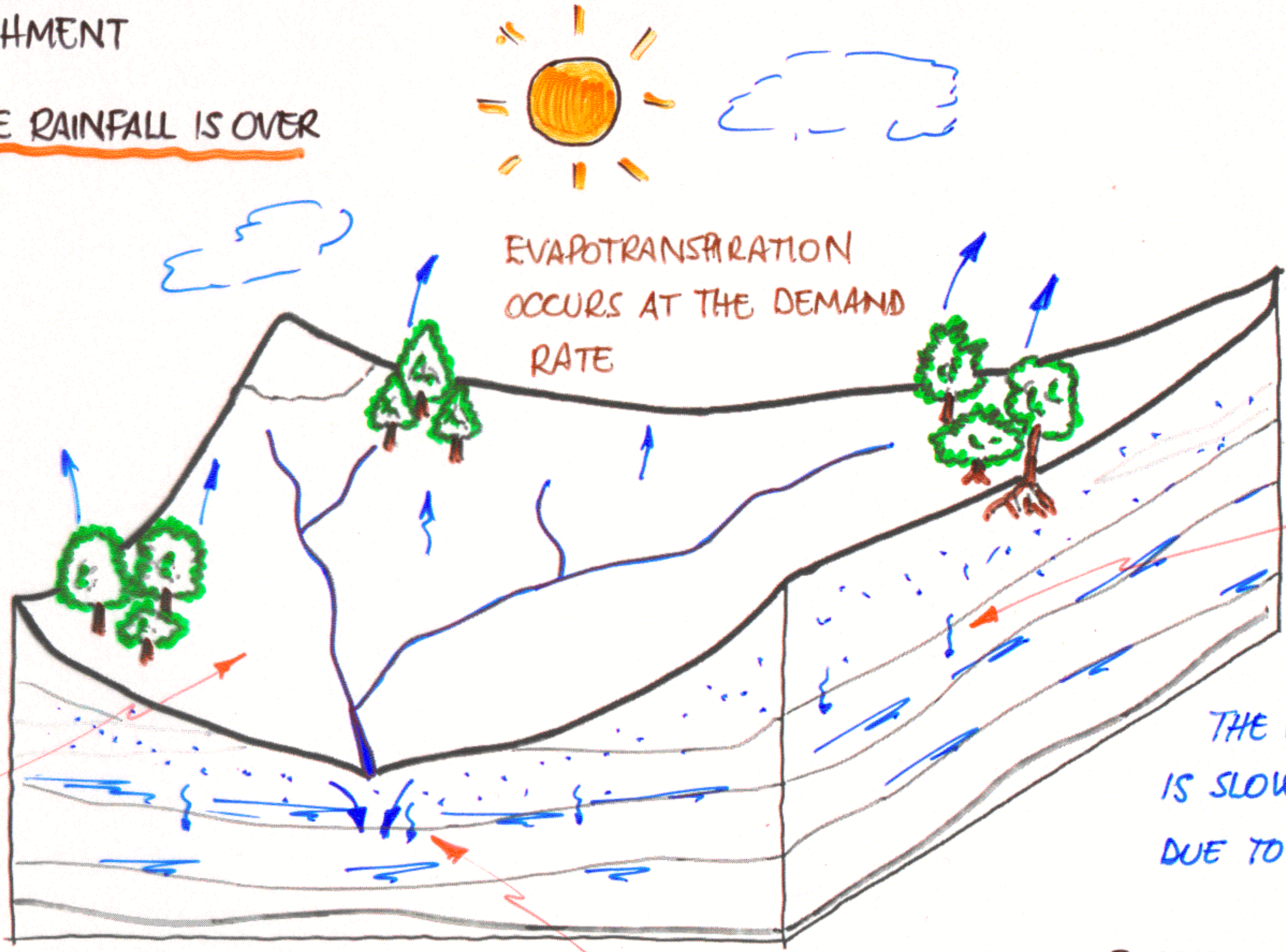
MAX CONTRIBUTION OF BASEFLOW TO RIVER FLOWS

RIVER FLOWS START REDUCING BECAUSE OF LOWER AMOUNT OF SURFACE RUNOFF

INTERFLOW IS AT ITS MAXIMUM CONTRIBUTION TO RIVER FLOWS

THE CATCHMENT

WHEN THE RAINFALL IS OVER



EVAPOTRANSPIRATION OCCURS AT THE DEMAND RATE

DIRECT RUNOFF HAS COME TO AN END

PERCOLATION STILL CONTINUES BUT AT A REDUCED RATE

THE WATER TABLE IS SLOWLY LOWERING DUE TO

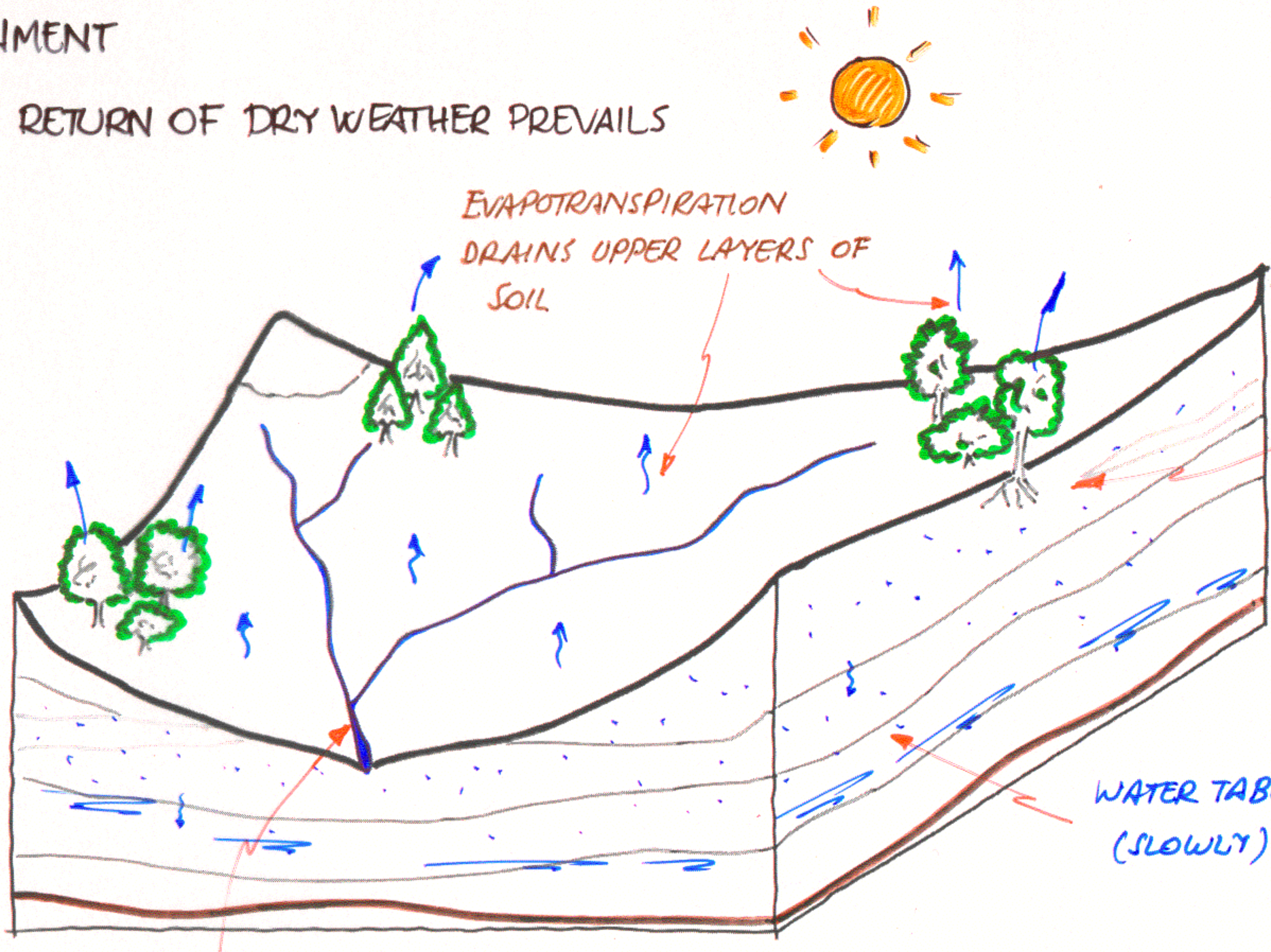
BASEFLOW, WHICH IS STILL HIGH, BUT RECEDING

RIVER FLOWS ARE (SLOWLY) RECEDING

INTERFLOW IS SIGNIFICANTLY REDUCED

THE CATCHMENT

WHEN THE RETURN OF DRY WEATHER PREVAILS



EVAPOTRANSPIRATION DRAINS UPPER LAYERS OF SOIL

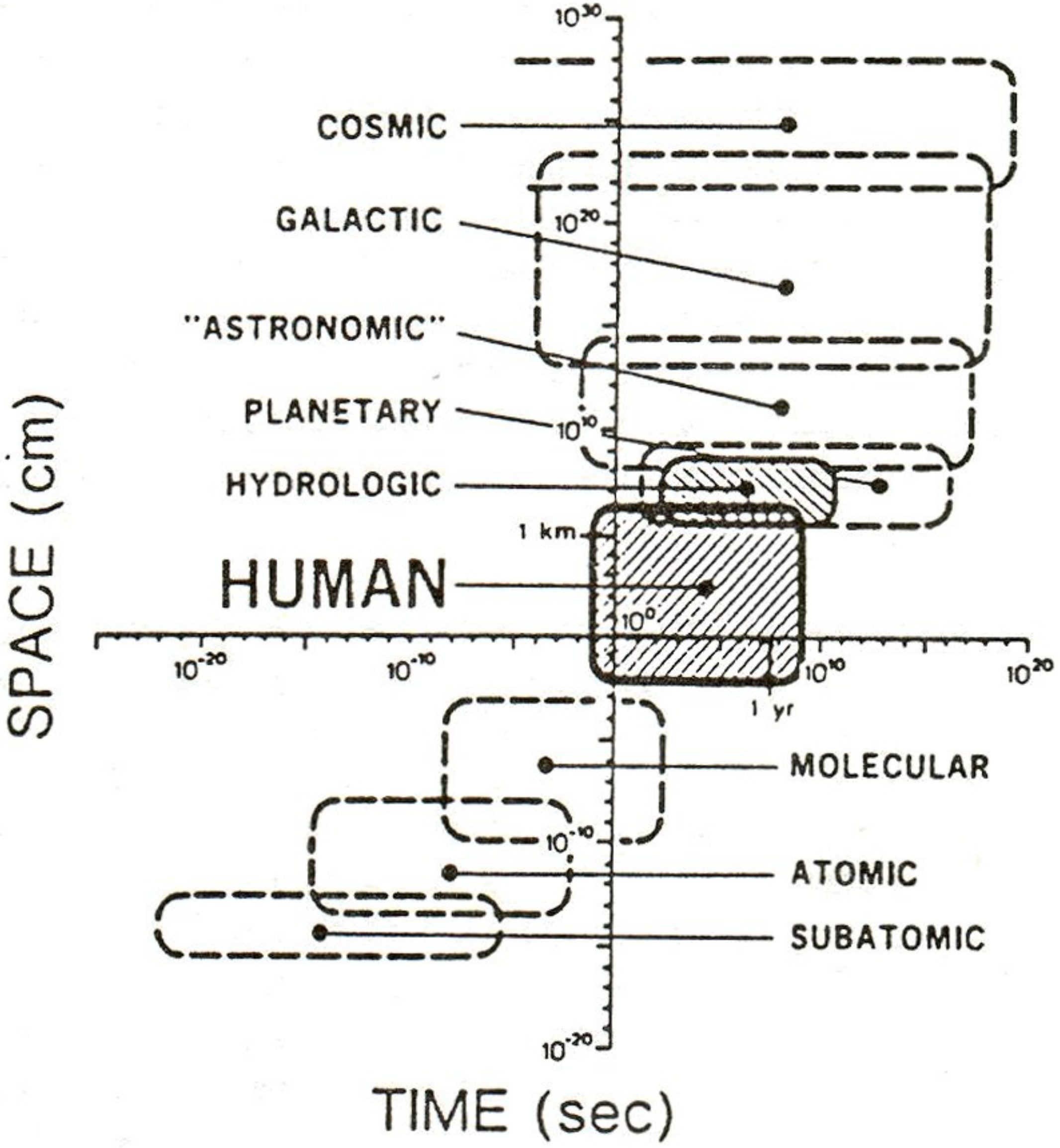
UNSATURATED ZONES DRYING UP

WATER TABLE (SLOWLY) DECREASING

RIVER FLOWS ARE AT THE LOW FLOWS STAGE (RECEDING INTERFLOW & BASEFLOW)

Characteristic temporal and spatial scales
and
hydrological data

Space and time scales of hydrological processes



typically:

space: 1 m "point scale" (1D)
1 m^2 (2D)
↓
10^6 m (1D)
10^6 km^2 "watershed" (2D)

time: 1 s "instantaneous"
↓
1 year

Technical space and time scales of hydrological processes

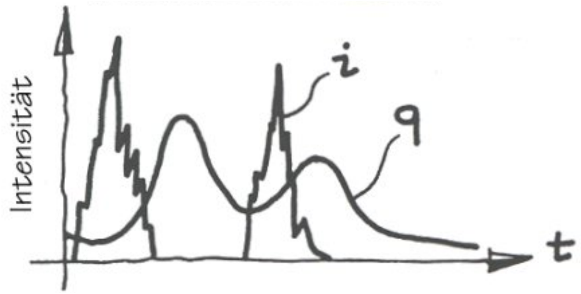
[s]

		1	$3.6\ 10^3$	$\approx 8.6\ 10^4$	$\approx 2.6\ 10^6$	$\approx 3.2\ 10^7$	
		instantaneous	**hourly**	**daily**	**monthly / seasonal**	**annual**	**multi annual**
1	**point**	•	•	•	•	•	•
	hillslope	•	•	(•)	(•)	(•)	
[m]	**watershed**		•	•	•	•	•
	regional		•	•	•	•	•
$>10^6$	**global**		•	•	•	•	•

- • used, consistent with typical process scales
- (•) generally not used, inconsistent with typical process scales

Temporal and spatial nature of hydrological data

continuous = sequence of instantaneous data

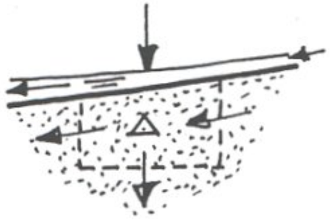


discrete =

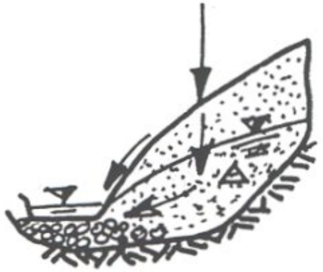
a) aggregated from continuous to larger temporal scales (e.g. from 1h to 1 day, from 1h to 1 month, etc.)

b) measured at discrete times

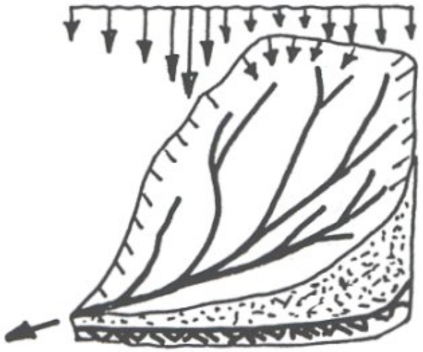
point / local



hillslope

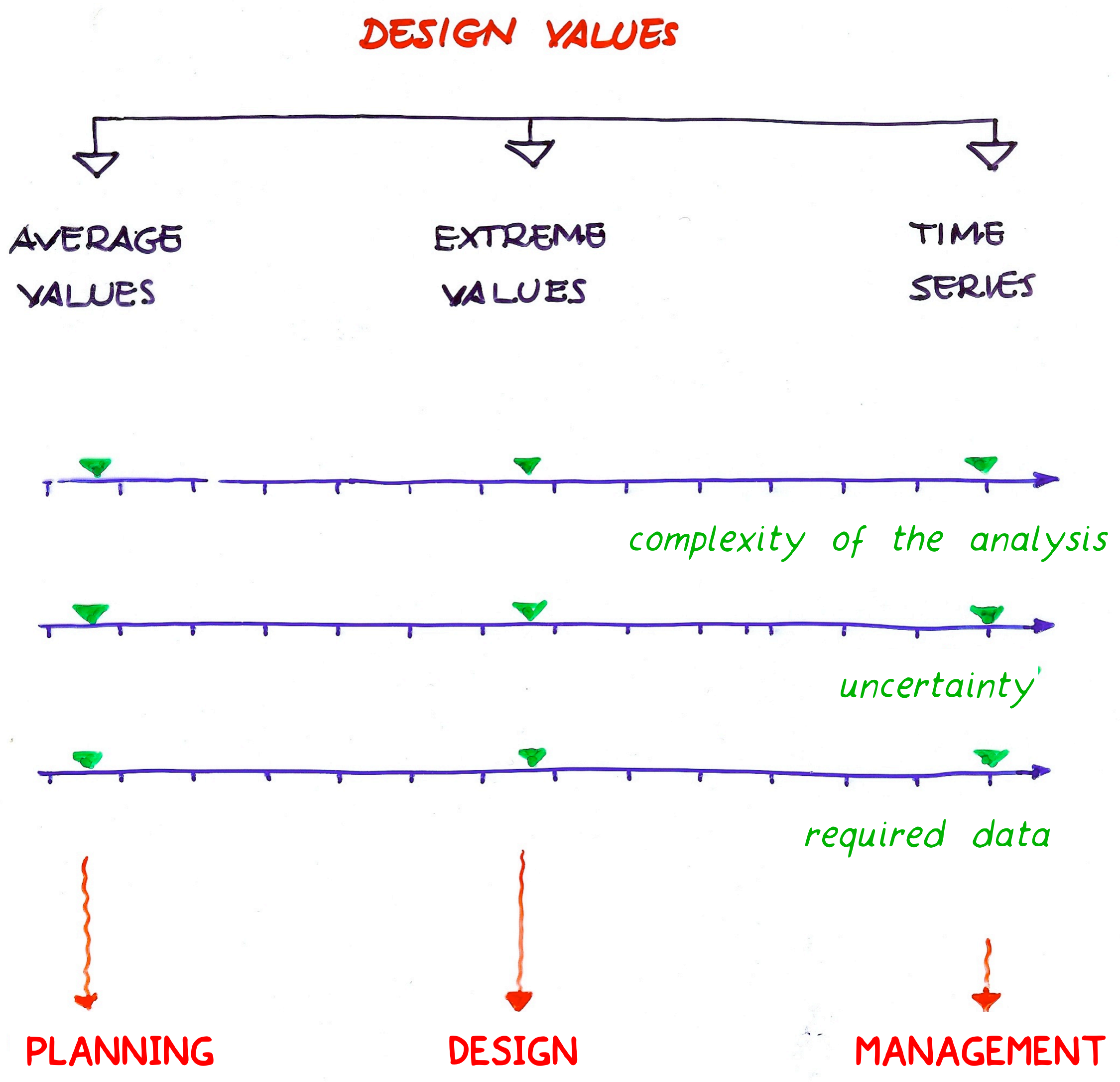


watershed



Use of hydrological data in water engineering problems

- ***average values*** are used in ***planning*** problems and preliminary analyses
- ***extreme values*** are used to ***design*** water engineering infrastructures against extreme events (e.g. floods, low flows, droughts, …)
- ***continuous data*** (time series) are used in ***management*** and and optimization of water resources infrastructures

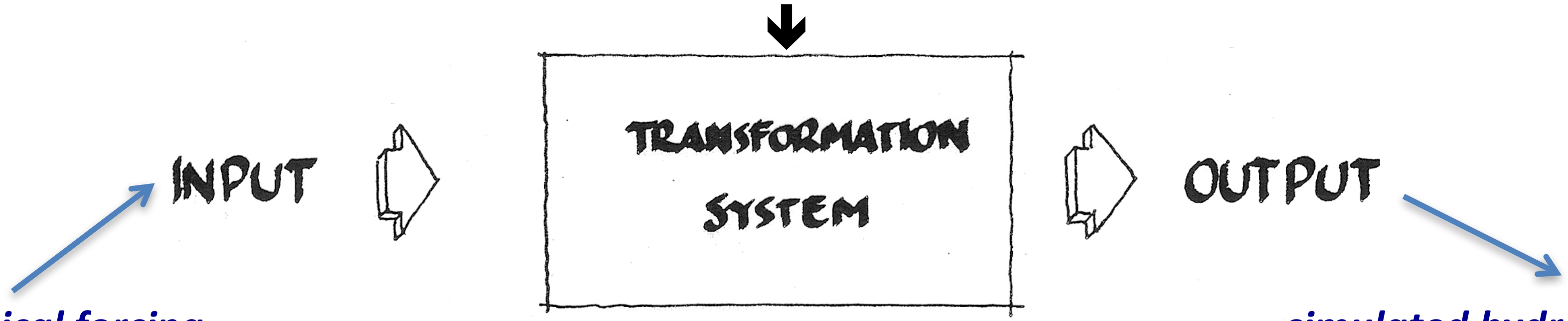


Water engineering problems and hydrologic variables

Water engineering problem	***Typical reference hydrologic variable***
Design of flood protection measures	*Peak flow discharge* *Flood volume and duration*
Design of storm drainage	*Extreme values of rainfall depth* *Peak flow discharge*
Design of a reservoir	*Annual water yield* *Seasonal/monthly water yield*
Design of an irrigation system	*Evapotranspiration* *Soil water content*
Landslide risk analysis	*Extreme values of rainfall depth and intensity*
River bed erosion	*River discharge*
Surface erosion	*Overland flow*
Water allocation to multiple users (hydropower, irrigation, water supply, …)	*Discharge time series*
…	…

Uncertainties

HYDROLOGICAL MODEL CONCEPTUALIZATION



meteorological forcing
(precipitation, temperature, radiation, wind, etc.)

- ***watershed representation*** (topography, land cover, soil, …)
- ***mathematical model*** of basin hydrological processes (infiltration, runoff formation, evapotranspiration, etc.)

simulated hydrological variables
(streamflow, soil water content, evapotranspiration, …)

typical uncertainties

- *due to lack of data*
- *due to climate variability*
- *uncertainties due to spatial variability of meteorological forcing*
- *uncertainties due to measurement errors*

typical uncertainties

- *due to poor knowledge of the physical system*
- *due to spatial heterogeneities and anisotropies*
- *model approximations*
- *model parameters*

output is uncertain

↓

design values are uncertain

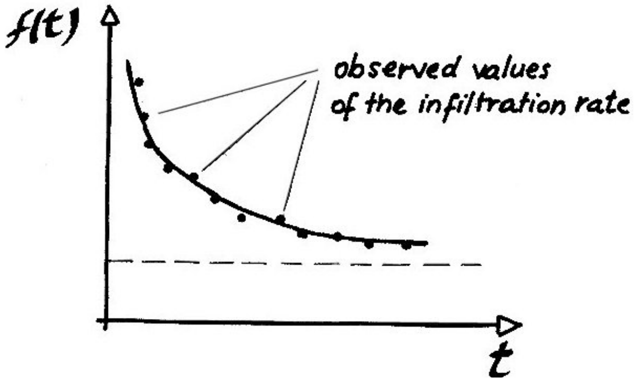
↓

probabilistic analysis

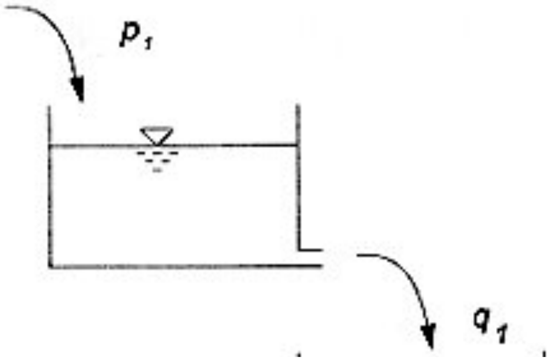
From physical processes to hydrological models

Models can be

- ***empirical*:** description of hydrological processes based on cause-effect relationships experimentally derived or inferred from data analysis



- ***conceptual*:** description of hydrological processes based on the conceptualisation of the physical mechanisms



- ***physically based*:** description of hydrological processes based on the representation of the physical mechanisms by means of physics laws

- CONTINUITY EQUATION
  (one-dimensional flow)
  $$\frac{\partial \theta}{\partial t} + \frac{\partial q}{\partial z}$$
- MOMENTUM EQUATION
  $$q = -\left(k + D \frac{\partial \theta}{\partial z}\right)$$

Keywords

- *water balance*
- *time scales*
- *spatial scales*
- *volumes*
- *fluxes*
- *storage*
- *hydrological cycle*
- *systems analysis*
- *hydrological data*
- *continuous*
- *discrete*
- *event*
- *hydrological process*
- *hydrological model*

- *precipitation*
- *interception*
- *evaporation*
- *evapotranspiration*
- *infiltration*
- *percolation*
- *unsaturated zone*
- *saturated zone*
- *water table*
- *groundwater*
- *runoff*
- *overland flow*
- *interflow*
- *baseflow*

- *river basin / watershed / catchment*
- *river network*