Hydrology of catchments, rivers and deltas (CIE5450)

Prof.dr.ir. Uhlenbrook

Lecture ‘Catchment and water balance’

Hydrology of Catchments, River Basins and Deltas

Part ONE – Catchment and Water Balance

Professor Stefan Uhlenbrook, PhD, MSc, habil.
Professor Dr. Ir. Hubert H.G. Savenije
Professor of Hydrology

UNESCO-IHE Institute for Water Education and
Delft University of Technology
The Netherlands

E-mail: s.uhlenbrook@unesco-ihe.org
s.uhlenbrook@tudelft.nl

UNESCO-IHE Institute for Water Education

TU Delft
Delft University of Technology

Introduction of the Lecturer

- Hydrologist originally from Freiburg, Germany
- MSc, PhD and ‘habilitation’ in Freiburg
- In Delft, the Netherlands, since January 2005: Professor of Hydrology at UNESCO-IHE, Delft
- Since November 2009: part-time Professor of Experimental Hydrology at TU Delft
- Working experiences mainly in catchments in Germany, Austria, USA, East Africa, sub-Saharan Africa, Vietnam, Iran and Palestine, and recently some other more humid places (i.e. Thailand and Malaysia)
- “experimentalist” and “modeler”

Books, course notes and further information

- **Books (classical text books):**
  - Brutsaert, 2005: Hydrology – An Introduction. Wiley & Sons.
  - Dingman, 2002: Physical Hydrology, 2nd edition, Prentice Hall.
  - Hornberger et al. 1998: Physical Hydrology, …
  - Bedient and Huber, 2002: Hydrology and Floodplain Analysis, 3rd edition, Prentice and Hall.
  - (Davie, 2002: Fundamentals of Hydrology. Routledge Fundamentals of Physical Geography – often too basic!)
  - Shaw, E.M., 1994: Hydrology in practice. Van Nostrand Reinhold, 569 p.
  - Shaw, E.M., 1989: Engineering hydrology techniques in practice. Ellis Horwood, 350 p.
  - Anderson M., McDonnell J.J. 2005: Encyclopedia of Hydrological Sciences. 5 volumes. Wiley.
    Available on-line at UNESCO-IHE library!

- **Lecture notes:**
  Savenije HHG, 2006: Hydrology of Catchments, River Basins and Deltas. Find PDF at the Blackboard.

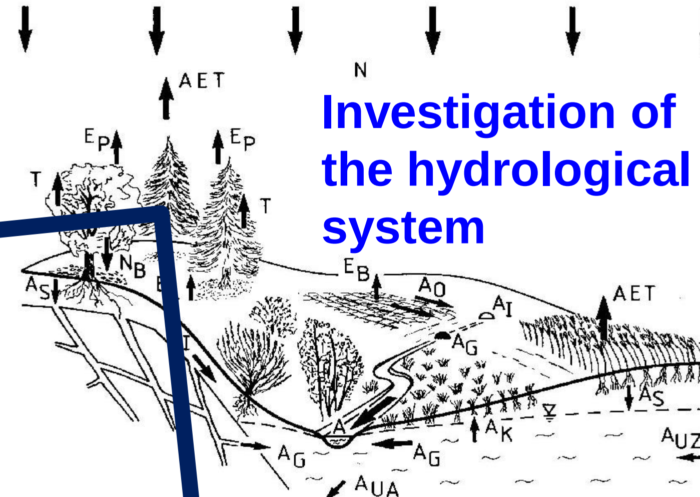
- **Web pages:**
  1. http://www.usgs.gov (free software etc.)
  2. Links at water/hydrology pages of UNESCO
  3. Etc.!

Objectives of this Lecture

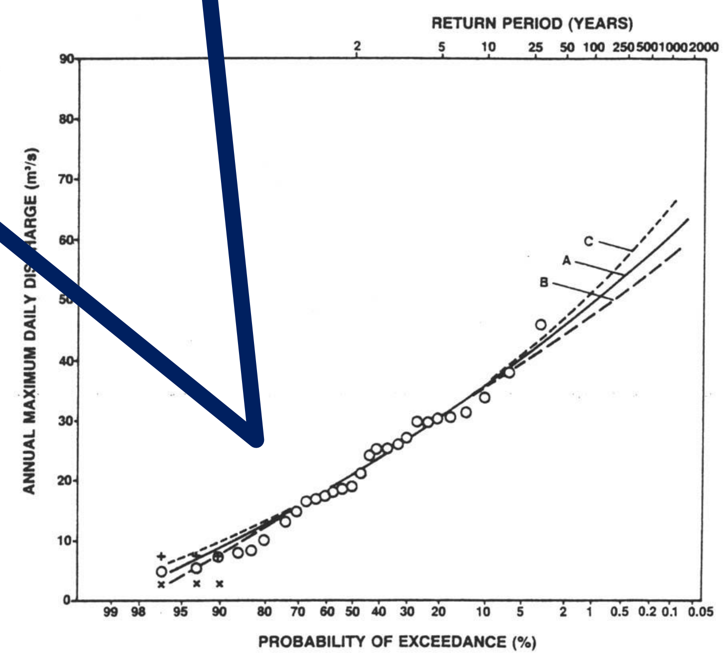
- Introduction
- Hydrological cycle
- Water balance estimation
- Understanding a catchment as the hydrological unit
- Influence of man on hydrological cycle
- Review of hydrological data handling

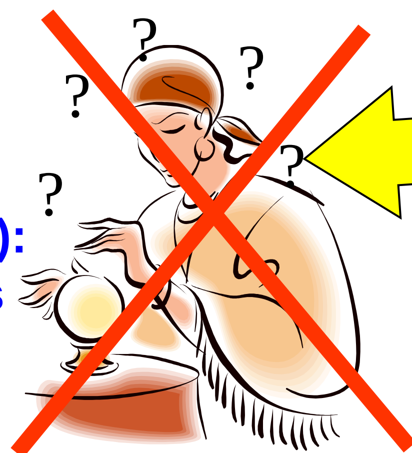
INTRO: How do we get a better (sustainable) IWRM?

Data analysis and modeling



Investigation of the hydrological system

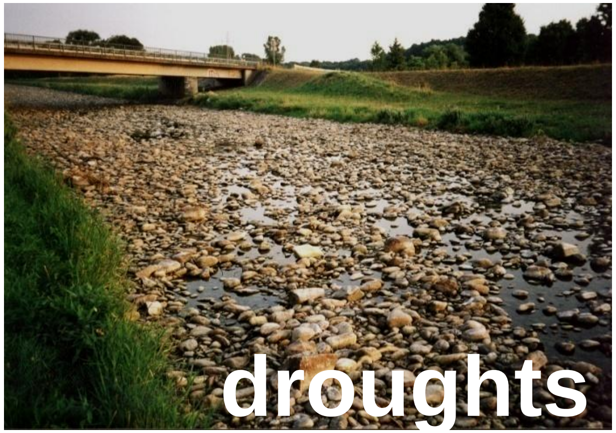




Integrated Water Resources Management (IWRM): Estimation of risks and economic impact

IWRM needs information about …

- Water balance: $P = R + E + dS/dt$
- Hydrological extremes:

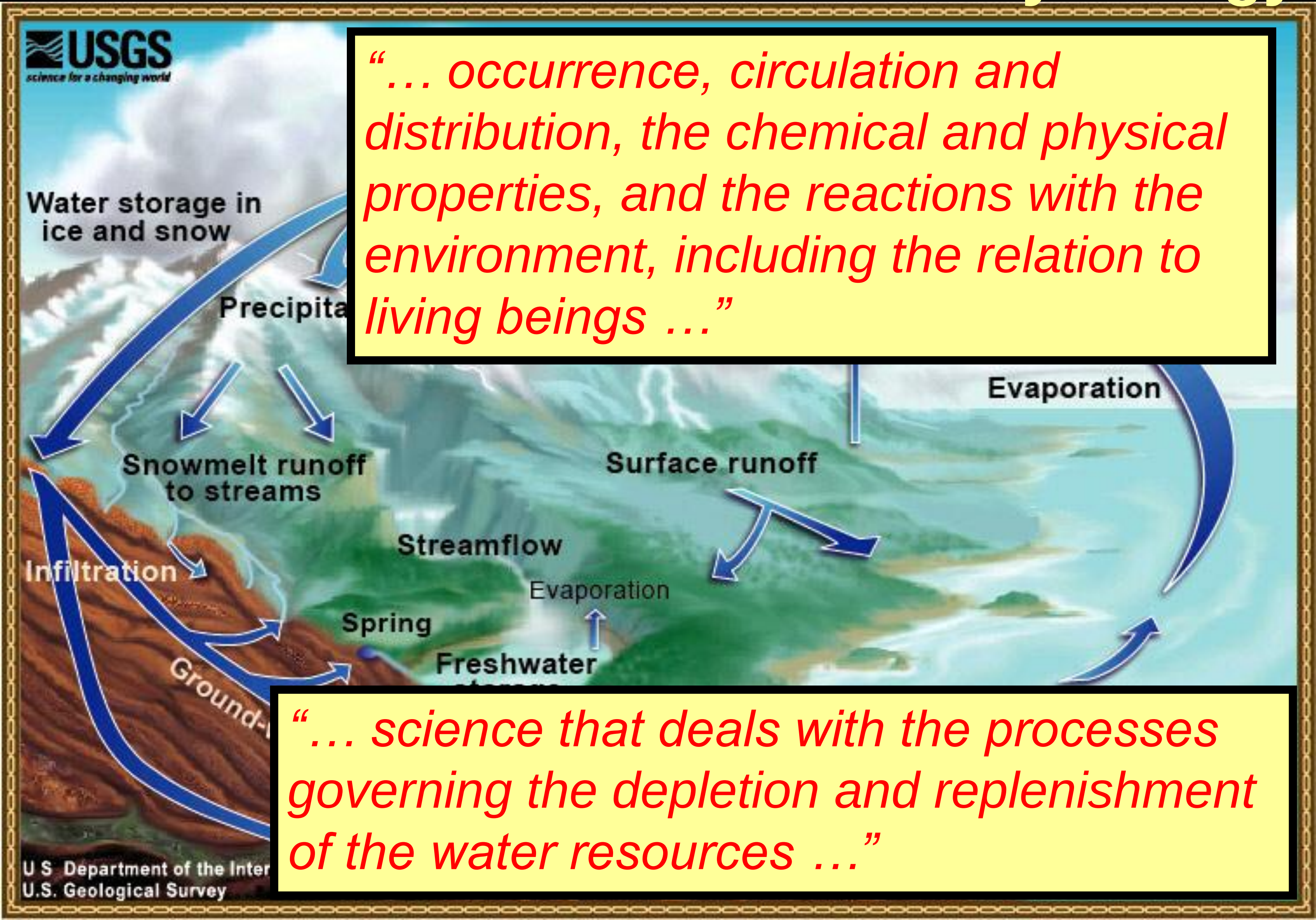


x-year flood

- Scenarios for:
  - ✓ Land use change
  - ✓ Climate chance
  - ✓ Different water management strategies

System understanding and modeling !!

IAHS Definition of the Science Hydrology:



"… occurrence, circulation and distribution, the chemical and physical properties, and the reactions with the environment, including the relation to living beings …"

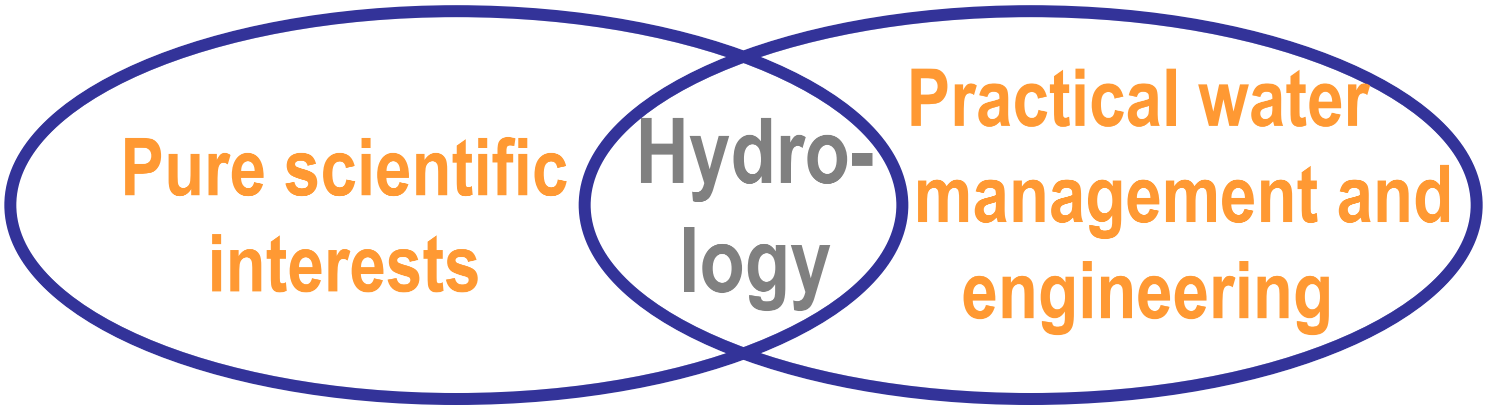
"… science that deals with the processes governing the depletion and replenishment of the water resources …"

Is hydrology a mature science ?

- Do we know enough for water resources engineering and management?
- Do we fully understand **“what happens to the rain”**?
- Do we know enough to predict what will happen under climate change?
- Can we predict in ungauged basins?

What can catchment hydrology contribute to solve water issues?

- Extensive flooding, water scarcity, water quality deterioration, ecosystem decline and effects of global changes …
  initiated through catchment hydrological processes
- Mitigation strategy needs to address whole catchments in a holistic way
- Interdisciplinary science!
- Attraction of hydrology as field of study:



⇨ **… to support life, civilization and sustainable development**

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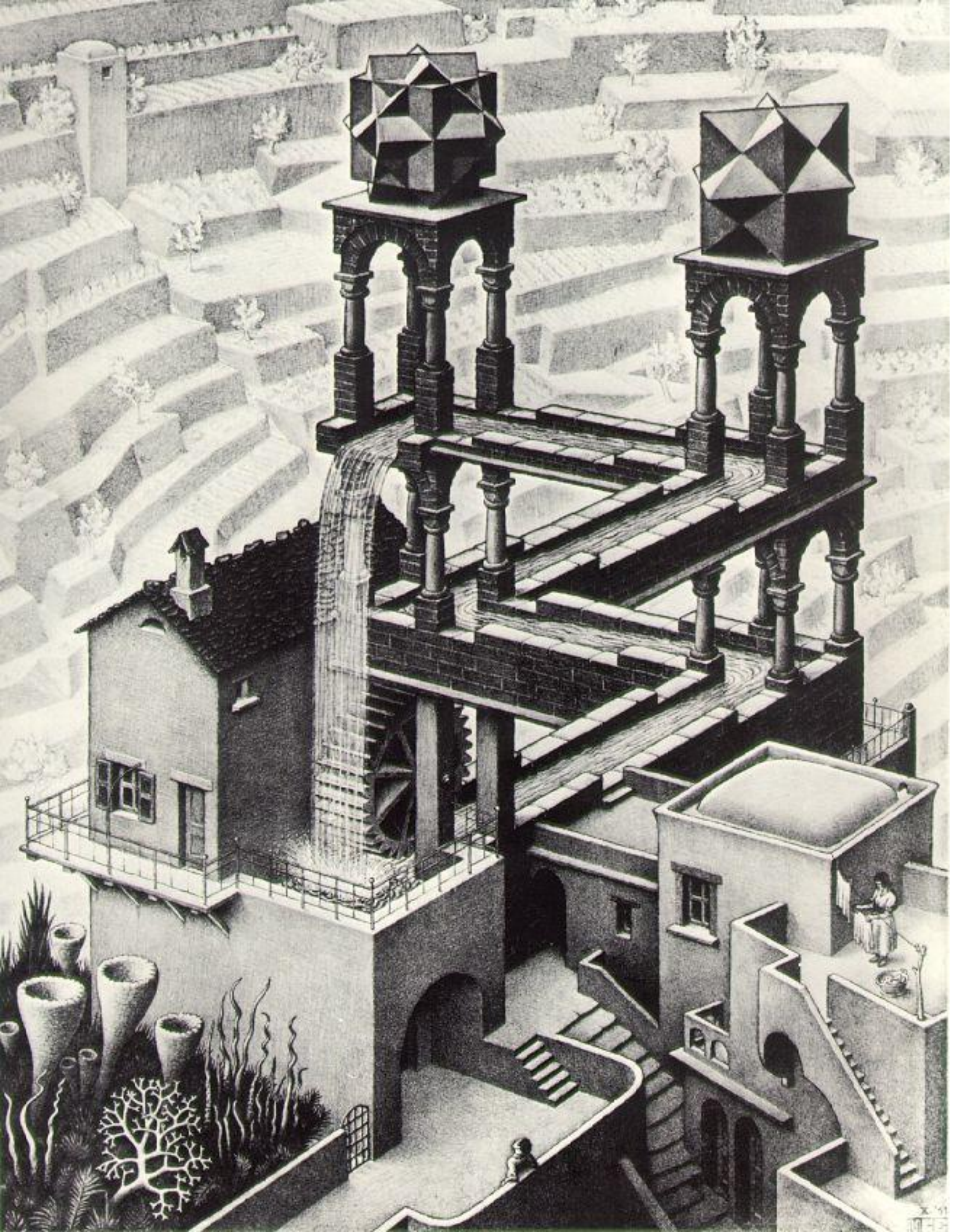
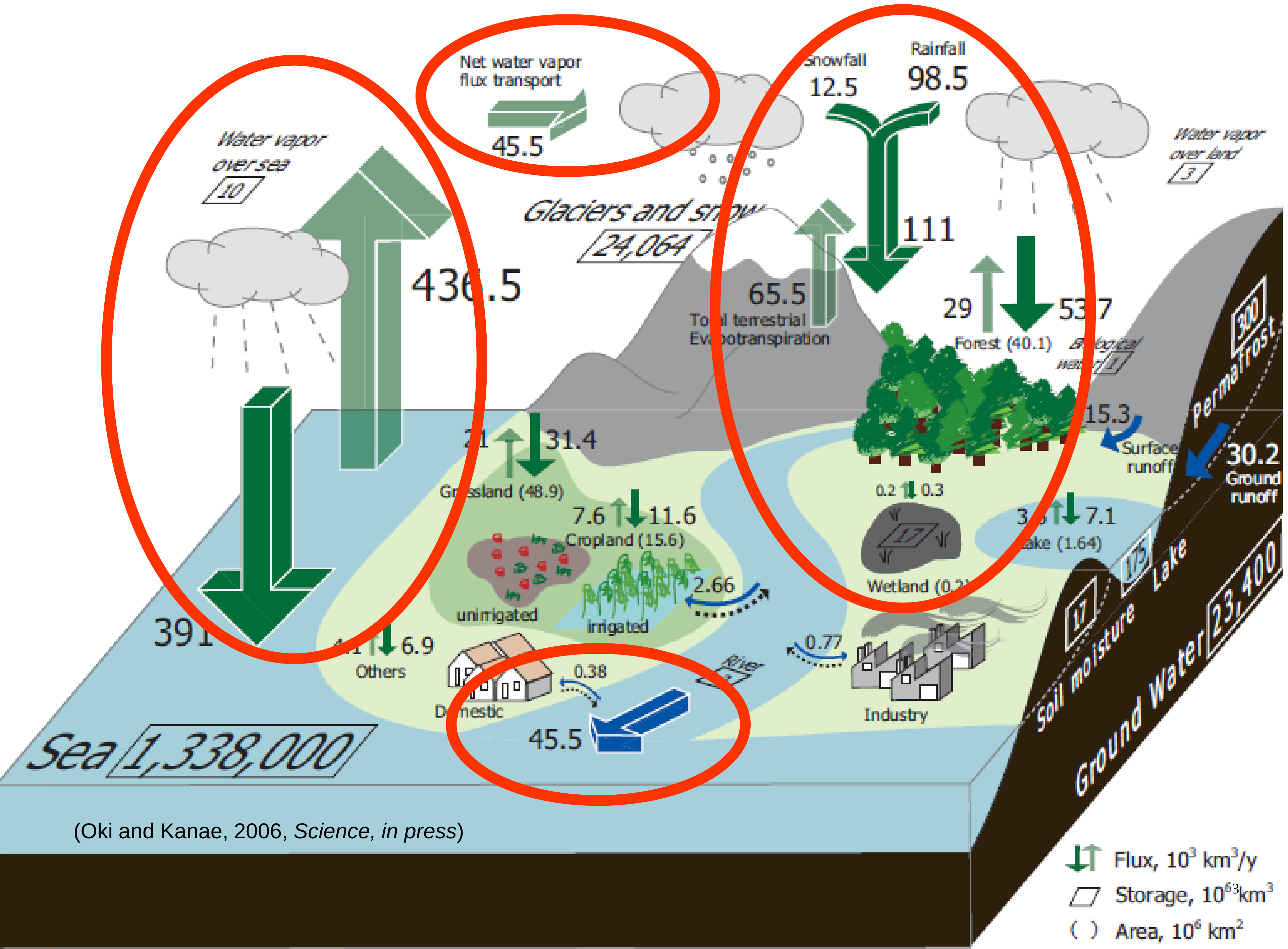


Water cycle

No begin and no end!

Maurits Cornelis Frans Escher



(Oki and Kanae, 2006, *Science, in press*)

Global Water Cycle (WWAP 2003)

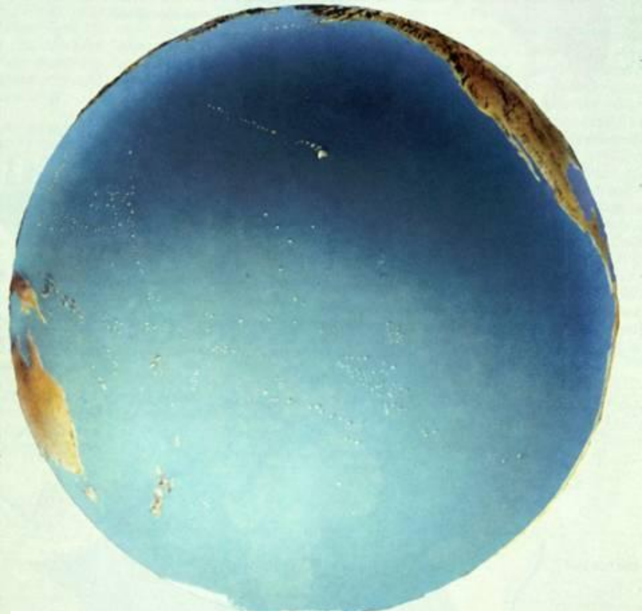
Table 4.1: The distribution of water across the globe

Location	Volume, (10^3 km^3)	% of total volume in hydrosphere	% of freshwater	Volume recycled annually (km^3)	Renewal period years
Ocean	1,338,000	96.5	–	505,000	2,500
Groundwater (gravity and capillary)	23,400[1]	1.7		16,700	1,400
Predominantly fresh groundwater	10,530	0.76	30.1		
Soil moisture	16.5	0.001	0.05	16,500	1
Glaciers and permanent snow cover:	24,064	1.74	68.7		
Antarctica	21,600	1.56	61.7		
Greenland	2,340	0.17	6.68	2,477	9,700
Arctic Islands	83.5	0.006	0.24		
Mountainous regions	40.6	0.003	0.12		
Ground ice (permafrost)	300	0.022	0.86		
Water in lakes:	176.4	0.013	–		
Fresh	91.0	0.007	0.26		
Salt	85.4	0.006	–		
Marshes and swamps	11.5	0.0008	0.03		
River water	2.12	0.0002	0.006		
Biological water	1.12	0.0001	0.003		
Water in the atmosphere	12.9	0.001	0.04		
Total volume in the hydrosphere	1,386,000	100	–		
Total freshwater	35,029.2	2.53	100		

[1] Excluding groundwater in the Antarctic estimated at 2 million km^3, including predominantly freshwater of about 1 million km^3.

This table shows great disparities: between the huge volume of saltwater and the tiny fraction of freshwater; between the large volumes of w
and between the amount of groundwater and the small volumes of water in rivers, lakes and reservoirs.

Source: Shiklomanov, forthcoming.



The 'blue' planet?!

Water balance of the earth surface

	Area in 10^{12} m^2	Area in %
Water surfaces	361	71
Continents	149	29
Total	510	100

	Area in 10^{12} m^2	Area in % of total	Area in % of continents
Deserts	52	10	35
Forests	44	9	30
Grasslands	26	5	17
Arable lands	14	3	9
Polar regions	13	2	9
Oceans	361	71	

World Water Resources (Oki et al. 2005)

MRT := Volume / mean flux

Table 1: World water reserves.

Form of water	Covering Area (km^2)	Total Volume (km^3)	Mean Depth (m)	Share of Volume (%)	Mean Residence Time
World oceans	361 300 000	1 338 000 000	3 700	96.539	2 500 years
Glaciers and permanent snow cover	16 227 500	24 064 100	1 463	1.736	56 years
Ground water[a]	134 800 000	23 400 000	174	1.688	8 years
Gound ice in zones of permafrost strata	21 000 000	300 000	14	0.0216	
Water in lakes	2 058 700	176 400	85.7	0.0127	
Soil moisture	82 000 000	16 500	0.2	0.0012	
Atmospheric water	510 000 000	12 900	0.025	0.0009	9 days
Marsh water	2 682 600	11 470	4.28	0.0008	
Water in rivers	148 800 000	2120	0.014	0.0002	18 days
Biological water	510 000 000	1 120	0.002	0.0001	
Total water reserves	510 000 000	1 385 984 610	2 718	100.00	

[a] excluding Antarctic groundwater (approximately 2 000 000 km^3).

Mean Residence of the Water

(not estimated by tracers!)

- Mean residence time :=
  Volume of water [m^3] in a sub-system divided by flux [$m^3\ s^{-1}$]

  For example, atmosphere (values from Dyck & Peschke 1995):
  13000 km^3 / 577000 km^3/a = 8.2 days

- renewal coefficient :=
  reciprocal of mean residence time

  For example, atmosphere (values from Dyck & Peschke 1995): 44.4 a^{-1}

Interpretation of Mean Residence Time (MRT):

- Short MRT = small system or high fluxes
  (e.g. atmosphere or small lakes etc.)

- Long MRT = large system or low fluxes
  (e.g. oceans, deep groundwater, some glaciers, some lakes etc.)

- Impact for contamination („memory effect“)

Water Balance Equation

Water Budget

Balance Equation

Storage Equation

Continuity Equation

Law of Conservation of Mass

$$I(t) - O(t) = \frac{\Delta S}{\Delta t}$$

I(t) = inflow

O(t) = outflow

$\Delta S / \Delta t$ = change in storage

Application requires that the control volume and the account period (Δt) are well defined

Units:

Volume/Time (L^3/T)

Mass/Time (M/T)

Depth over fixed area per time (L/T)

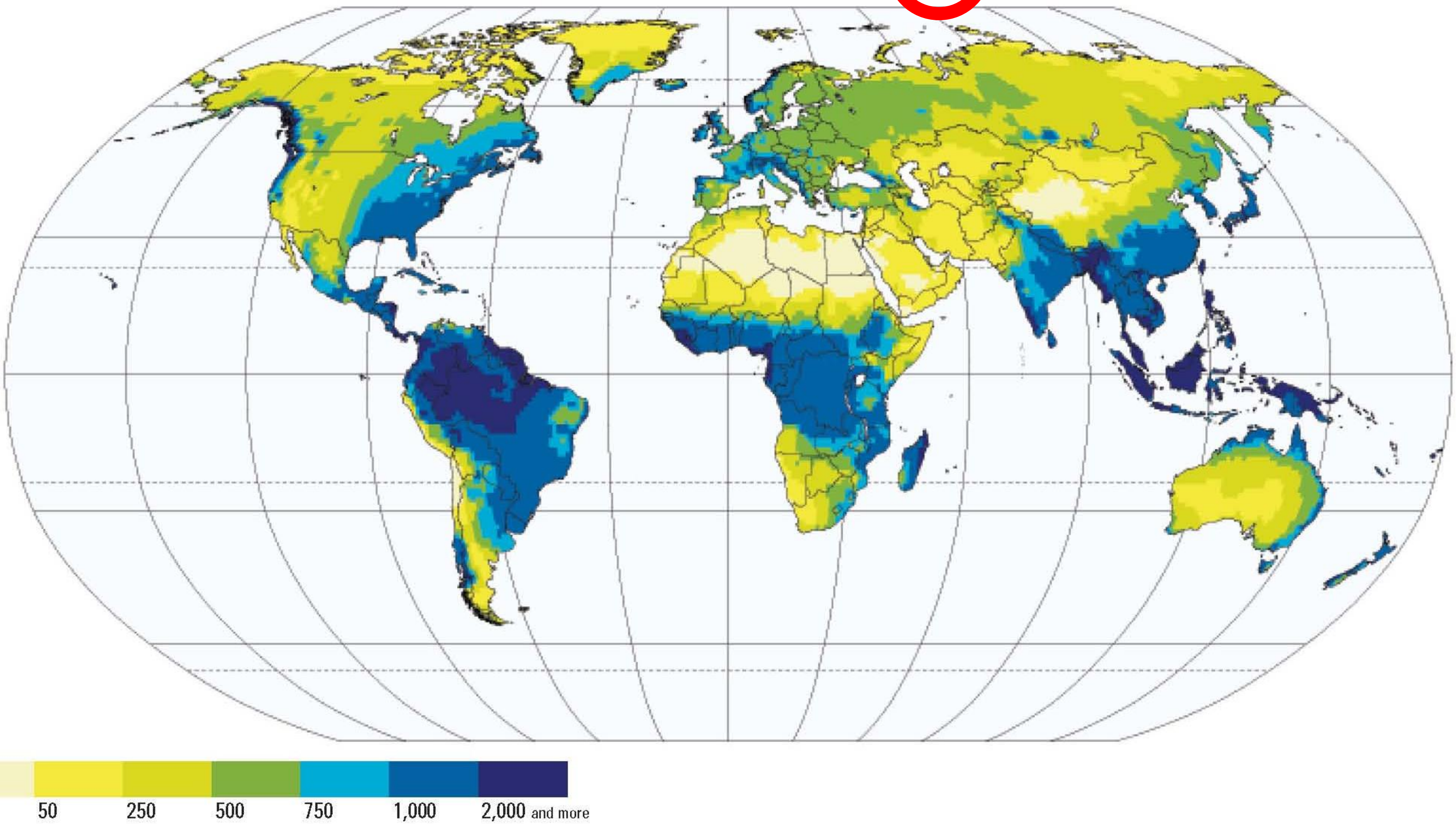
Water balance of the earth surface

Region	Area	Precipitation		Evaporation		Runoff	
	10^{12} m²	m/a	10^{12} m³/a	m/a	10^{12} m³/a	m/a	10^{12} m³/a
Oceans	361	1.12	403	1.25	449	-0.13	-46
Continents	149	0.72	107	0.41	61	0.31	46

Ocean	Surface area	P-E	Land run-off	Ocean exchange	P-E	Land run-off	Ocean exchange	
	10^{12} m²	mm/a	mm/a	mm/a	10^{12} m³/a	10^{12} m³/a	10^{12} m³/a	m³/s
Arctic	8.5	44	307	351	0.4	2.6	3	94,544
Atlantic	98	-372	197	-175	-36.5	19.3	-17	-543,466
Indian	77.7	-251	72	-179	-19.5	5.6	-14	-440,739
Pacific	176.9	90	69	159	15.9	12.2	28	891,318

Global Mean AnnualPrecipitation
(WWAP 2003)

$P = R + E + dS/dt$



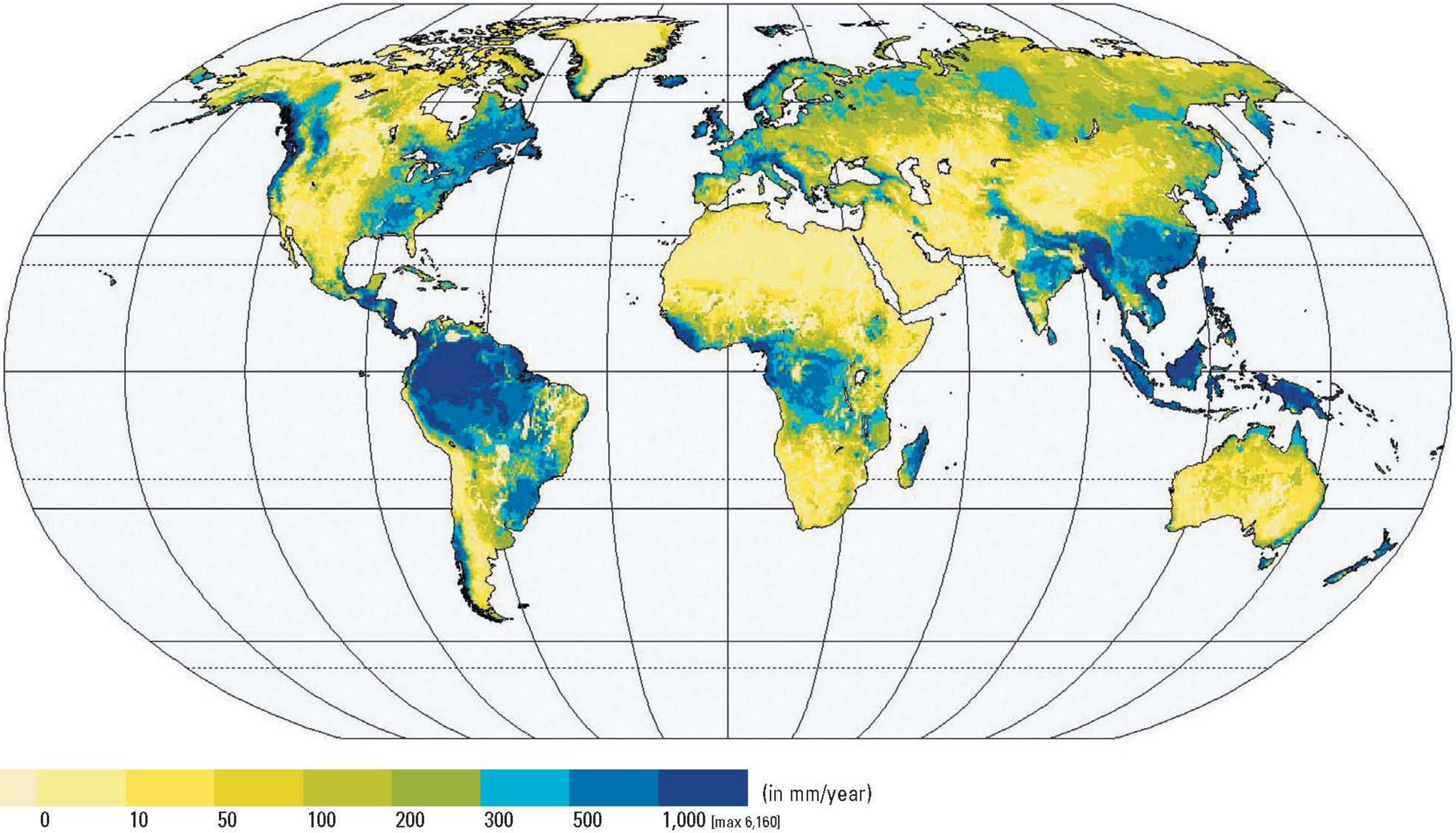
The world pattern of precipitation shows strong disparities between large annual rainfall in the tropics (some areas get in excess of 10,000 mm), and semi-arid and arid regions (such as the Sahara Desert). Differences within the African continent are particularly significant.

Source: Map prepared for the World Water Assessment Programme (WWAP) by the Centre for Environmental Research, University of Kassel, based on an Analysis by the Global Precipitation Climatology Centre (GPCC) (data extracted from the GPCC website in 2002 and Rudolf et al., 1994).

Long-term Mean Annual Runoff per Grid

(WWAP 2003)

$$P = R + E + dS/dt$$



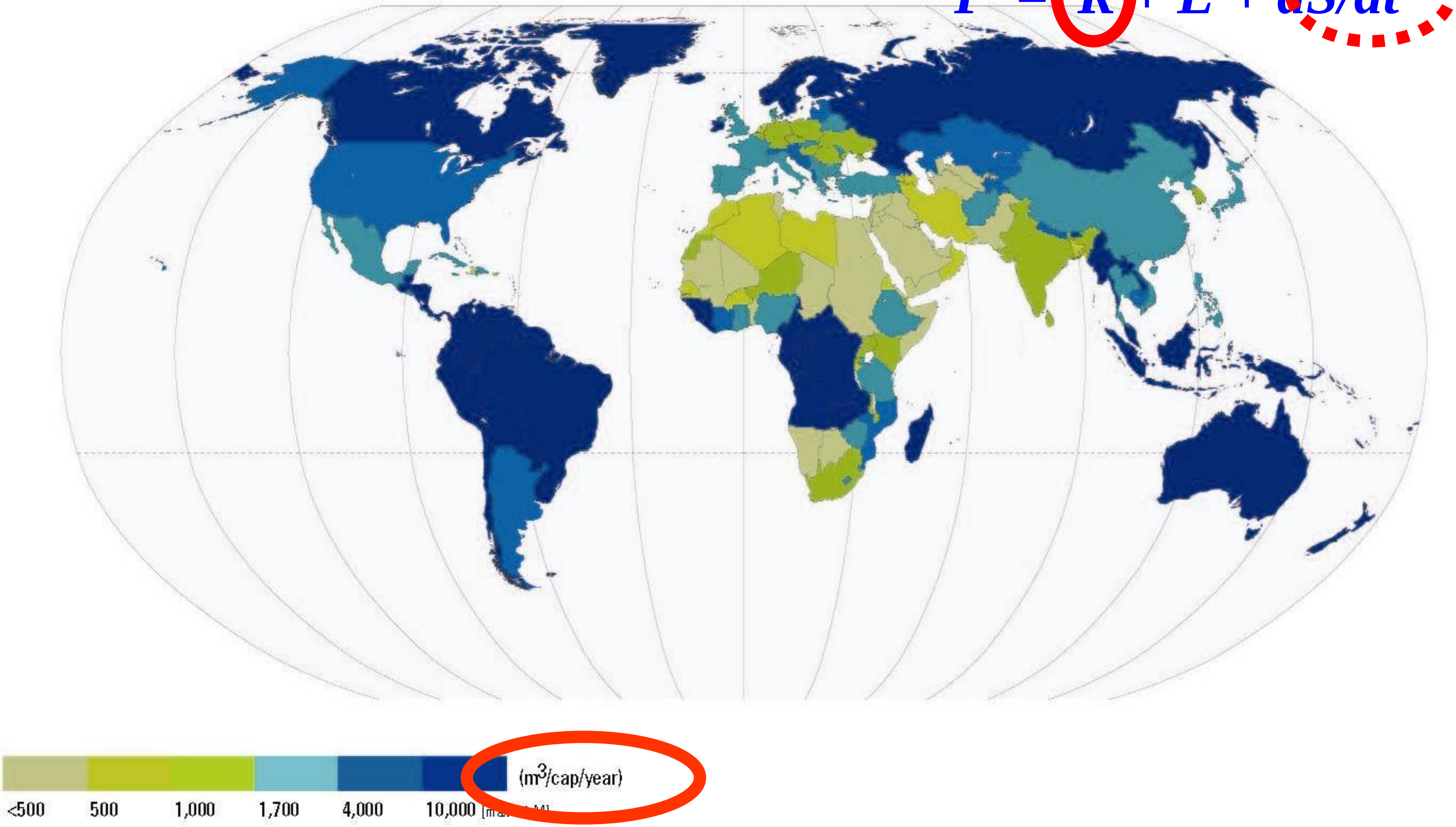
The enormous variation in climate around the Earth leads to great variability in the streamflow, which is in line with the rainfall. This map shows similar patterns to map 4.1.

Source: Map prepared for the World Water Assessment Programme (WWAP) by the Centre for Environmental Research, University of Kassel, based on Water Gap Version 2.1.D, 2002.

Renewable Water Resources per Country

(WWAP 2003)

$P = R + E + dS/dt$



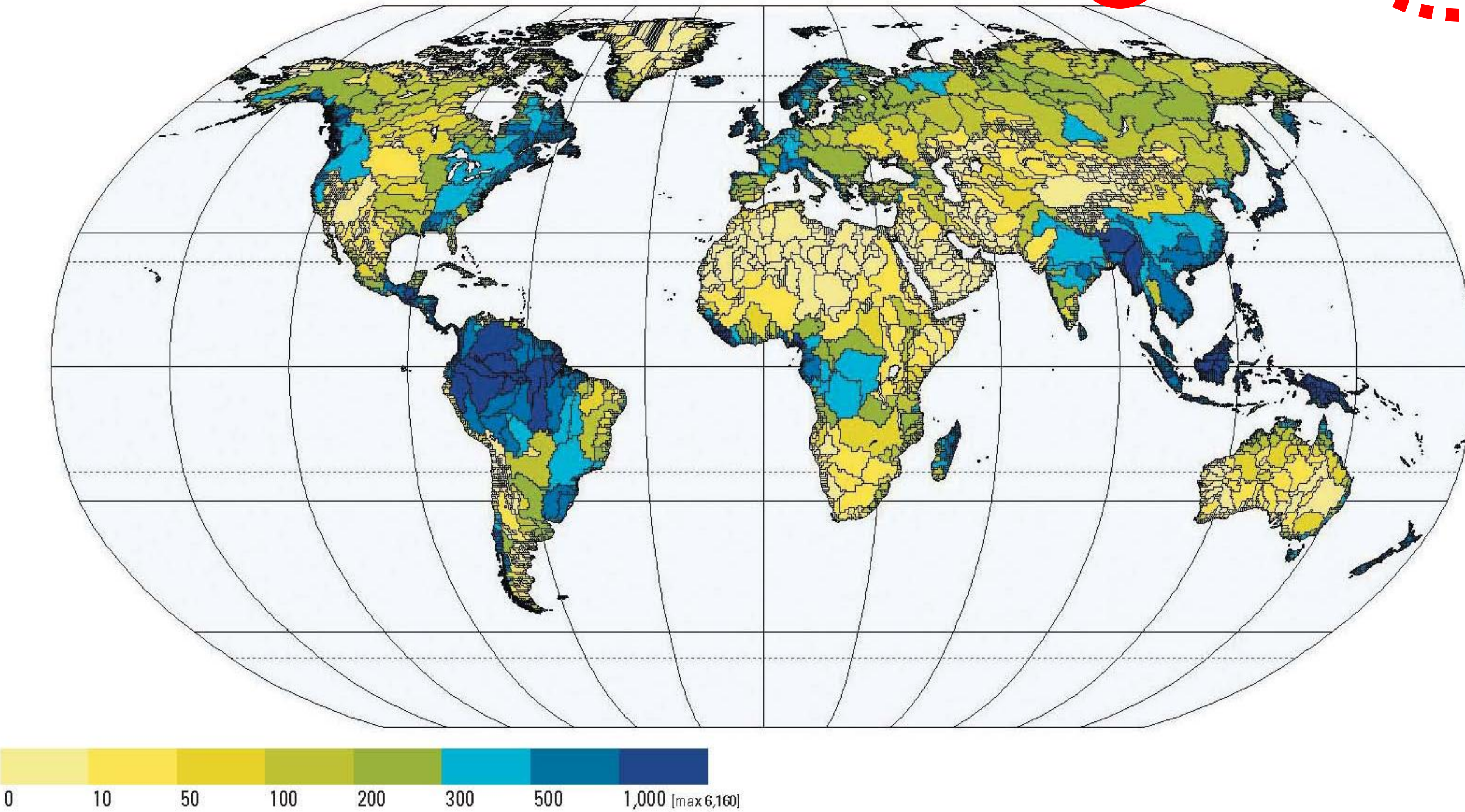
This map shows the per capita total internal renewable water availability by country, i.e. the fraction of the country's water resources generated within the country.

Source: Map prepared for the World Water Assessment Programme (WWAP), by the Centre for Environmental Research, University of Kassel, based on Water Gap Version 2.1 D, 2002.

Water Resources per Drainage Basin

(WWAP 2003)

$$P = R + E + dS/dt$$



The long-term average of water resources by drainage basin is used as an indicator of water available to the populations in the basin. The use of the drainage basin as the basic unit sharpens the contrast between adjacent water-rich and water-poor countries, compared to map 4.4, based on a grid scale.

Source: Map prepared for the World Water Assessment Programme (WWAP) by the Centre for Environmental Research, University of Kassel, based on Water Gap Version 2.1.D, 2002.

Renewable Water Resources

Table 1.2 Annual renewable water resources per capita (1990 figures) of the seven resource-richest and poorest countries (and other selected countries). Annual renewable water resource is based upon the rainfall within each country; in many cases this is based on estimated figures

Water resource richest countries	*Annual internal renewable water resources per capita (thousand m^3/yr)*	*Water resource poorest countries*	*Annual internal renewable water resources per capita (thousand m^3/yr)*
Iceland	671.9	Bahrain	0.00
Suriname	496.3	Kuwait	0.00
Guyana	231.7	Qatar	0.06
Papua New Guinea	199.7	Malta	0.07
Solomon Islands	149.0	Yemen Arab Republic	0.12
Gabon	140.1	Saudi Arabia	0.16
New Zealand	117.5	United Arab Emirates	0.19
Canada	109.4	Israel	0.37
Australia	20.5	Kenya	0.59
USA	9.9	United Kingdom	2.11

Source: Data from Gleick (1993)

Water Scarcity Indicators

EU	1995	2025
Austria	11,224	10,873
Belgium	*1,234*	*1,217*
Denmark	2,489	2,442
Finland	22,126	21,345
France	3,408	3,279
Germany	2,096	2,114
Greece	5,610	5,822
Ireland	14,100	13,430
Italy	2,919	3,227
Luxembourg	12,285	10,730
Netherlands	5,813	5,576
Portugal	7,091	7,374
Spain	2,809	2,968
Sweden	20,482	18,925
United Kingdom	*1,222*	*1,193*

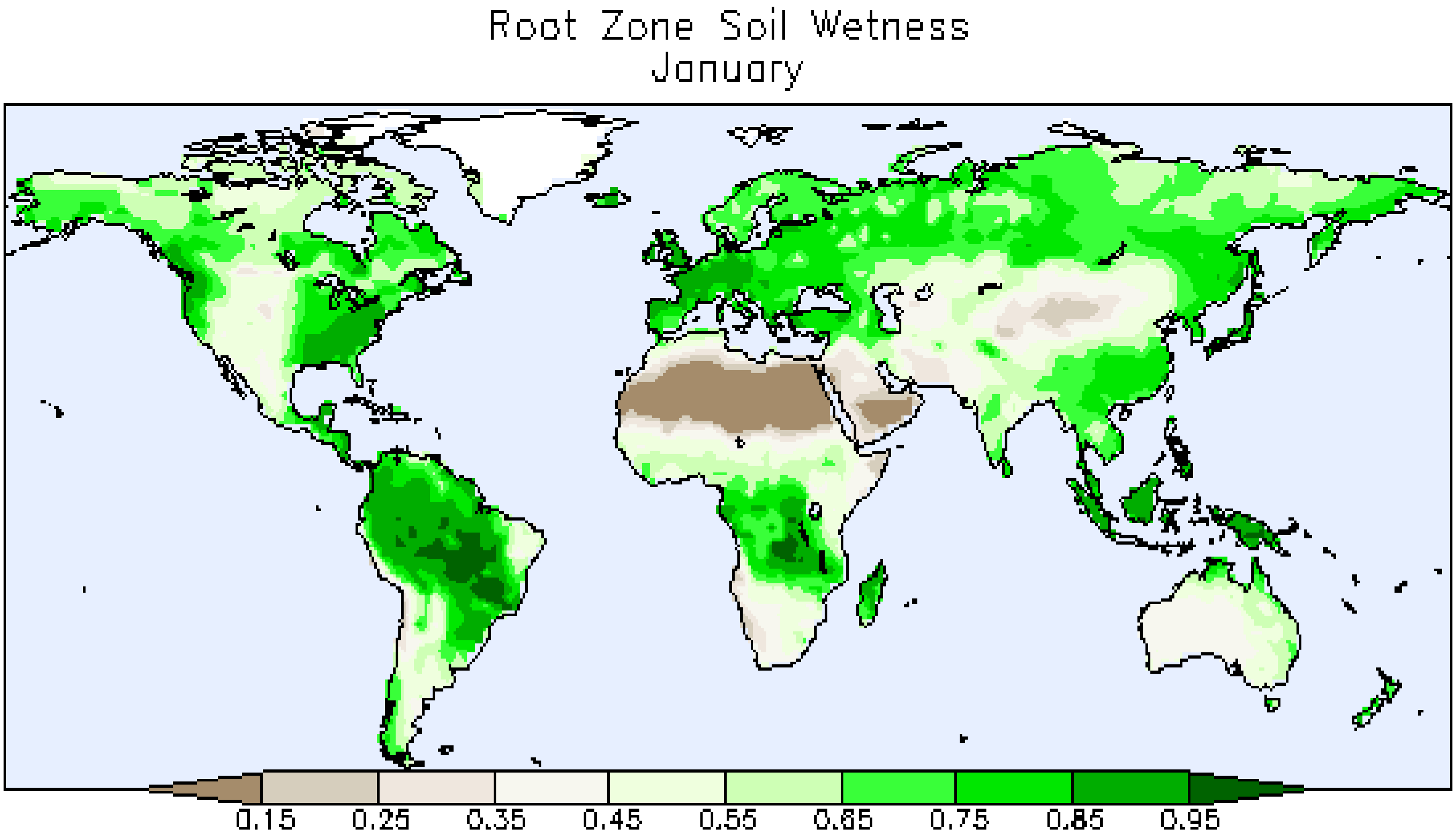
figures in *italics*: water stress (<1,700 m^3/cap/yr)
figures in **bold**: water scarcity (<1,000 m^3/cap/yr)

SADC	1995	2025
Angola	17,012	7,202
Botswana	10,138	5,707
Lesotho	2,565	*1,290*
Malawi	1,933	**917**
Mauritius	1,970	*1,485*
Mozambique	12,051	5,868
Namibia	29,622	15,172
South Africa	*1,206*	**698**
Swaziland	5,251	2,687
Tanzania	2,964	*1,425*
Zambia	14,355	7,177
Zimbabwe	1,787	*1,034*

Mekong	1995	2025
Cambodia	102,900	25,300
China	4,600	1,800
Laos	138,800	27,900
Thailand	7,900	2,400
Vietnam	11,700	3,200

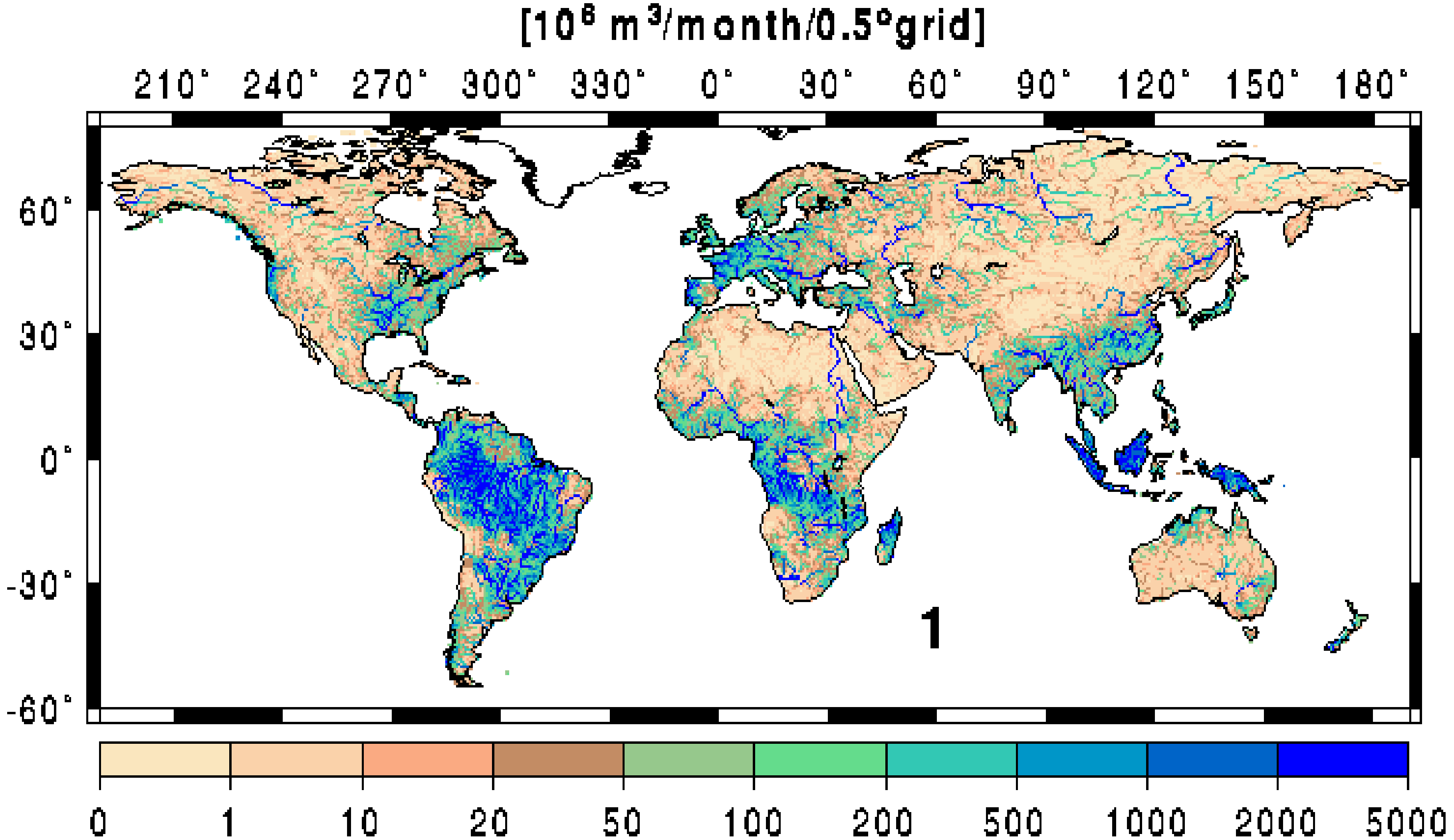
Simulation of Global Soil Water Distribution

(from Taikan Oki, Univ. Tokyo, Japan; 2002)



Simulation of Monthly Runoff on the Global Scale

(from Taikan Oki, Univ. Tokyo, Japan; 2002)



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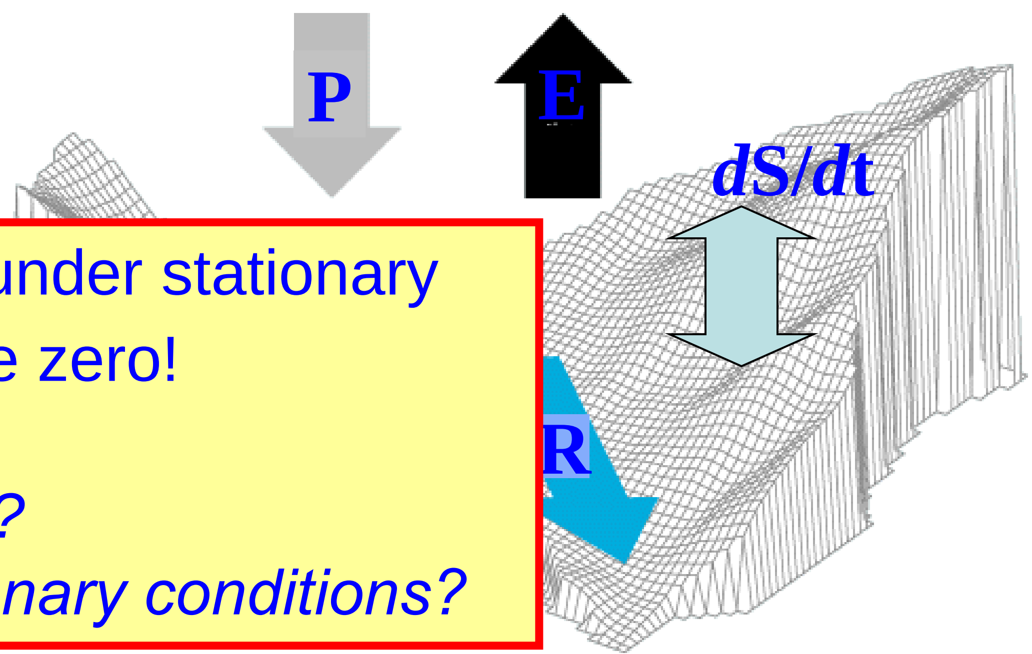
Water Balance

$$P = R + E + dS/dt$$

P	:	precipitation [mm a^{-1}]
R	:	runoff [mm a^{-1}]
E	:	evaporation [mm a^{-1}]
dS/dt	:	storage changes per time step [mm a^{-1}]



For long-term averages under stationary conditions dS/dt become zero!

… but, what is long-term?
… but, do we have stationary conditions?

Elements of the Hydrological Cycle

(from lecture notes, De Laat & Savenije, 2008)

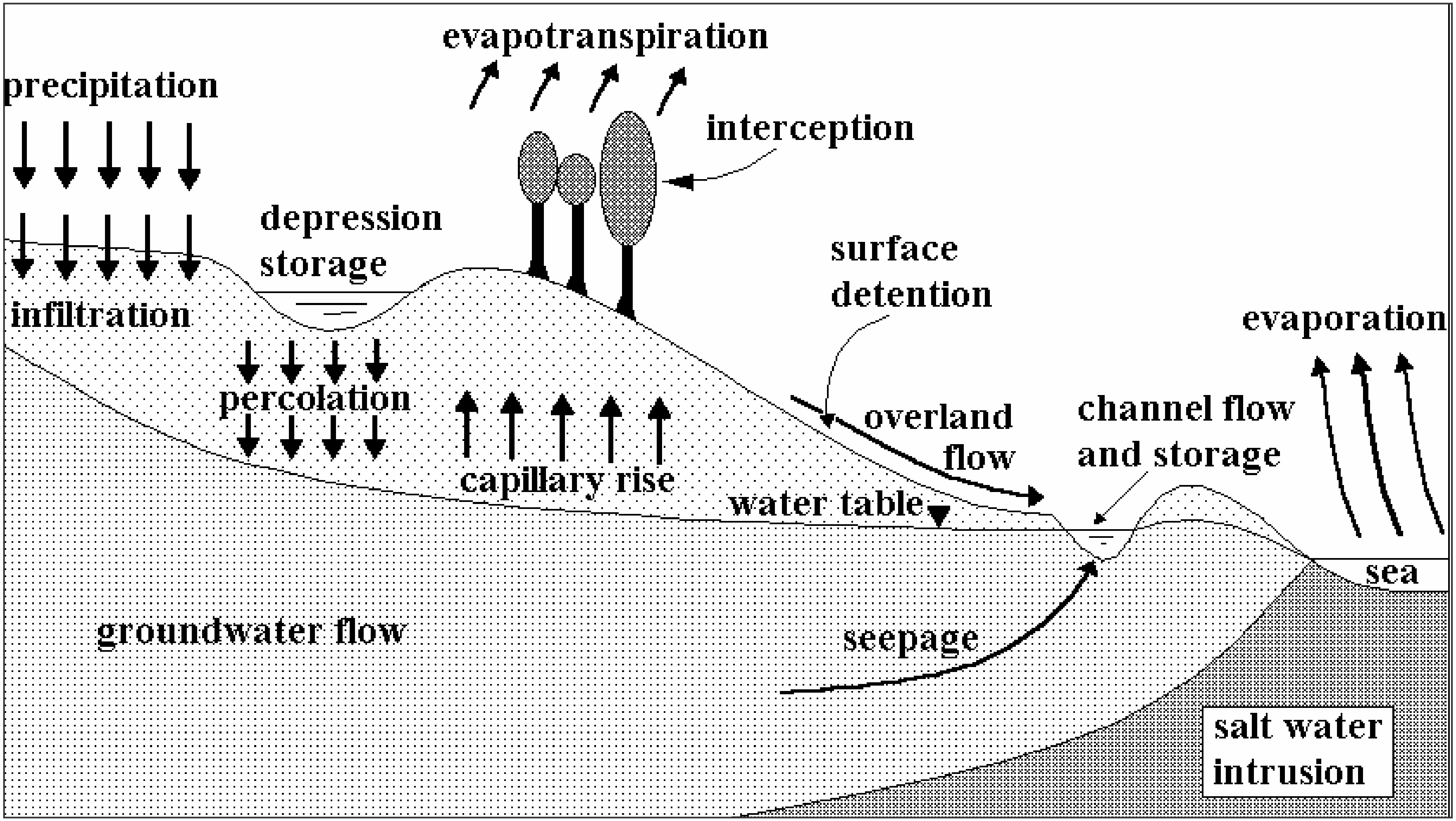
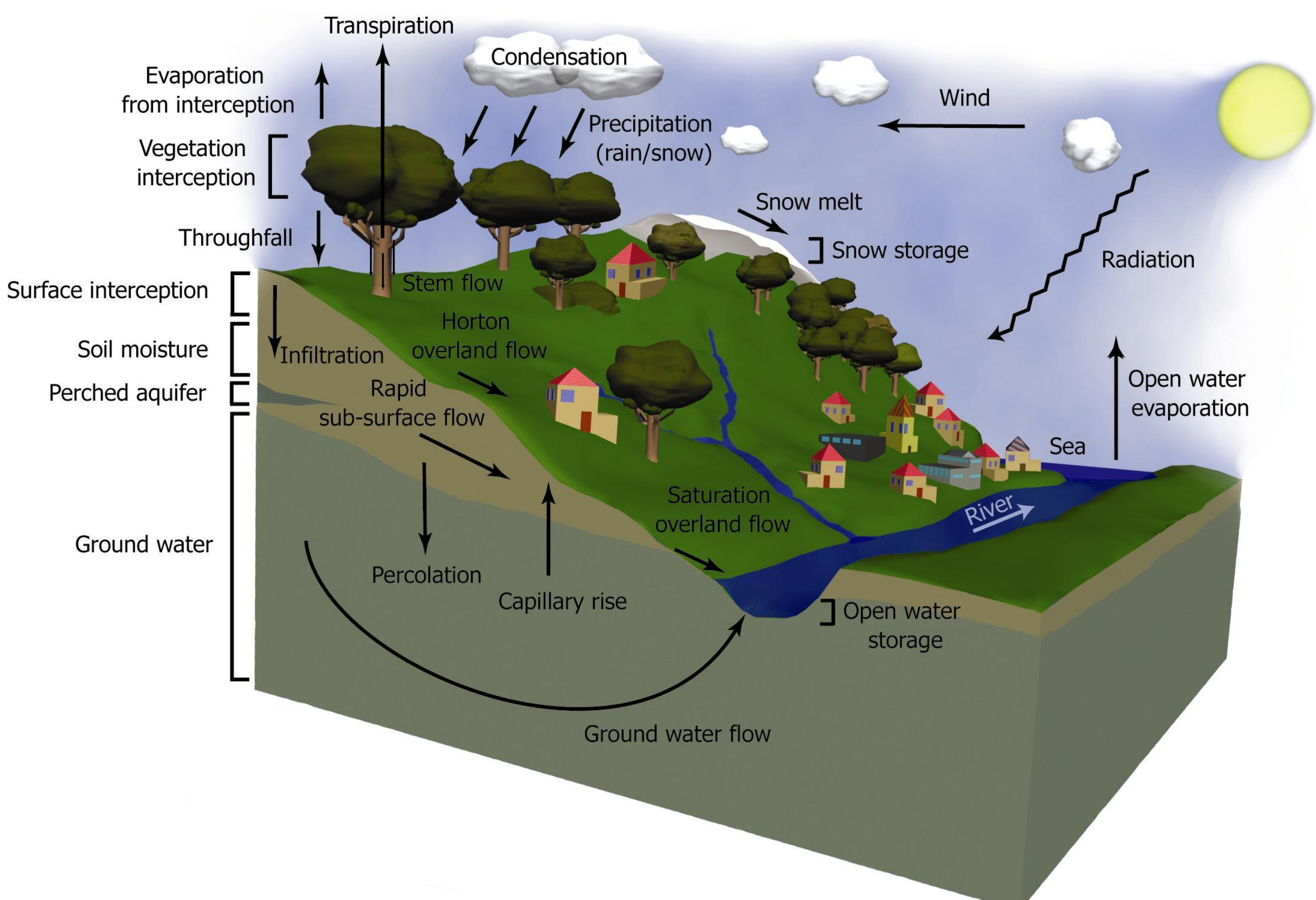


Fig. 1.1 Descriptive representation of the hydrological cycle

Let us develop the water balance equation at the blackboard!

Hydrological System



Water Balance Equation:

$$\left(\frac{dS_I}{dt}+E_I\right)+\left(\frac{dS_s}{dt}+E_s+Q_s\right)+\left(\frac{dS_u}{dt}+E_T+E_u+Q_f\right)+\left(\frac{dS_g}{dt}+Q_g\right)=P$$

Where:

$$\left(\frac{dS_I}{dt}+E_I\right)$$

Interception processes

$$\left(\frac{dS_s}{dt}+E_s+Q_s\right)$$

Surface water processes

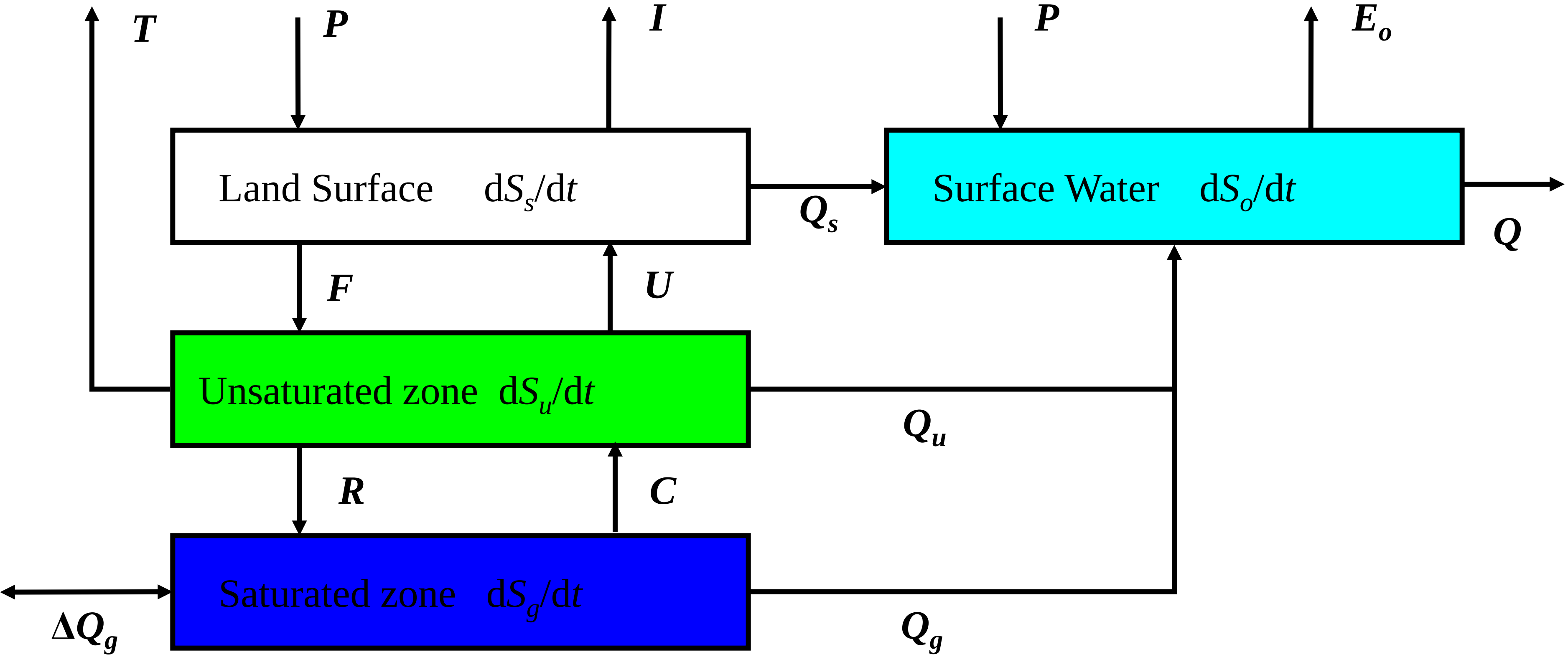
$$\left(\frac{dS_u}{dt}+E_T+E_u+Q_f\right)$$

Root zone moisture processes

$$\left(\frac{dS_g}{dt}+Q_g\right)$$

Groundwater processes

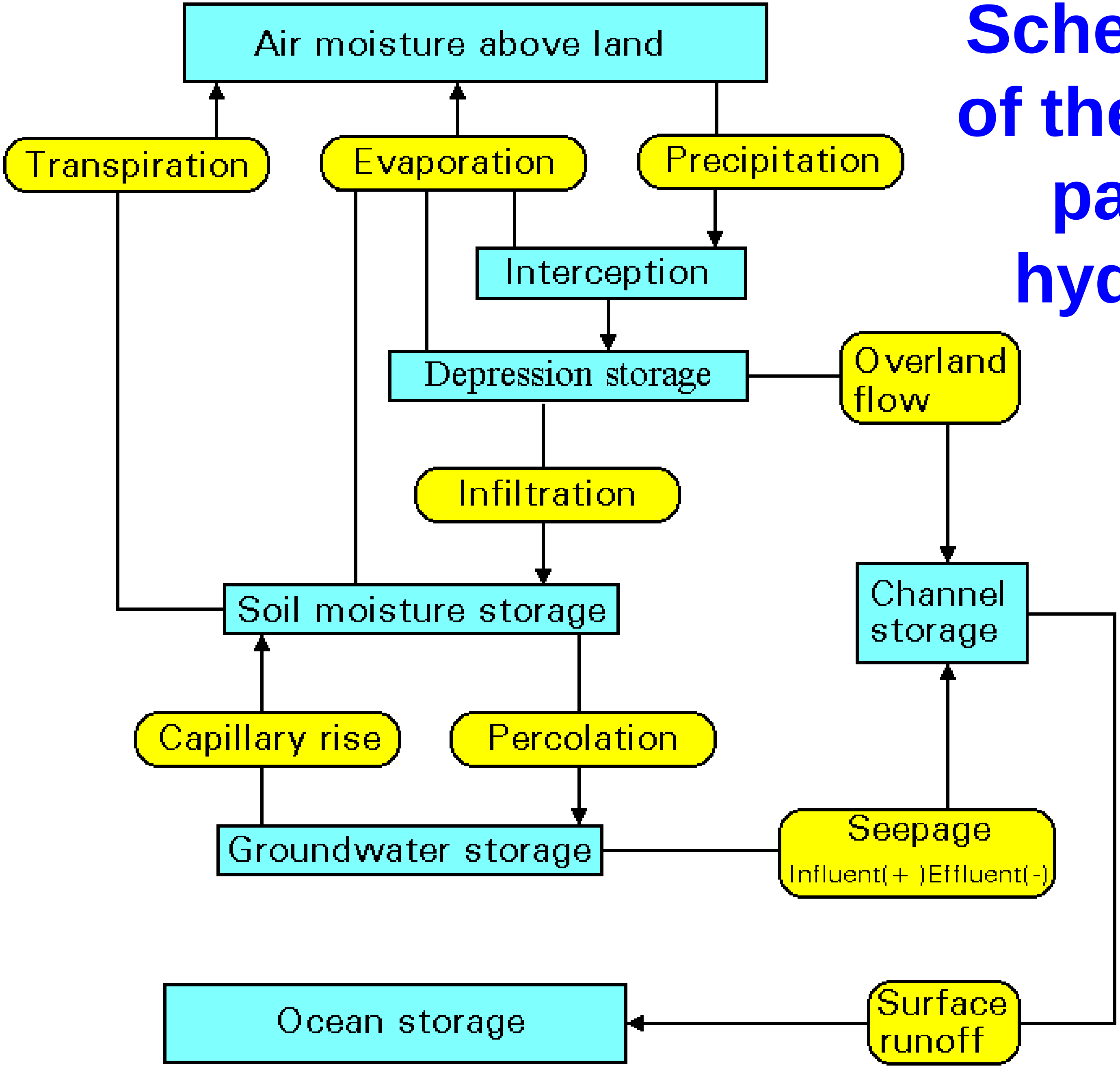
System Scheme



Processes

- distinguish between:
  - runoff production (the component of the rainfall that generates runoff = P_e)
  - runoff routing (the temporal distribution of the effective rainfall)

Schematization of the terrestrial part of the hydrological cycle

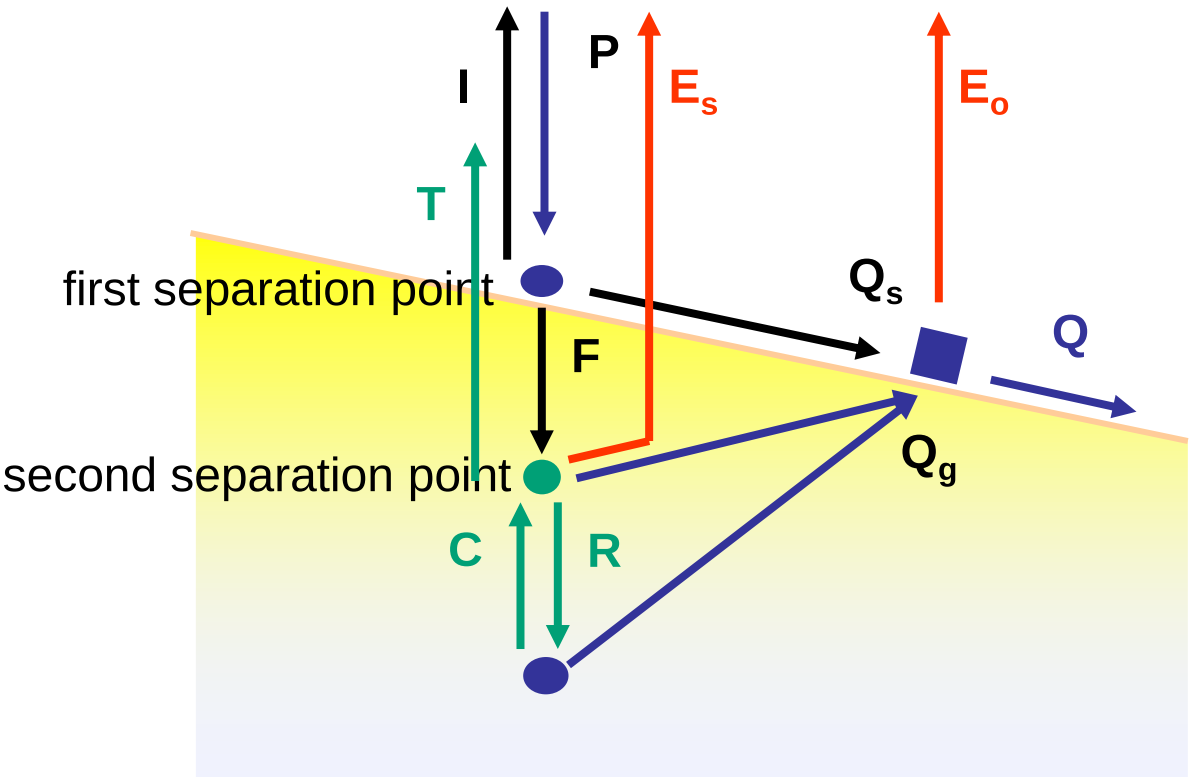


Storage

Flux

(De Laat & Savenije, 2006)

Again, the water balance in a different way …



$E = I+T+E_o+E_s$

P = rainfall

I = interception

Q_s = overland flow

F = infiltration

T = transpiration

R = percolation

C = capillary rise

E_s = soil evaporation

Q_g = seepage

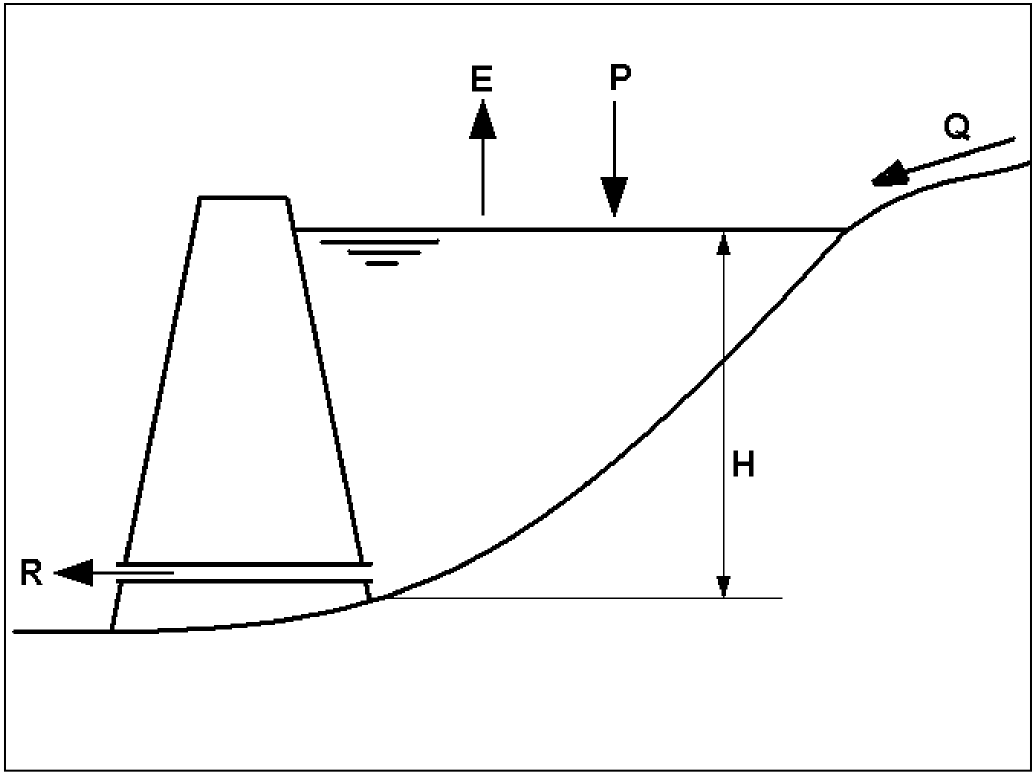
E_o = open water evaporation

Example ONE: Water balance of a reservoir

$$P + Q - E - R = \Delta S/\Delta t$$

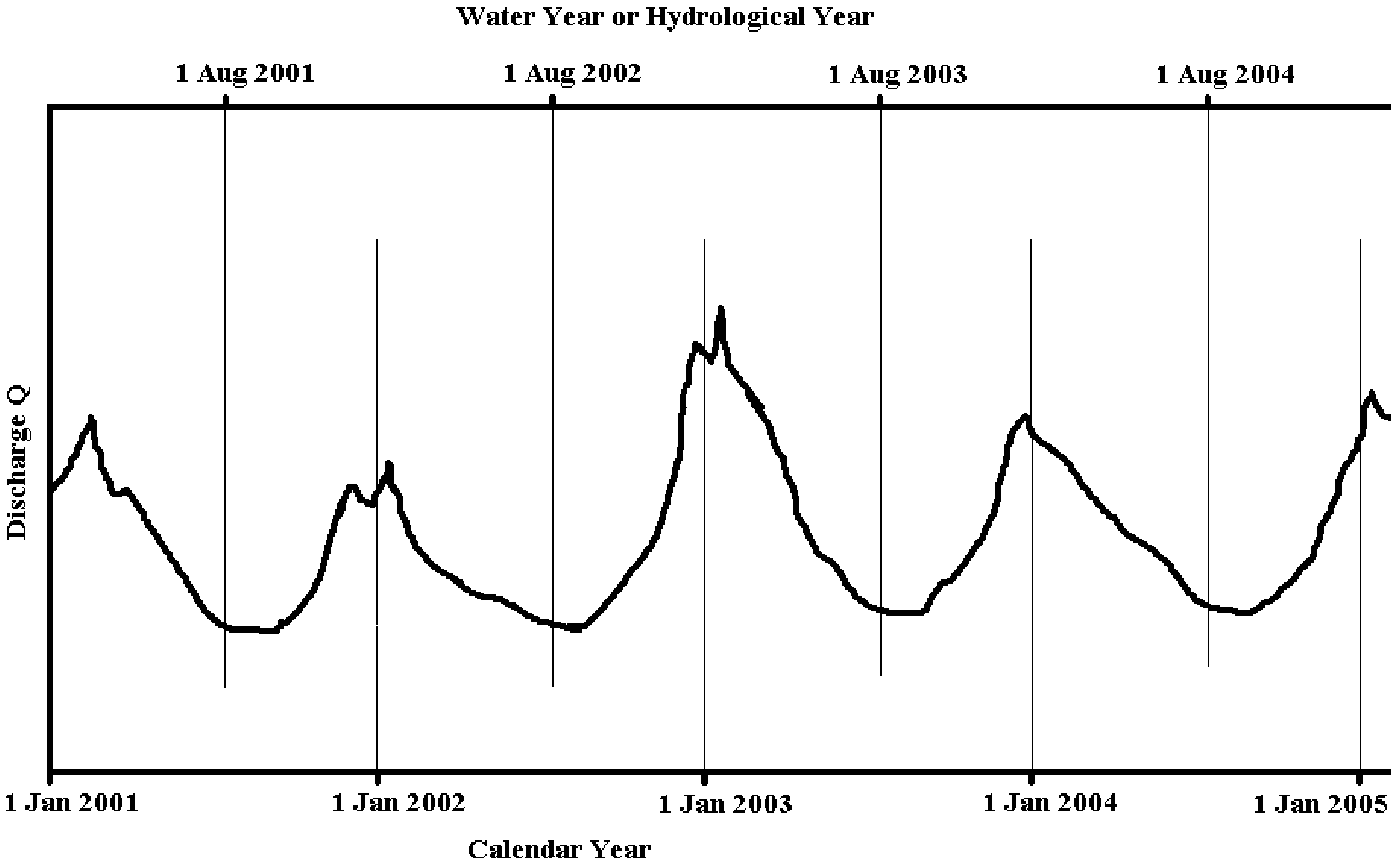
Questions:

1. **Indicate the control volume.**
2. **Could you think of more inflow and outflow components?**
3. **What is most appropriate unit?**
4. **How to compute ΔS?**
5. **What would be a typical Δt?**



Hydrological Year or Water Year

Is this really a useful break of the year??



Example TWO

Average annual water balance for a housing area in the new town Lelystad, The Netherlands

	Rainfall	*Sewer discharge*	*Subsurface drain discharge*	*Total Eva-poration*
In mm	*687*	*159*	*212*	*316*
In %	*100*	*23*	*31*	*46*

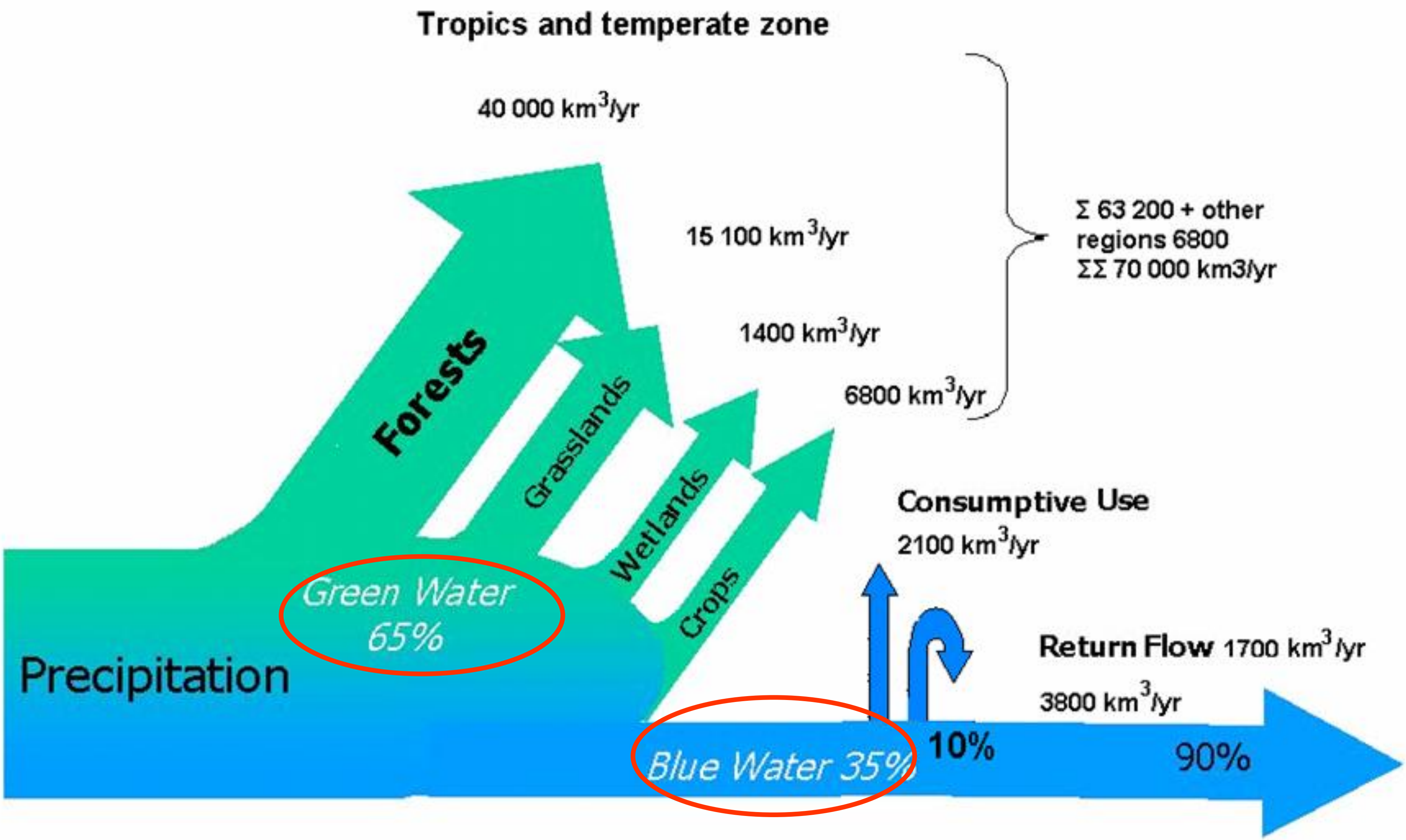
Definition of Runoff Coefficient, RC:
Percentage of rainfall coming to runoff

RC = (R / P) x 100 [%]

For the above example: RC = (371 / 687) x 100 = 54 %

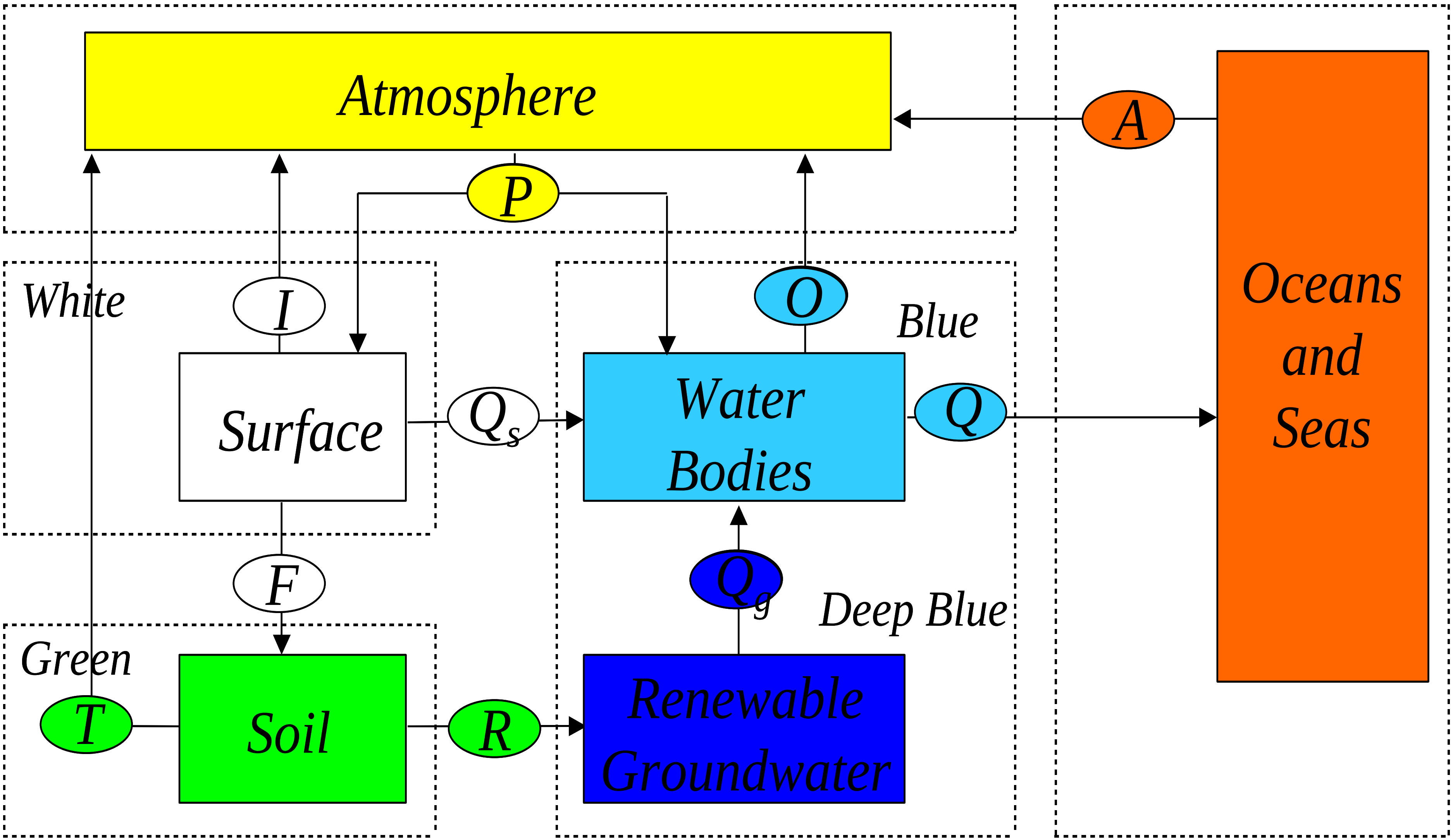
Consumptive use by terrestrial ecosystems (global perspective)

(from Falkenmark, 2001)



Consumptive water use by terrestrial ecosystems as seen in a global perspective. (Falkenmark in SIWI Seminar 2001).

The Rainbow of Water at the Global Scale



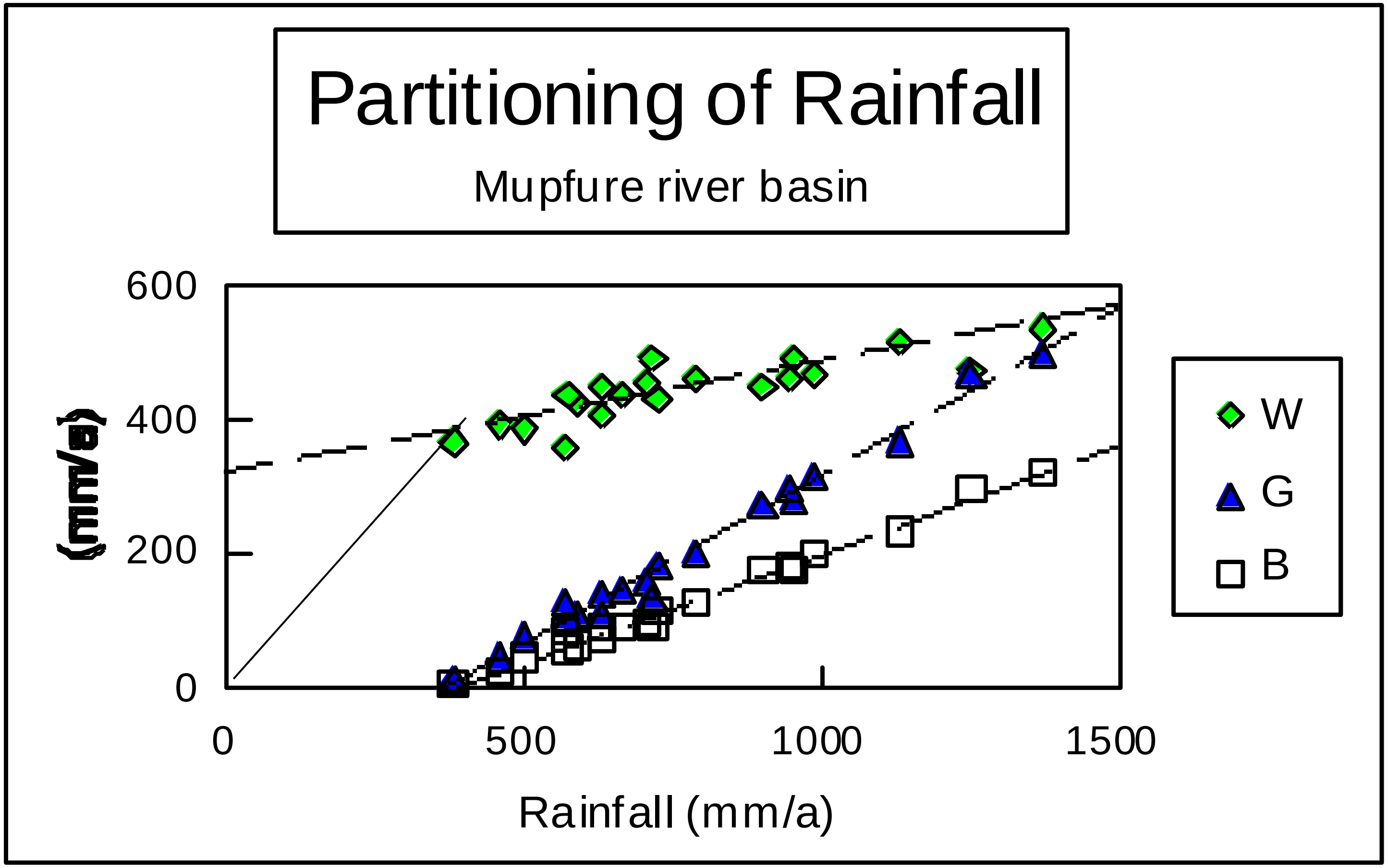
Global Water Resources

Re-source	Flux	[L/T] or [L3/T]	Stor-age	[L] or [L3]	Resi-dence time	[T]
Green	T	100 mm/month	S_u	440 mm	S_u/T	4 months
White	I	4 mm/d	S_s	3-5 mm	S_s/I	1 day
Blue	Q	46×10^{12} m^3/a	S_w	124×10^{12} m^3	S_w/Q	2.7 years
Deep blue	Q_g	5×10^{12} m^3/a	S_g	750×10^{12} m^3	S_g/Q_g	150 years
Atmos-phere	P	510×10^{12} m^3/a	S_a	12×10^{12} m^3	S_a/P	0.3 month
Oceans	A	46×10^{12} m^3/a	S_o	1.3×10^{18} m^3	S_o/A	28.000 years

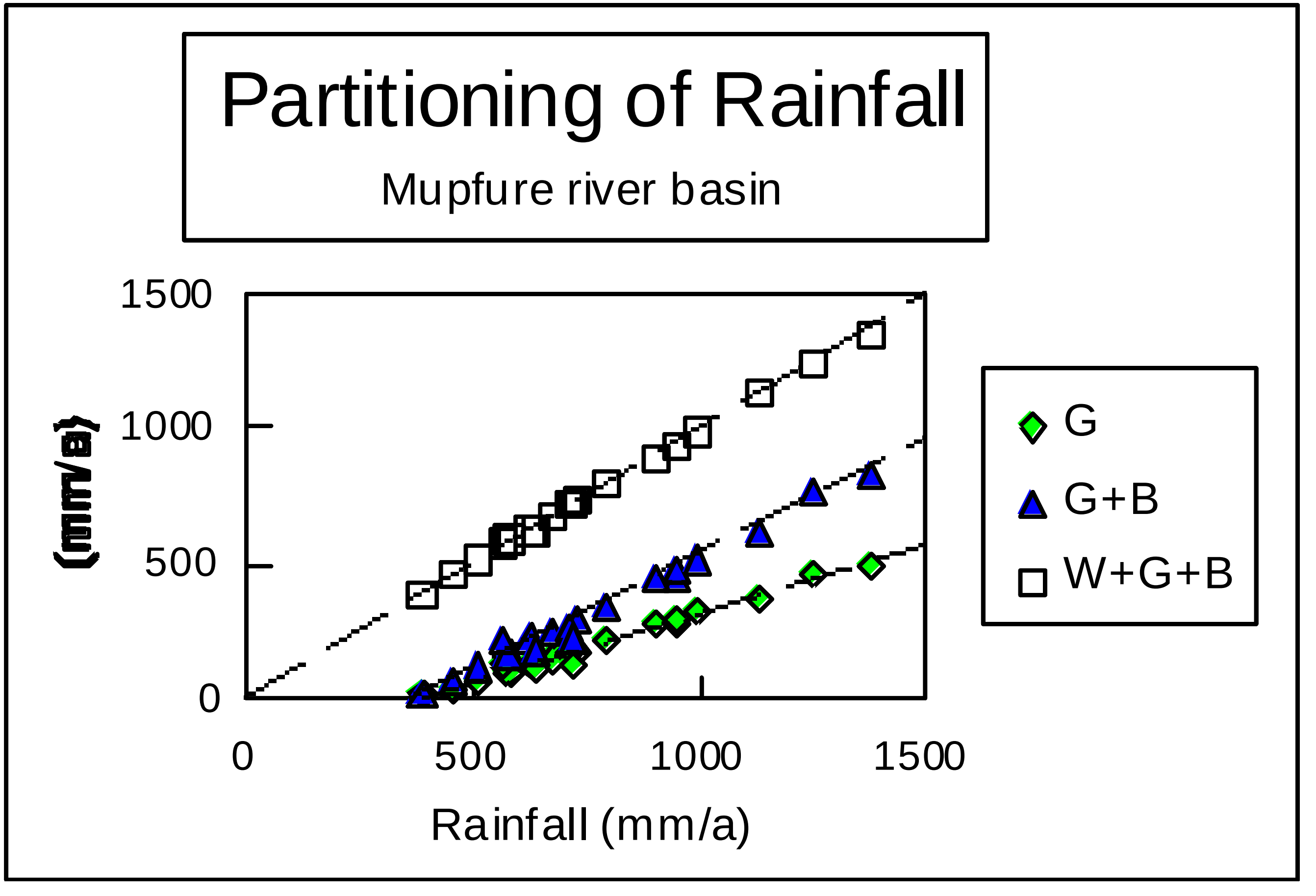
Global Water Resources

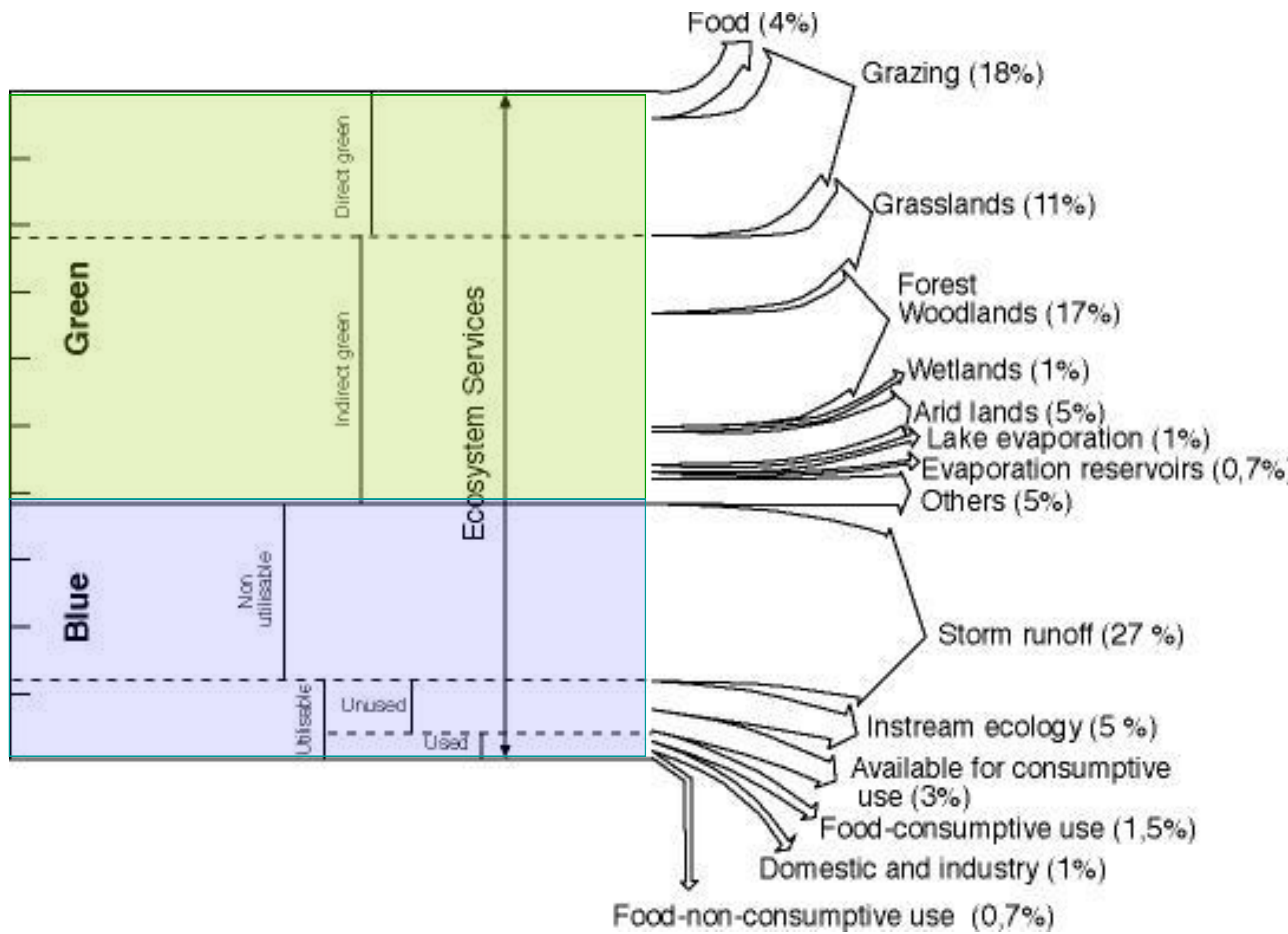
Mupfure river **Station: C70** **Catchment area: 1.2 Gm²** **Record length: 1969-1989**	**Source**	**Vertical component**		**Horizontal component**
Resource type	Rainfall (P)	“White” (W)	“Green” (G)	“Blue” (B)
Mean annual flux (μ)	775 mm/a	446 mm/a	202 mm/a	126 mm/a
Partitioning	100%	62%	23%	15%
Standard deviation (σ)	265 mm/a	48 mm/a	135 mm/a	87 mm/a
Interannual variability (σ/ μ)	34%	11%	67%	69%

Global Water Resources



Global Water Resources





Food (4%)
Grazing (18%)
Grasslands (11%)
Forest
Woodlands (17%)
Wetlands (1%)
Arid lands (5%)
Lake evaporation (1%)
Evaporation reservoirs (0,7%)
Others (5%)
Storm runoff (27 %)
Instream ecology (5 %)
Available for consumptive
use (3%)
Food-consumptive use (1,5%)
Domestic and industry (1%)
Food-non-consumptive use (0,7%)
Green
Blue
Direct green
Indirect green
Ecosystem Services
Non
utilisable
Utilisable
Unused
Used

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- Introduction
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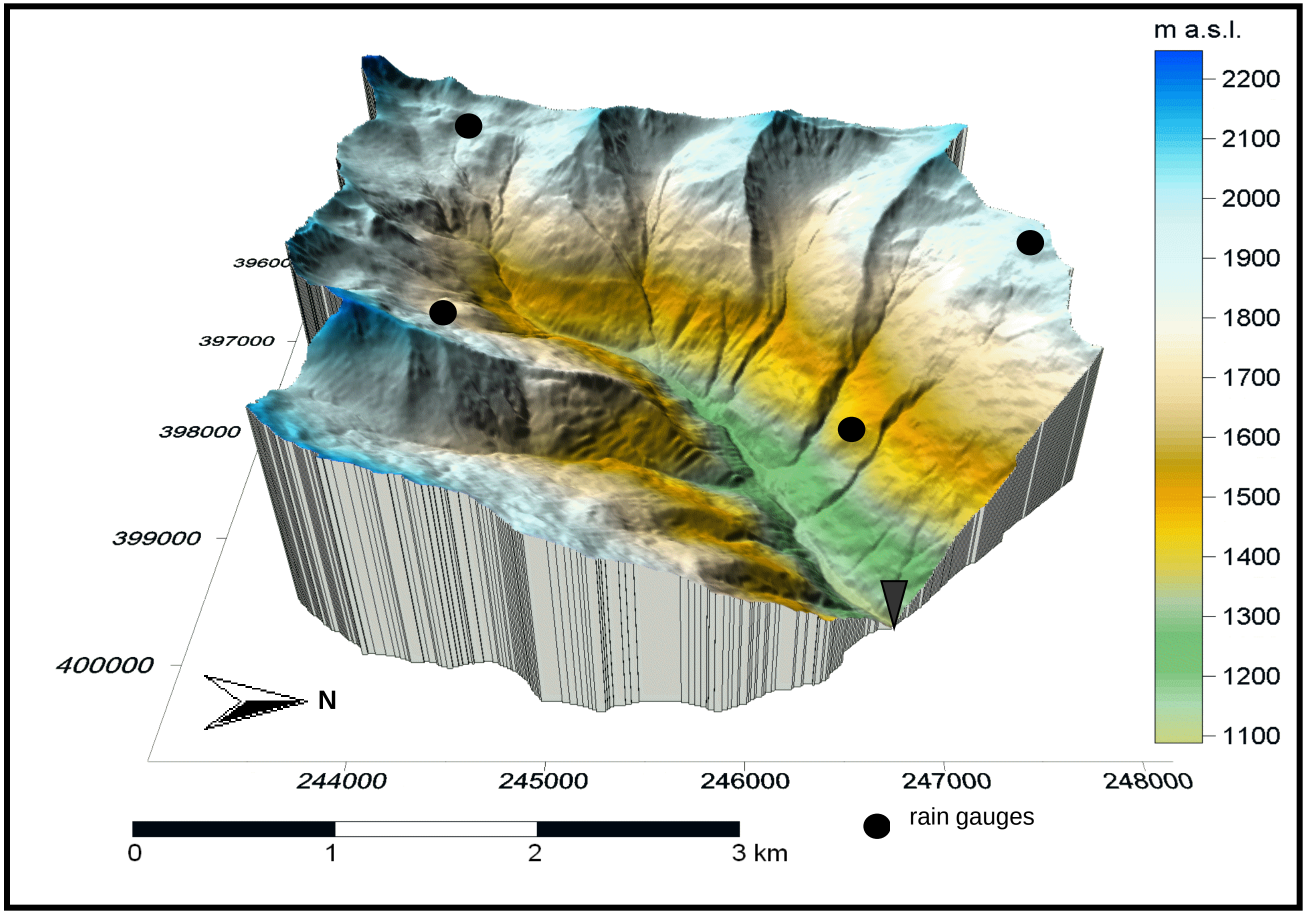
What is the role of the catchment in catchment hydrology?



$$P = R + E + dS/dt$$

P	:	precipitation [mm a^{-1}]
R	:	runoff [mm a^{-1}]
E	:	evaporation [mm a^{-1}]
dS/dt	:	storage changes per time step [mm a^{-1}]

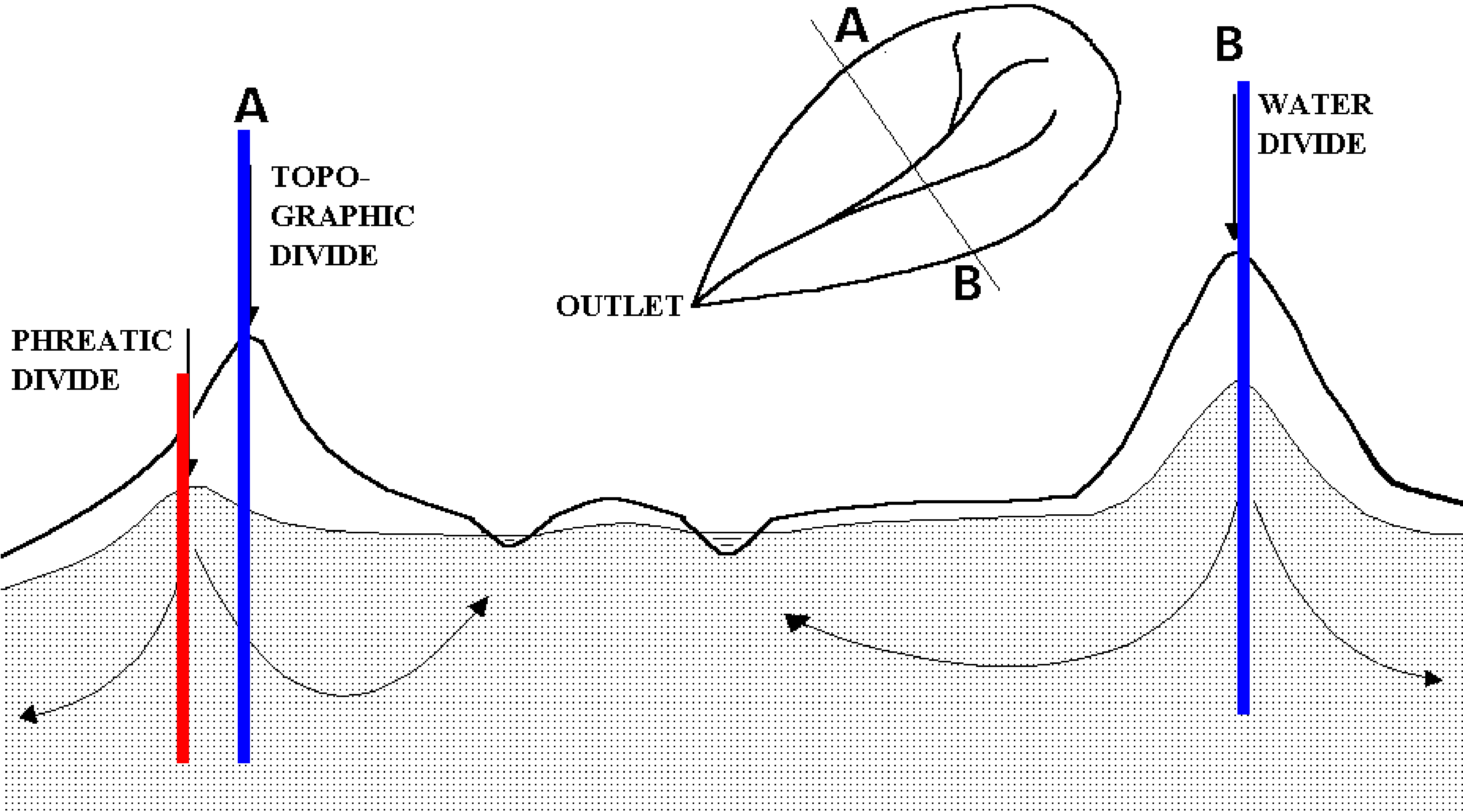
Topographic Control of the Watershed

(Maimai Catchment, New Zealand;
picture from prof. Jeff McDonnell, Corvallis, USA)

Example:

Upper Marxtengraben, Kitzbueheler Alpen, Austria

Topographic vs. Phreatic Divide



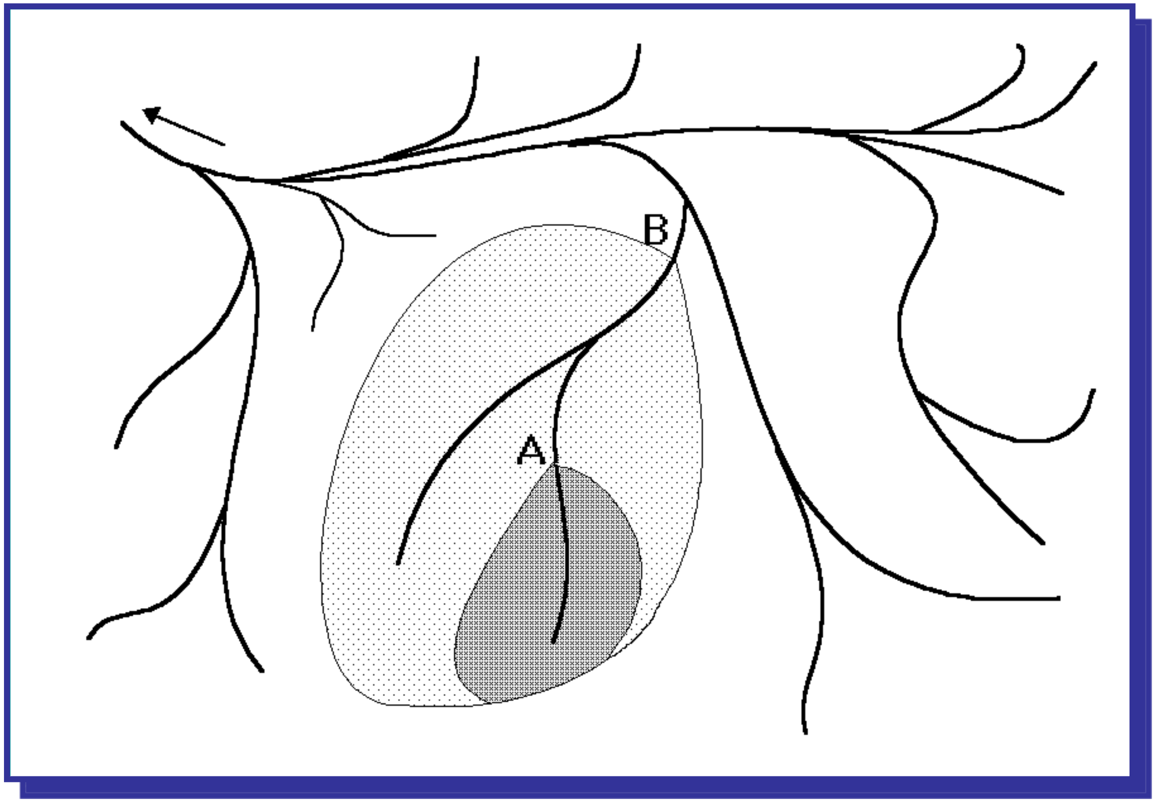
Delineating a devide

- Often difficult as no clear divide or temporal variable boundaries
- Also in the parts of the Netherlands (groundwater abstractions, im/export, channels etc.) or in wetlands/swamps etc.

Urwald um Manaus, Brasilien
Yann Arthus-Bertrand, 2002

Water balance of a drainage basin

$$(P - E) \cdot A - Q = \frac{\Delta S}{\Delta t}$$



Water balance of a drainage basin

River	Area	Rainfall size		Evaporation		Runoff		C_R
	Gm^2	mm/a	Gm^3/a	mm/a	Gm^3/a	mm/a	Gm^3/a	%
Nile	2803	220	620	190	534	30	86	14
Mississippi	3924	800	3100	654	2540	142	558	18
Parana	975	1000	980	625	610	382	372	38
Orinoco	850	1330	1150	420	355	935	795	70
Mekong	646	1500	970	1000	645	382	325	34
Amur	1730	450	780	265	455	188	325	42
Lena	2430	350	850	140	335	212	514	60
Yenisei	2440	450	1100	220	540	230	561	51
Ob	2950	450	1350	325	965	131	385	29
Rhine	200	850	170	500	100	350	70	41
Zambezi	1300	990	1287	903	1173	87	114	12

Remark:

Nowadays there are very few river basins in the world for which the rainfall – runoff relation is not affected by human activities.

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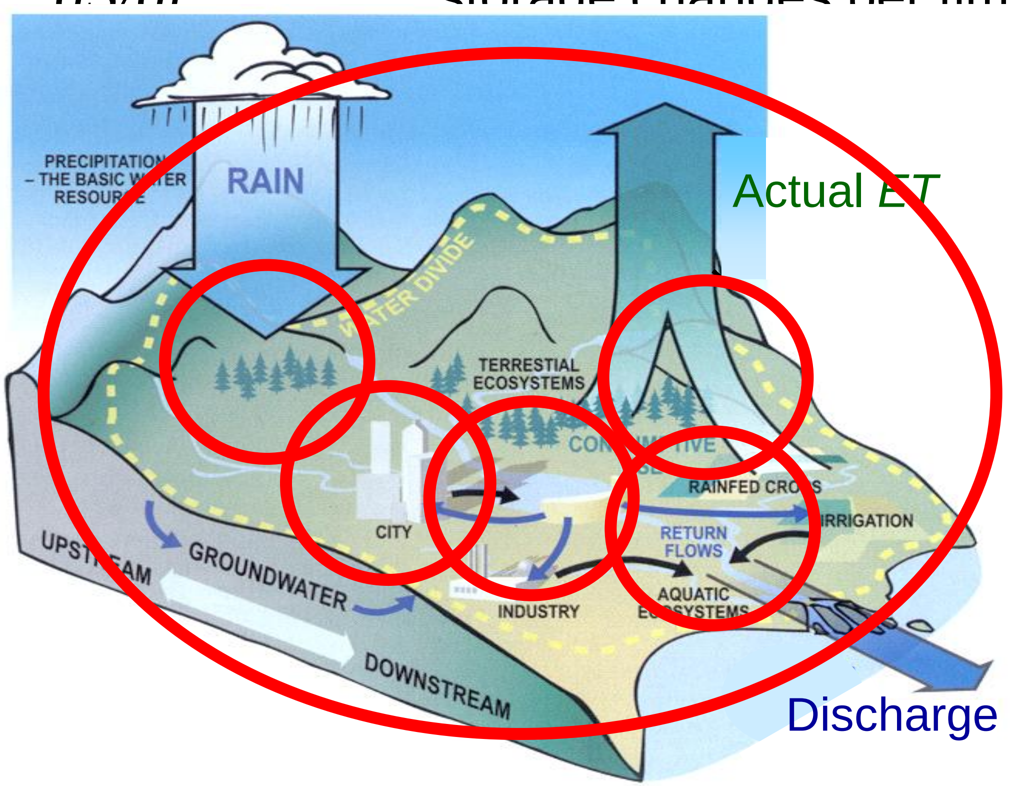
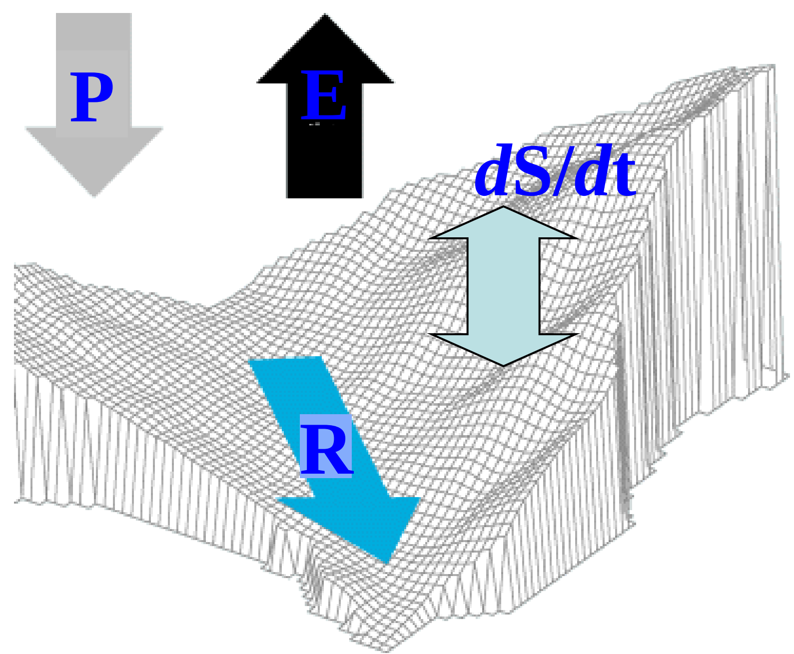
How do Hydrological Predictions Work?

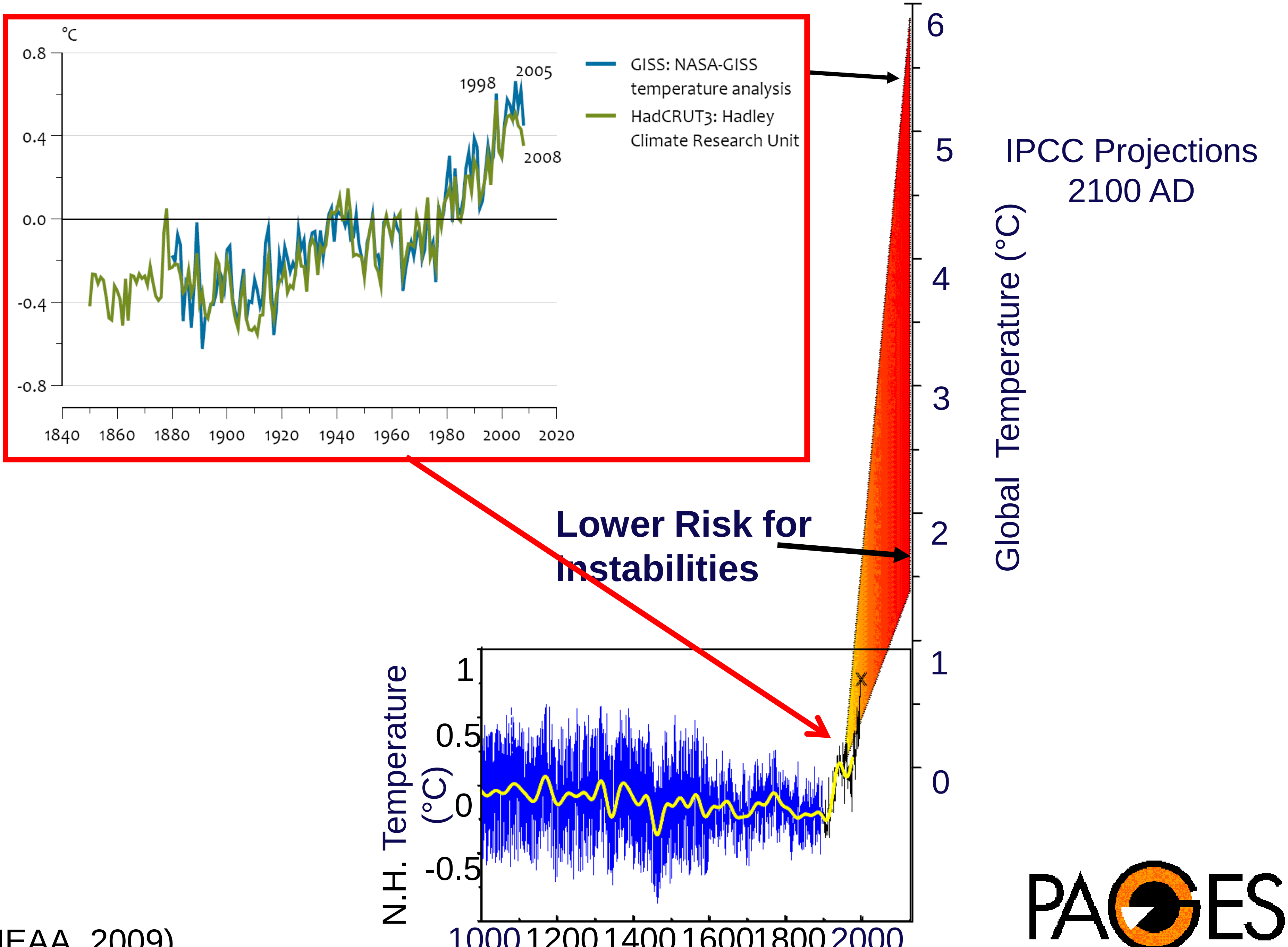
Water Balance:

$$P = R + E + dS/dt$$

P	:	precipitation [mm a^{-1}]
Q	:	discharge [mm a^{-1}]
E	:	evaporation [mm a^{-1}]
dS/dt	:	storage changes per time step [mm a^{-1}]





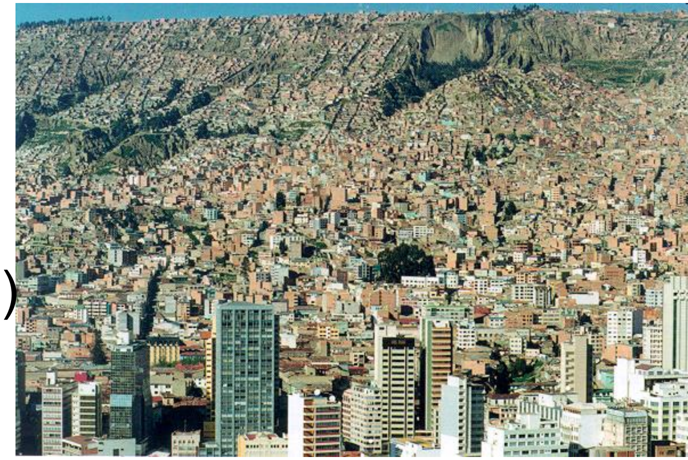


°C
0.8
0.4
0.0
-0.4
-0.8
1840 1860 1880 1900 1920 1940 1960 1980 2000 2020
1998
2005
2008
GISS: NASA-GISS temperature analysis
HadCRUT3: Hadley Climate Research Unit
IPCC Projections 2100 AD
Global Temperature (°C)
6
5
4
3
2
1
0
Lower Risk for Instabilities
N.H. Temperature (°C)
1
0.5
0
-0.5
1000 1200 1400 1600 1800 2000
PAGES

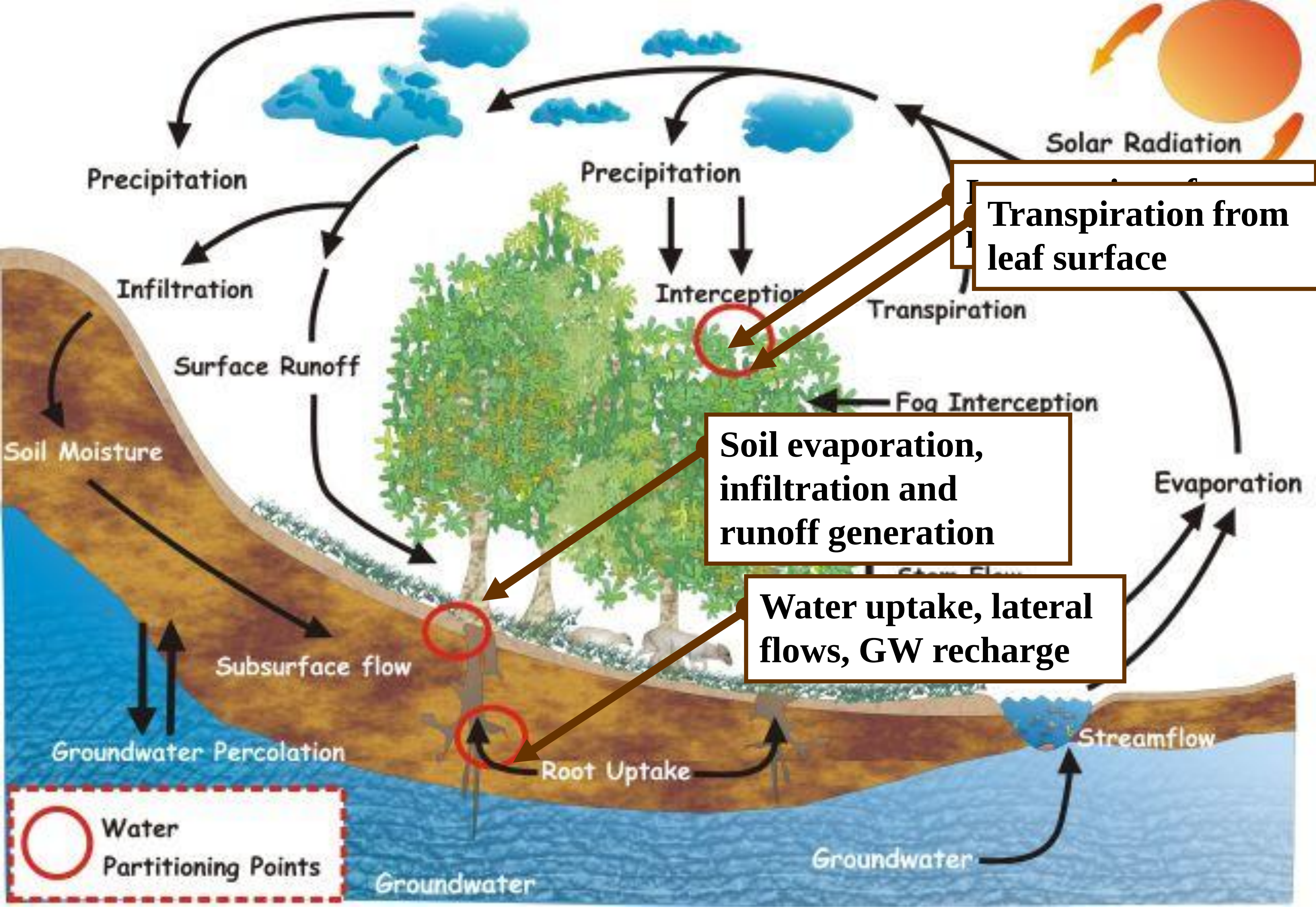
(NEAA, 2009)

Global Changes

- Climate (temperature, precipitation, radiation …)
- Land use, land cover
  - De-forestation / re-forestation
  - Urbanisation
  - Etc.
- Population (amount, density, structure, …)
- Water use in space and time
- Economic development
- Change of diet (more meat => more water)
- N- and P-fluxes to water bodies
- Pollution (new substances etc.)
- Change in composition of species
- etc. etc. etc.

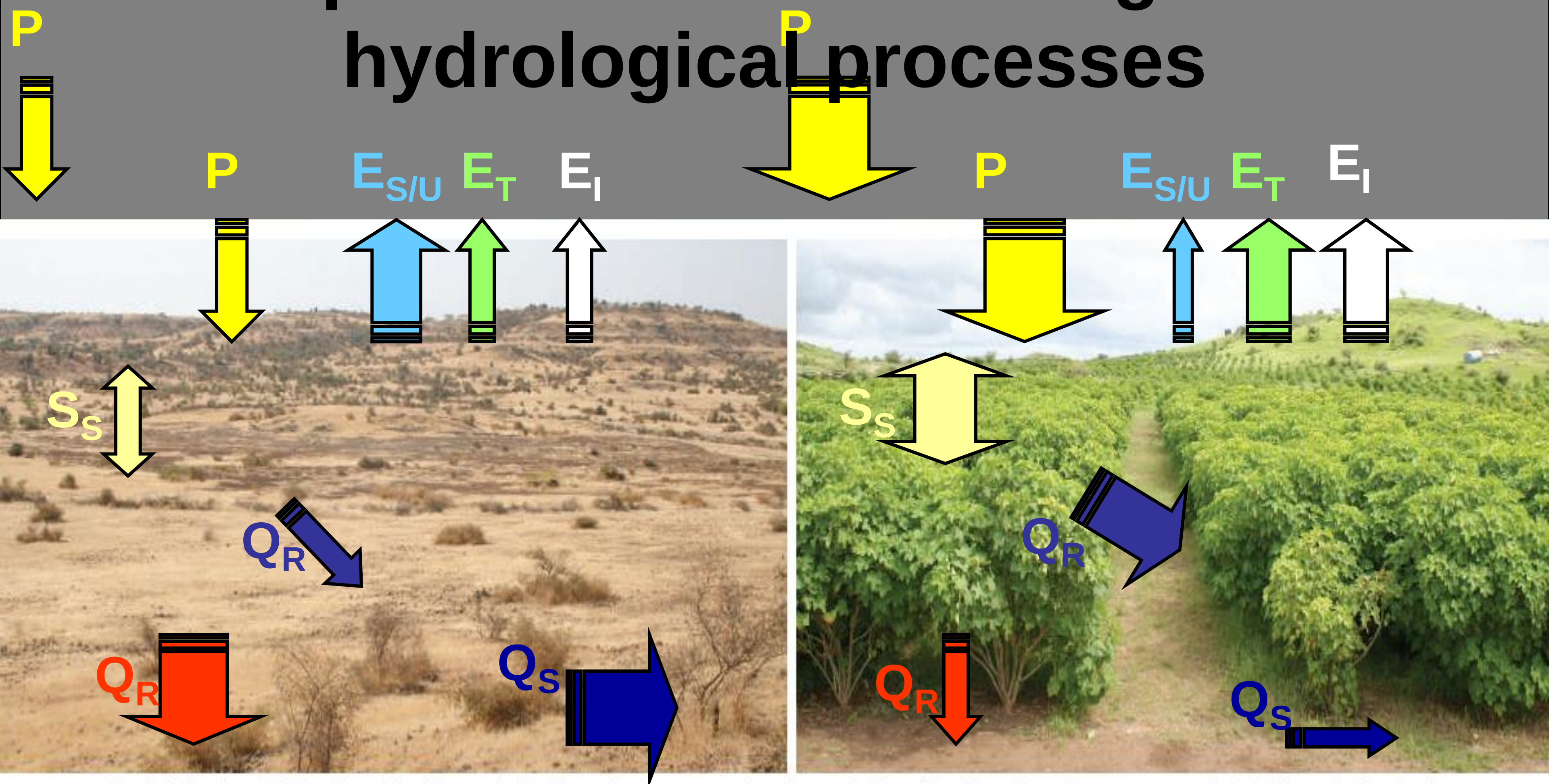


…. and many interdependencies/feedbacks!



Land use – Points of Impact (slide from G. Jewitt, UKZN, South Africa)

Impact of land use change on hydrological processes



Oasis in the desert: Jatropha cultivation can halt soil erosion, increase water storage in the soil and transform barren expanses into lush, productive land.

Short-term dynamics (e.g. interception, flood generation) *vs.* long-term dynamics (e.g. groundwater recharge, base flow)

Picture from Fairless, 2007, *Nature*

Water Balance Equation:

$$\left(\frac{dS_I}{dt}+E_I\right)+\left(\frac{dS_s}{dt}+E_s+Q_s\right)+\left(\frac{dS_u}{dt}+E_T+E_u+Q_f\right)+\left(\frac{dS_g}{dt}+Q_g\right)=P$$

Where:

$$\left(\frac{dS_I}{dt}+E_I\right)$$

Interception processes

$$\left(\frac{dS_s}{dt}+E_s+Q_s\right)$$

Surface water processes

$$\left(\frac{dS_u}{dt}+E_T+E_u+Q_f\right)$$

Root zone moisture processes

$$\left(\frac{dS_g}{dt}+Q_g\right)$$

Groundwater processes

Possible changes in <u>all</u> variables due to climate and/or land changes!!

Comparison of forested and deforested areas

Average annual water balances in forested and deforested areas in % (Baumgartner, 1972).

P = Precipitation
$E_{total} = E_S + E_I + E_T$
R = Runoff
E_S = Soil evaporation
E_I = Interception evaporation
E_T = Transpiration

				Expressed in % of E_{total}		
	P	***L***	***R***	E_S	E_I	E_T
Forests	***100***	***52***	***48***	***29***	***26***	***45***
Open land	***100***	***42***	***58***	***62***	***15***	***23***

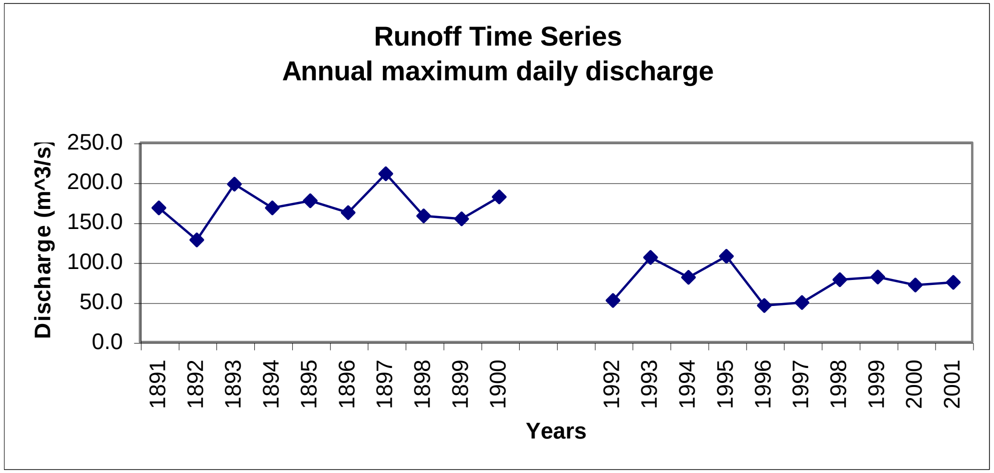
(from lecture notes, De Laat & Savenije 2008)

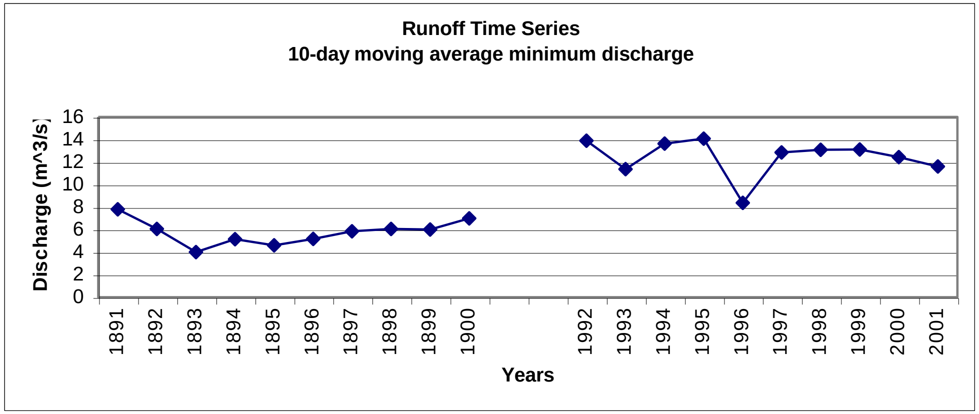
Human activities affect hydrological regime of river basin:

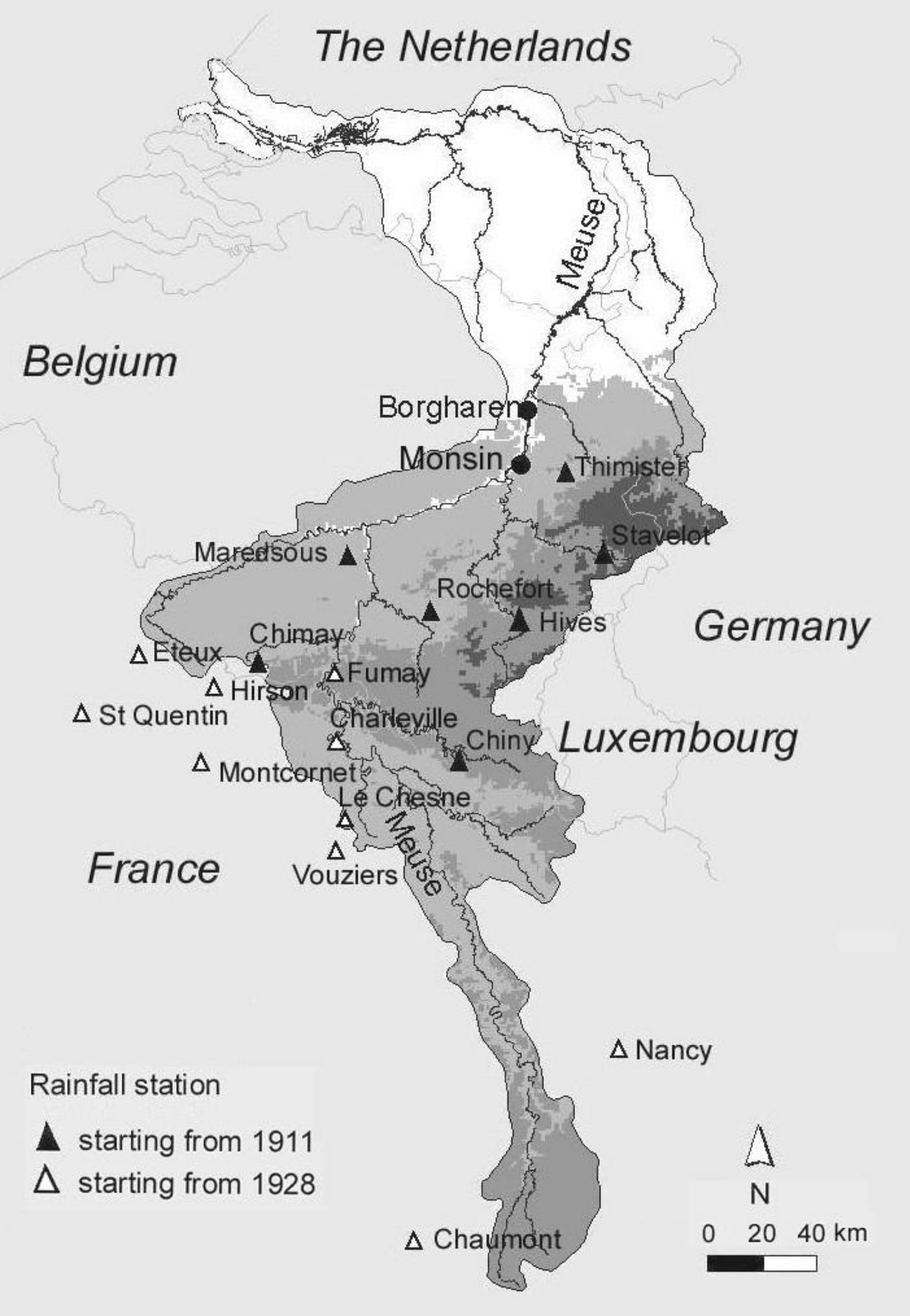
A – directly, e.g. building reservoirs, urbanisation, deforestation, etc.

B – more indirectly through anthropogenic induced climate change

A: Example Rur: Max and Min flow in 19th and 20th century (reservoir built in 1950)



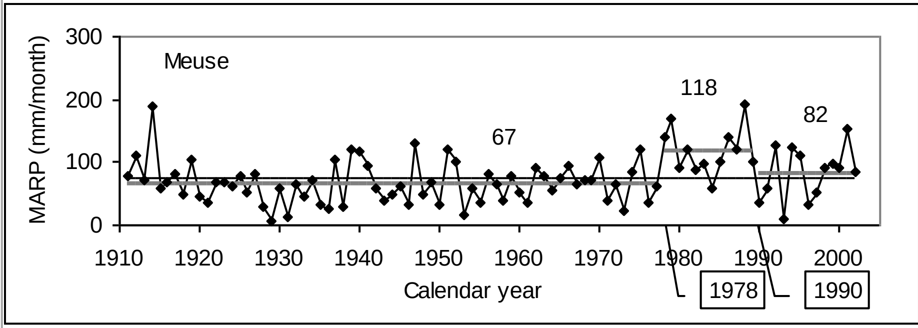


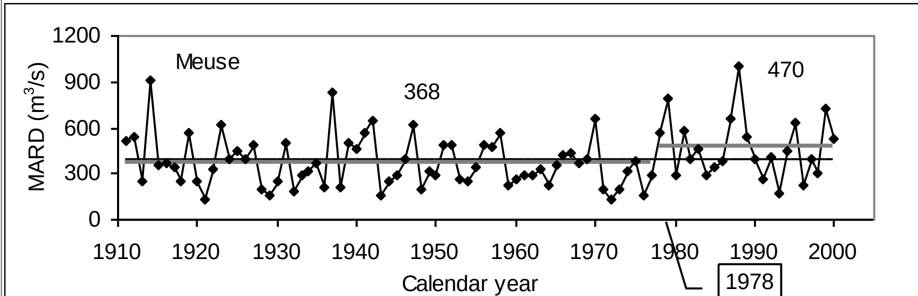


Human activities can affect hydrological regime of a river basin

B: Example Meuse:

Rainfall in the month of March increased since 1978, so did the discharge





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Sources of hydrological data

- National and regional archives or libraries (hydrological records but also aerial photographs etc.);
- Private organizations such as power authorities or companies having an interest in hydrological measurements, e.g. agricultural product marketing companies and oil drilling companies;
- Research papers and project reports;
- Survey reports of research and development agencies;
- Archives of established newspapers;
- Field observations;
- Interviews of people living in the area;
- Maps on related topics; and
- ETC!

Take Home Messages

- Hydrological cycle consists of many components (storages and fluxes)
- A catchment is the hydrological base unit
- Solve water balance equation for a catchment
- Linkage global vs. local hydrological cycle
- Knowledge of the fundamental hydrological processes within a catchment
- Understand the water balance equation
- The rainbow of water and water balance equation
- Hydrological regimes are affected by climate change and other global changes (often through human activities)
- Data handling (see also de Laat 2008, *Workshop on Hydrology*) essential for hydrological research