„Water and Wastewater Treatment“

Part 1: Wastewater

Christof Holliger
EPFL

Part 2: Drinking water

Urs von Gunten
EPFL and Eawag

Structure of lecture

- Lectures: Tuesdays, 8.15-10.00
- Exercise sessions: Tuesdays 10.15-13.00, first Nov. 12
- Exercises:
  - Posted on moodle one week before exercise sessions, should be solved before exercise session
  - Assistants will be present to answer questions during exercise sessions (Tianqi Zhang, Lucie Bertolaso, Adèle Soulier)
  - Preparation for exams

Exams

- Midterm Dec. 3, 8.15-9.45,
  lecture 10.15-12.00
- Final exam on Jan. 22, 2025
- Recommended text book:
  Water Treatment: Principles and Design
  MWH (Montgomery Watson Harza, Firm), available at EPFL library

Outline of lecture on drinking water (5. Nov. – 17. Dec., 2021)

- General Introduction Water Resources (5. Nov.)
- Particles + Particle removal (12. Nov.)
- Oxidation and disinfection (19., 26. Nov.)
- Midterm 2 (3. Dec.)
- Adsorption + Membrane processes (10. Dec.)
- Process combinations and water reuse (17. Dec.)
- Final exercise on process combinations (17. Dec.)

„Water and Wastewater Treatment“
Part 2: Drinking water

Introduction

Drinking Water: Interplay between Quantity and Quality

Quantity ⟷ **Quality**

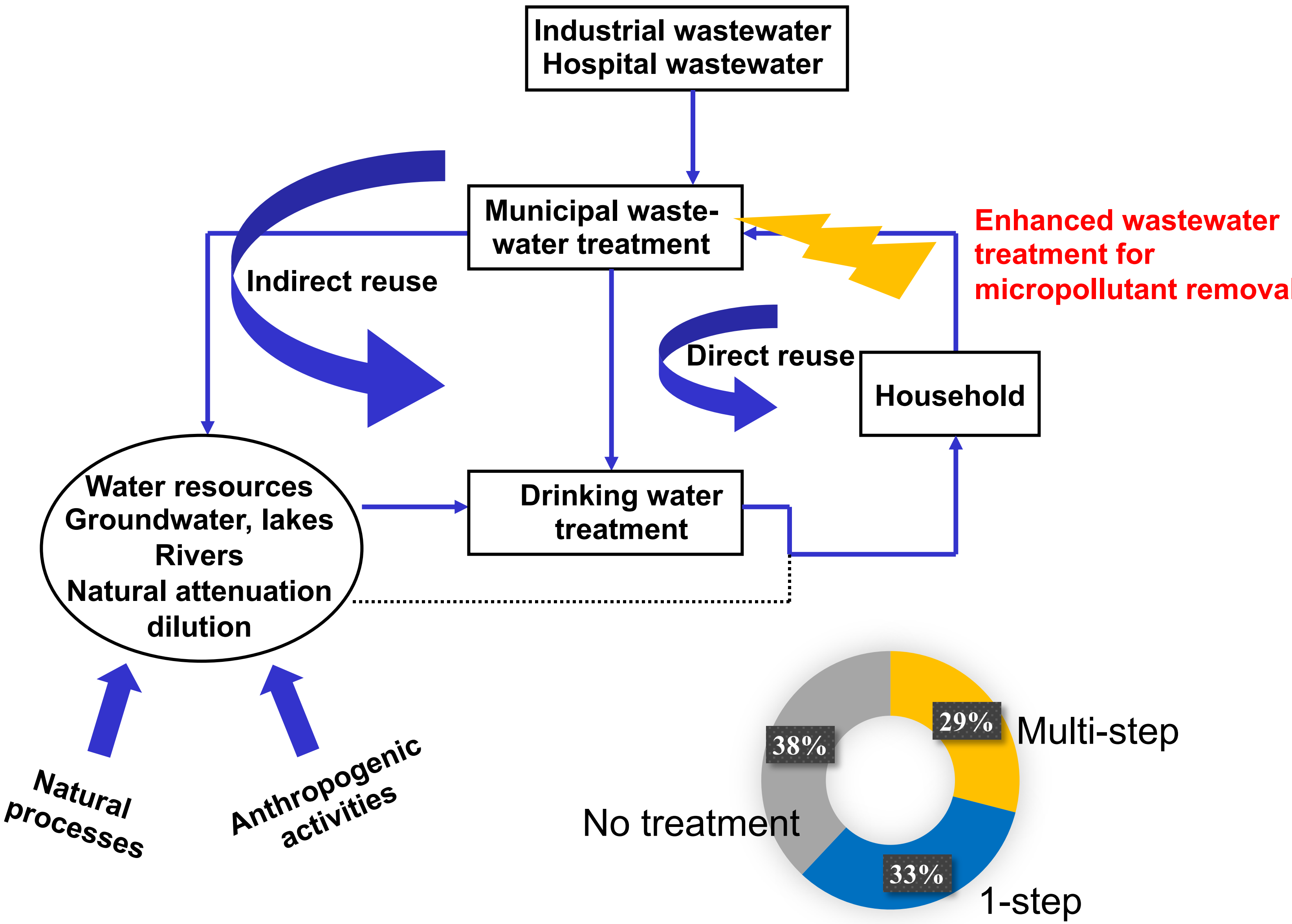
Quantity

- Precipitation
- Inflow
- Storage capacity
- Water use

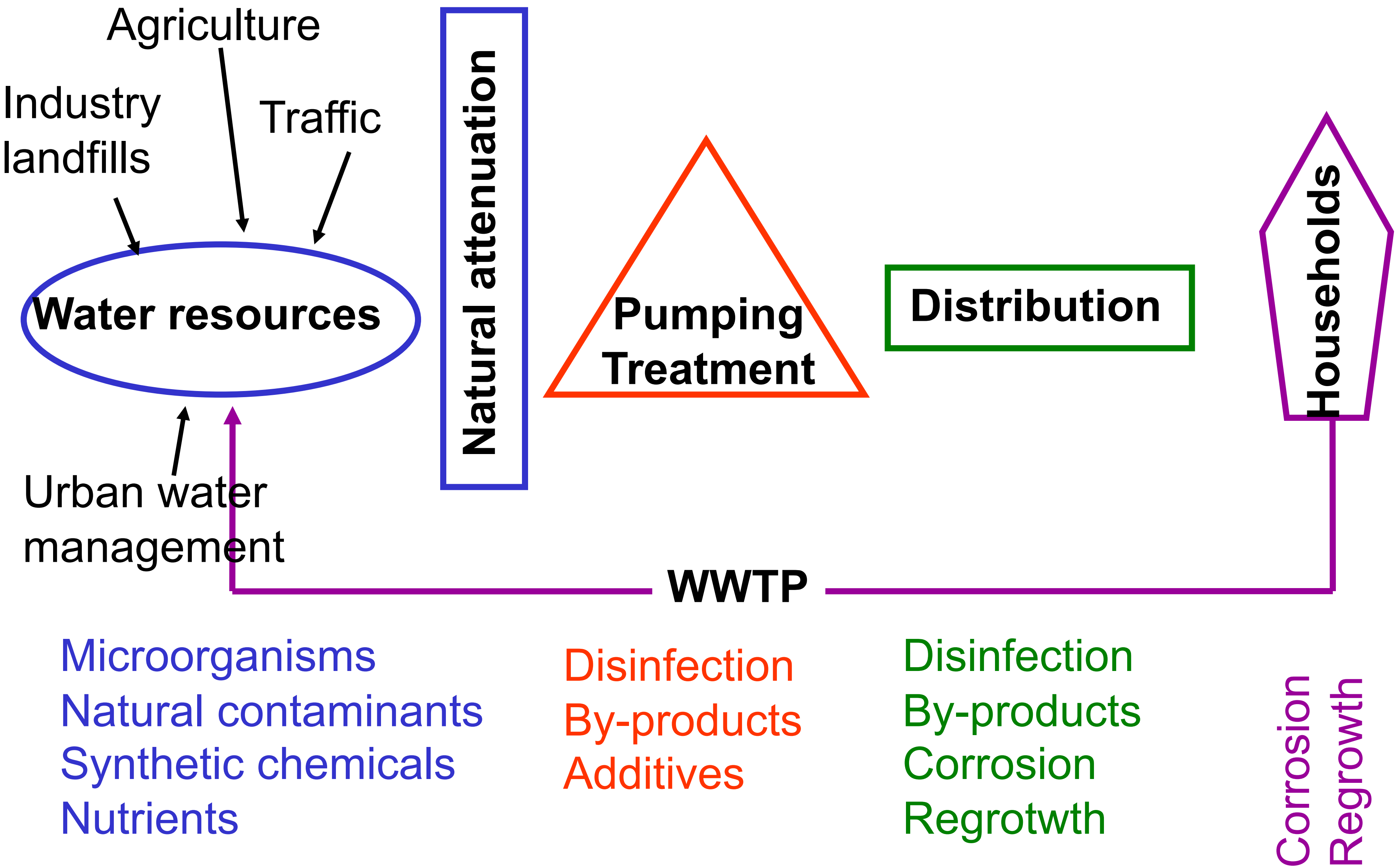
Quality

- Hygiene
  Viruses, Bacteria, Protozoa
- Chemical Parameters
  Water hardness, pH, DOC, dissolved O_2 taste, odor, color, micropollutants (inorganic/organic)

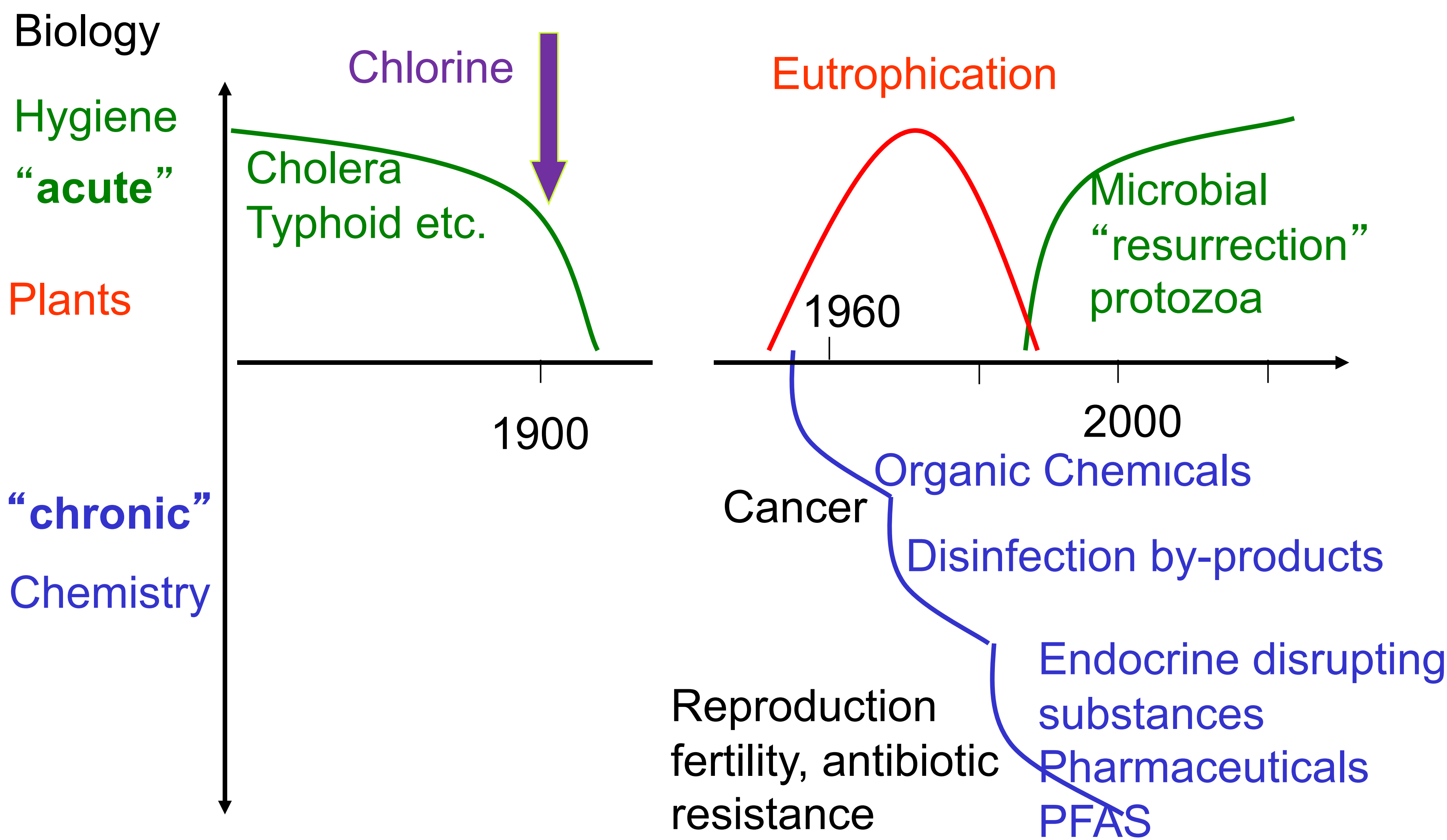
The anthropogenic/urban water cycle



Water supply: Possible disturbances of drinking water quality



Development of drinking water problems in industrialized countries in the 20. century



Discovery of drinking water hygiene in London

FUN.—August 18, 1866.

DEATH'S DISPENSARY.

OPEN TO THE POOR, GRATIS, BY PERMISSION OF THE PARISH.

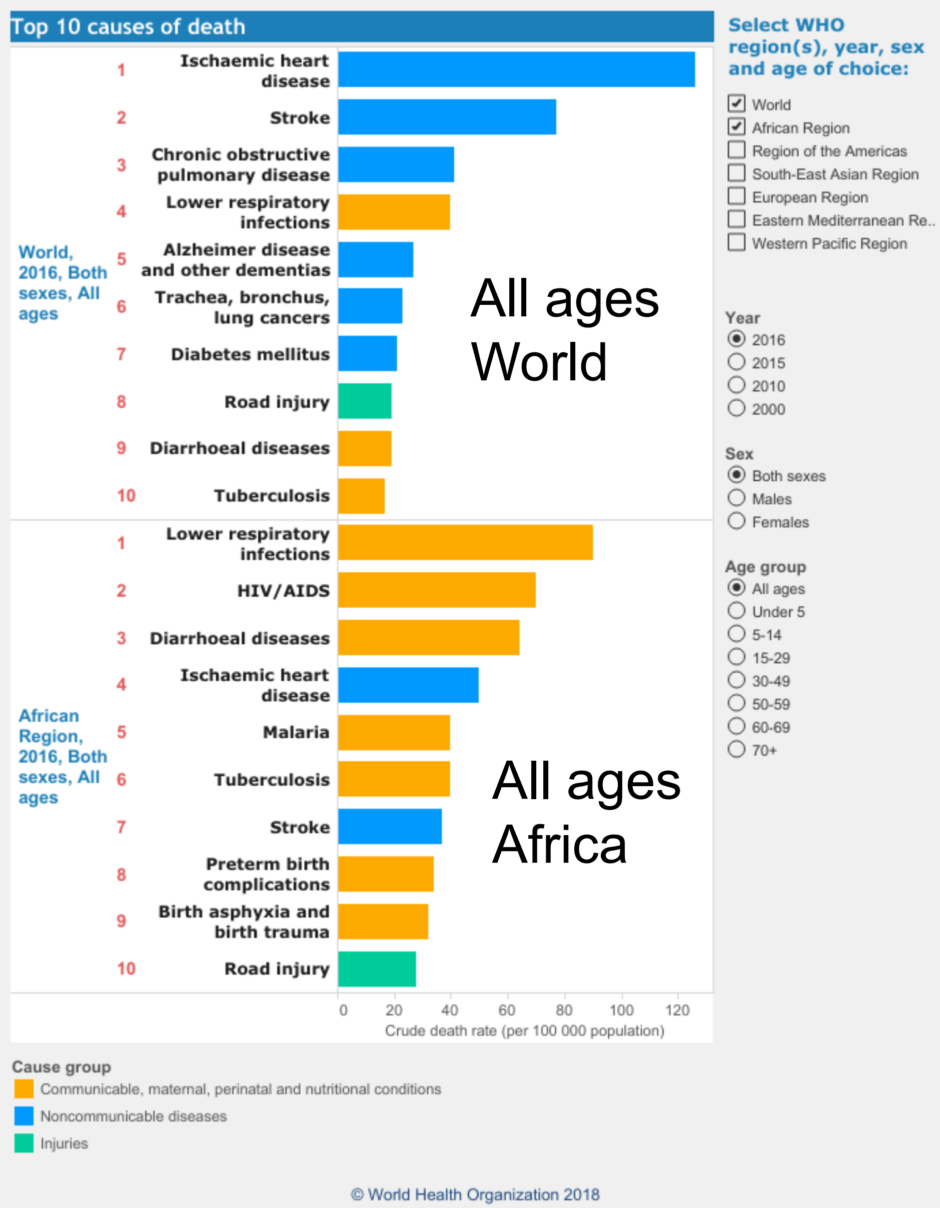
2 Cholera Epidemics in London:
1849, 1853
2 Drinking water companies
Southwark&Vauxall
Lambeth

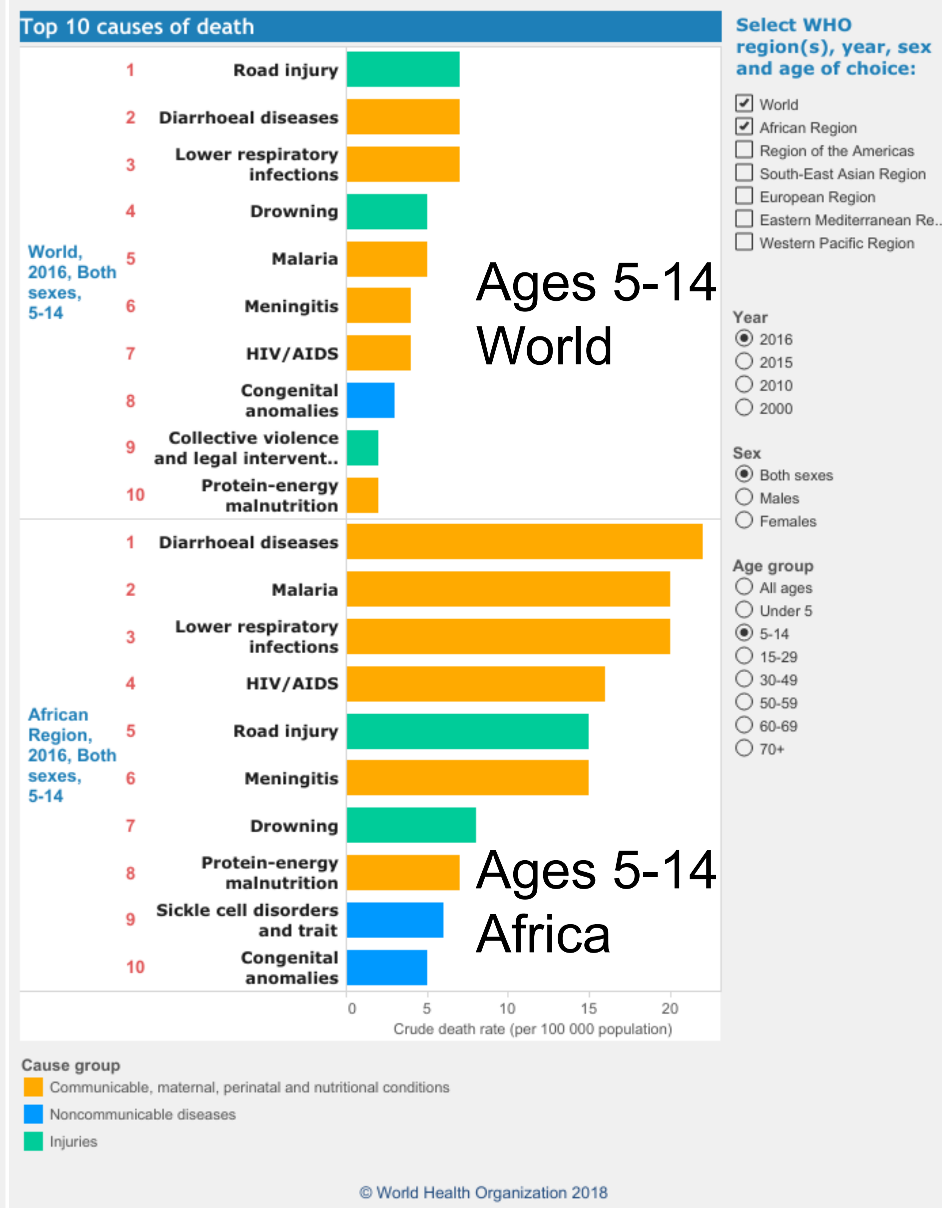
1849: both drinking waters contaminated with wastewater
1853: Lambeth used new water resource

1855:John Snow

On the Mode of Communication of Cholera, 1855

Leading causes of death (WHO 2016)





http://www.who.int/gho/mortality_burden_disease/causes_death/top_10/en/

Drinking water related epidemics in Switzerland I

Up to ca. 1900: Cholera/Typhoid fever in Zurich and other Swiss cities

Typhoid fever epidemics in **Glion**, 1945

101 cases of illness; 16 fatalities

Cause: Leaking sewer pipe in the catchment area of a spring

Typhoid fever epidemics in **Toggenburg**, 1955

30 children; 1 fatality

Cause: leaking sewer pipe and defective pipe to supply public fountains

Typhoid fever epidemics in **Zermatt**, 1963

437 cases of illness; 3 fatalities

Cause: With wastewater contaminated river water used as potable water resource was insufficiently treated (chlorination out of operation, chlorination with inadequate contact time)

Gastro-Enteritis epidemics in **La Neuveville**, 1998

Ca. 1600 cases of illness

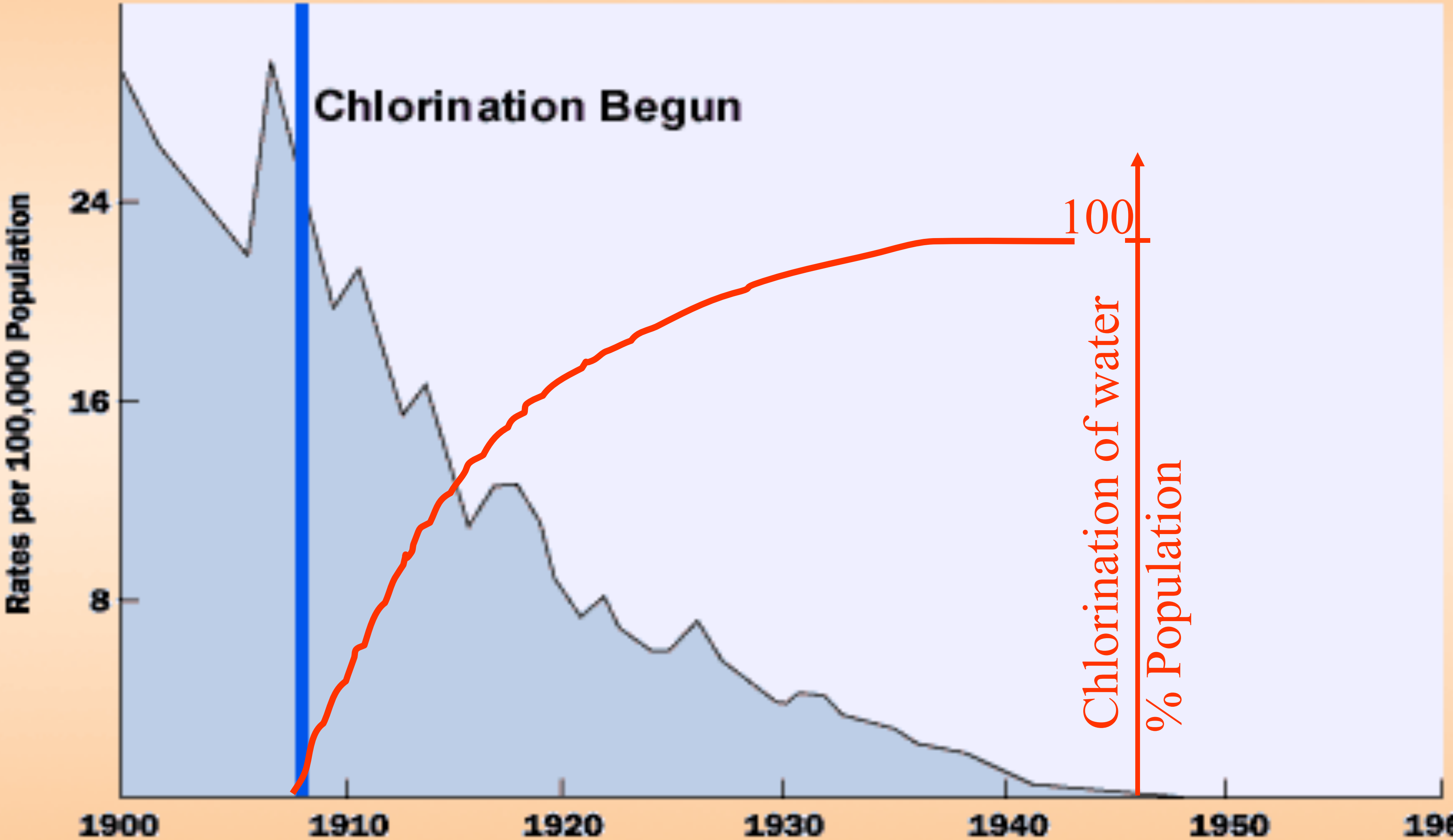
Cause: Groundwater water contamination by wastewater intrusion. Defective pump caused build-up of wastewater. Wastewater leached through defective sewer pipes.

Drinking water related epidemics in Switzerland II

Gastro-Enteritis in **Adlsiwil**, 2008
126 cases of illness (Norovirus/Campylobacter jejuni)
Cause: Cross-connection of service water of a wastewater treatment plant to a drinking water distribution system

Gastro-Enteritis in **Le Locle**, 2015
1000 cases of illness (Norovirus)
Cause: Contamination of a drinking water reservoir with wastewater

Death Rate for Typhoid Fever
United States, 1900-1960



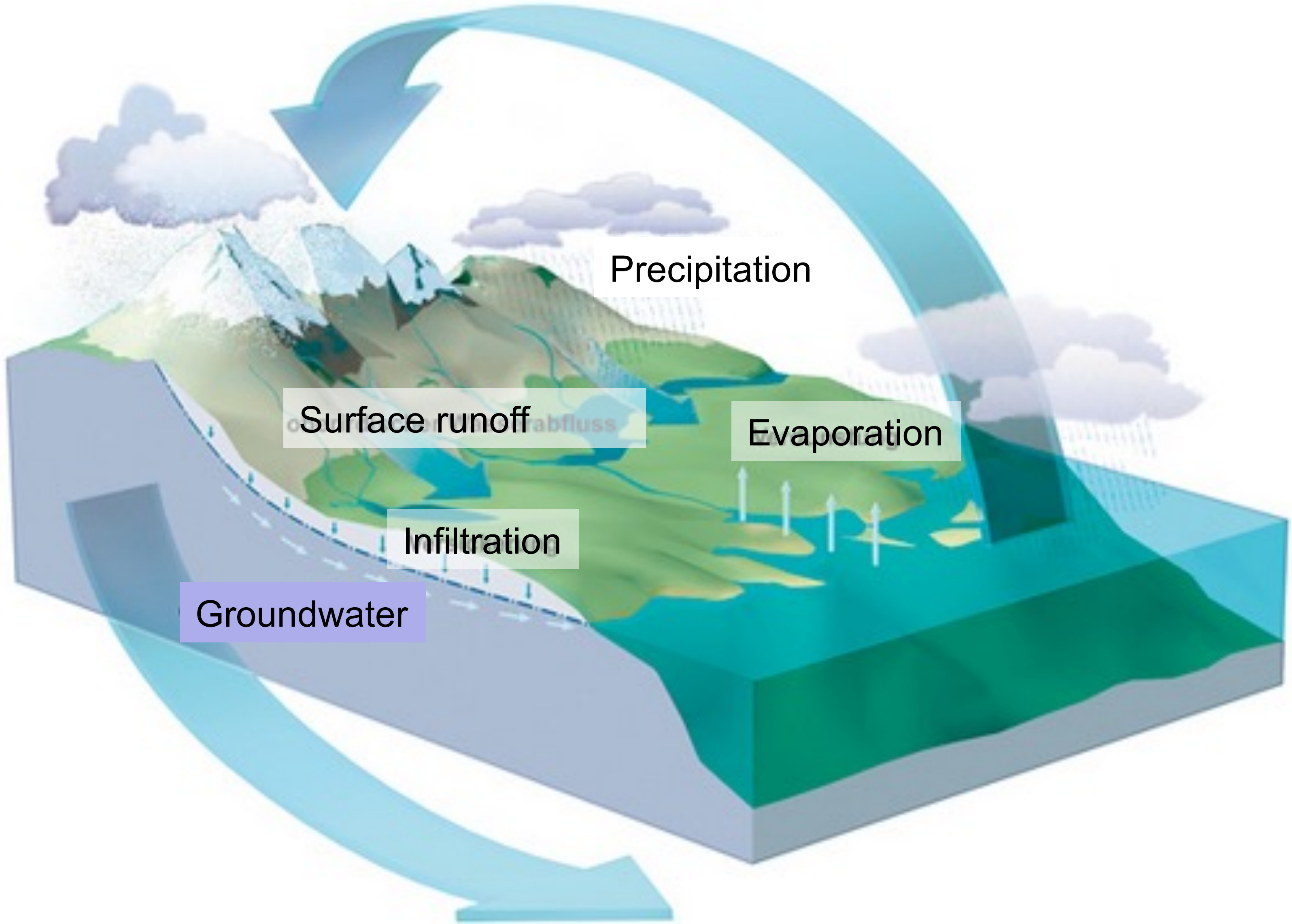
Source: U.S. Centers for Disease Control and Prevention, Summary of Notifiable Diseases, 1997

Interactive Polls with TurningPoint®

- Laptop/desktop: https://responseware.eu
- Smart phone: download TurningPoint app

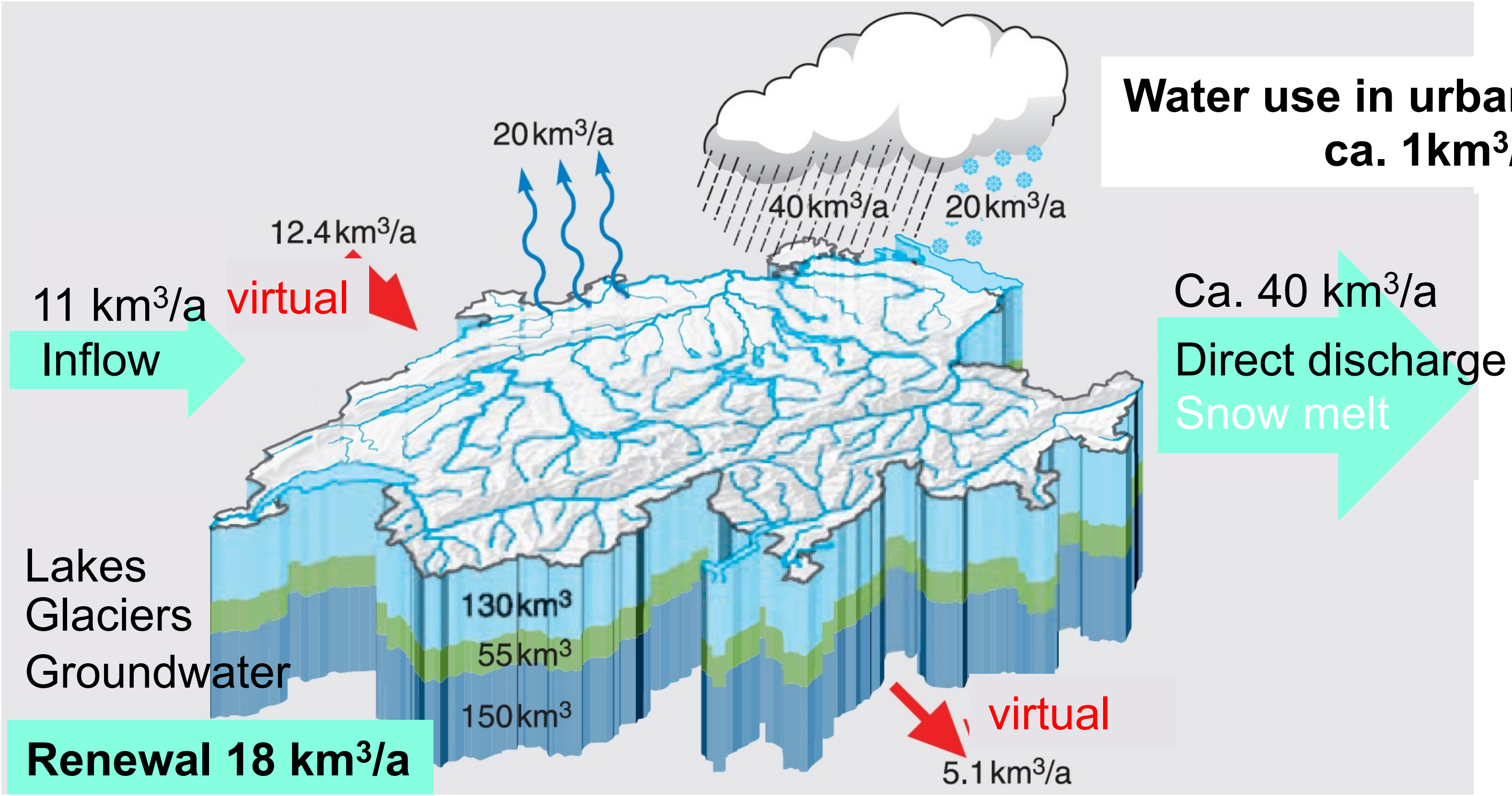
⇒Open webpage or app and insert session ID WWT24

Natural water cycle



Sinreich et al. Aqua & Gas, 2012

Water balance in Switzerland



Schweizerische Hydrologische Kommission, CHy 2013

Drought in Switzerland in 2018 (2022, etc.): Most severe in a century

https://www.schweizersee.ch/lac_brenet/

Lac Brenet, Anthony Anex, Keystone

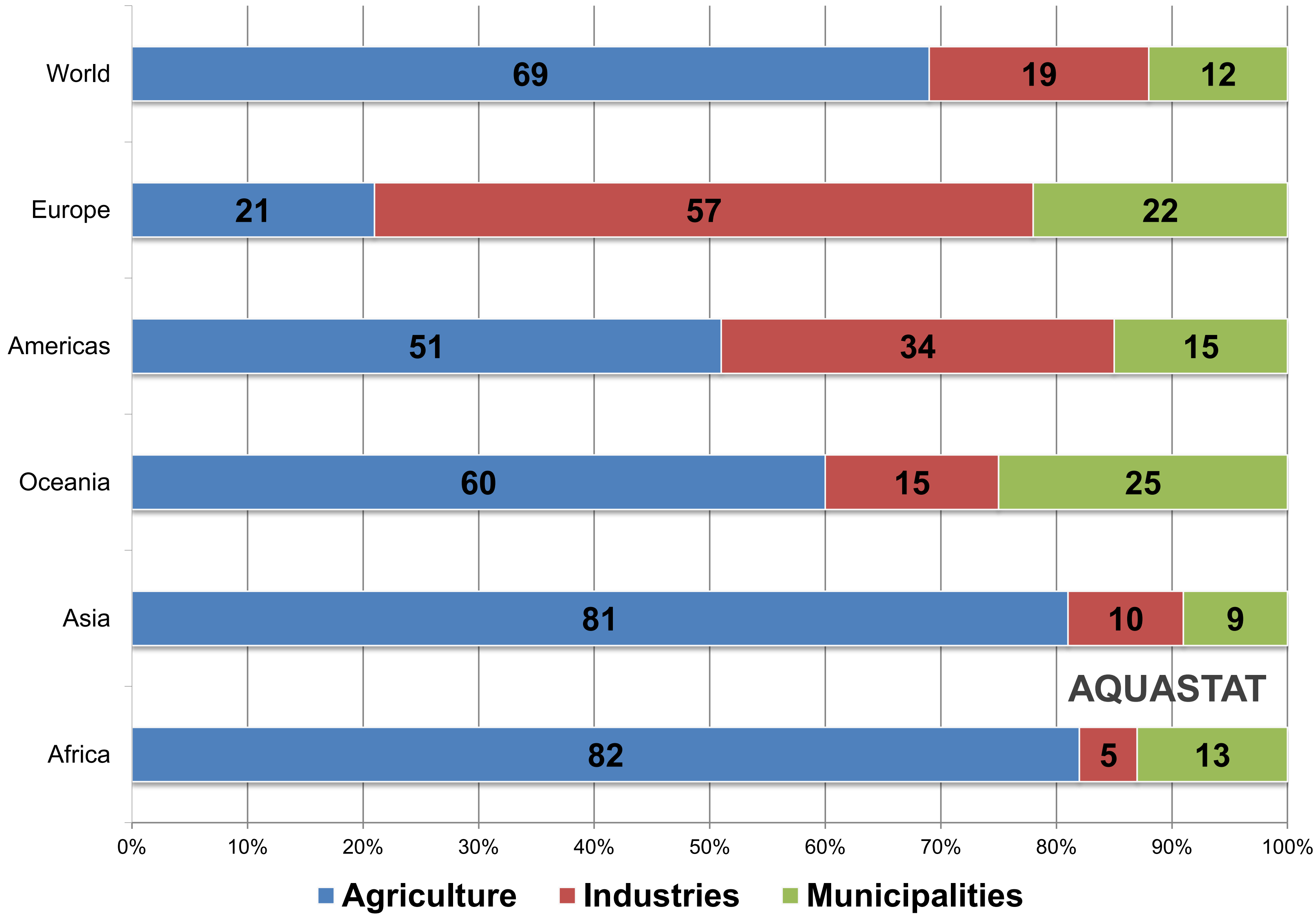
Aargauer Zeitung 3.8.2018

Switzerland: Europe‘s “water castle”

- Average: 1500 mm precipitation/year
  (60 billion m^3 = 60 km^3, available 20 km^3)
  - Use (household, (industry, agriculture)), ca.
    1 km^3/year (3 km^3/year including cooling water)
- 6% of freshwater resources of Europe are stored in CH (> 300 km^3, surface fraction 0.4%)
- Origin of important European rivers (Rhine, Rhone, Inn (Danube), Ticino)

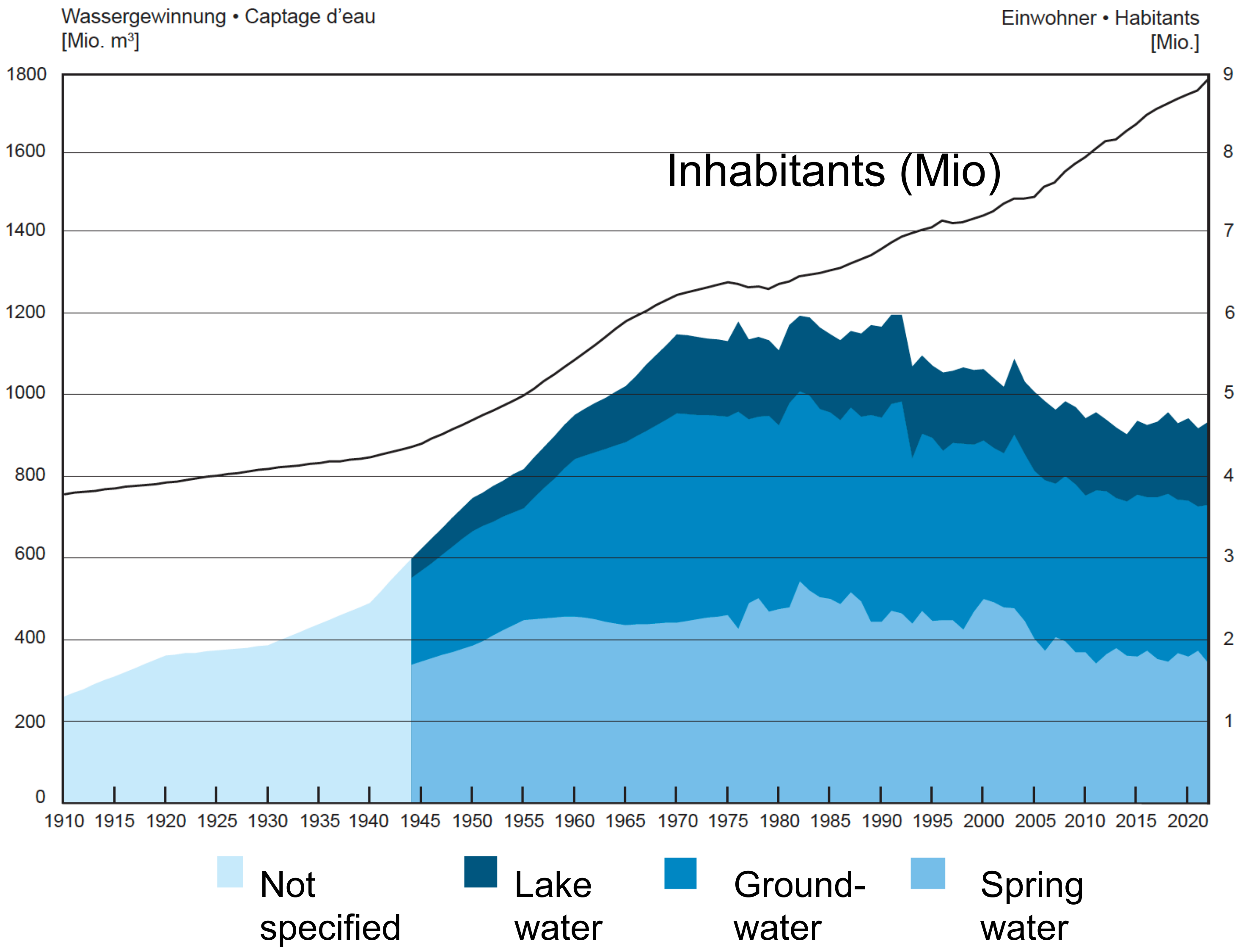
  $\Rightarrow$ International responsability

Water withdrawal ratios by continent



FAO Date of preparation: September 2015

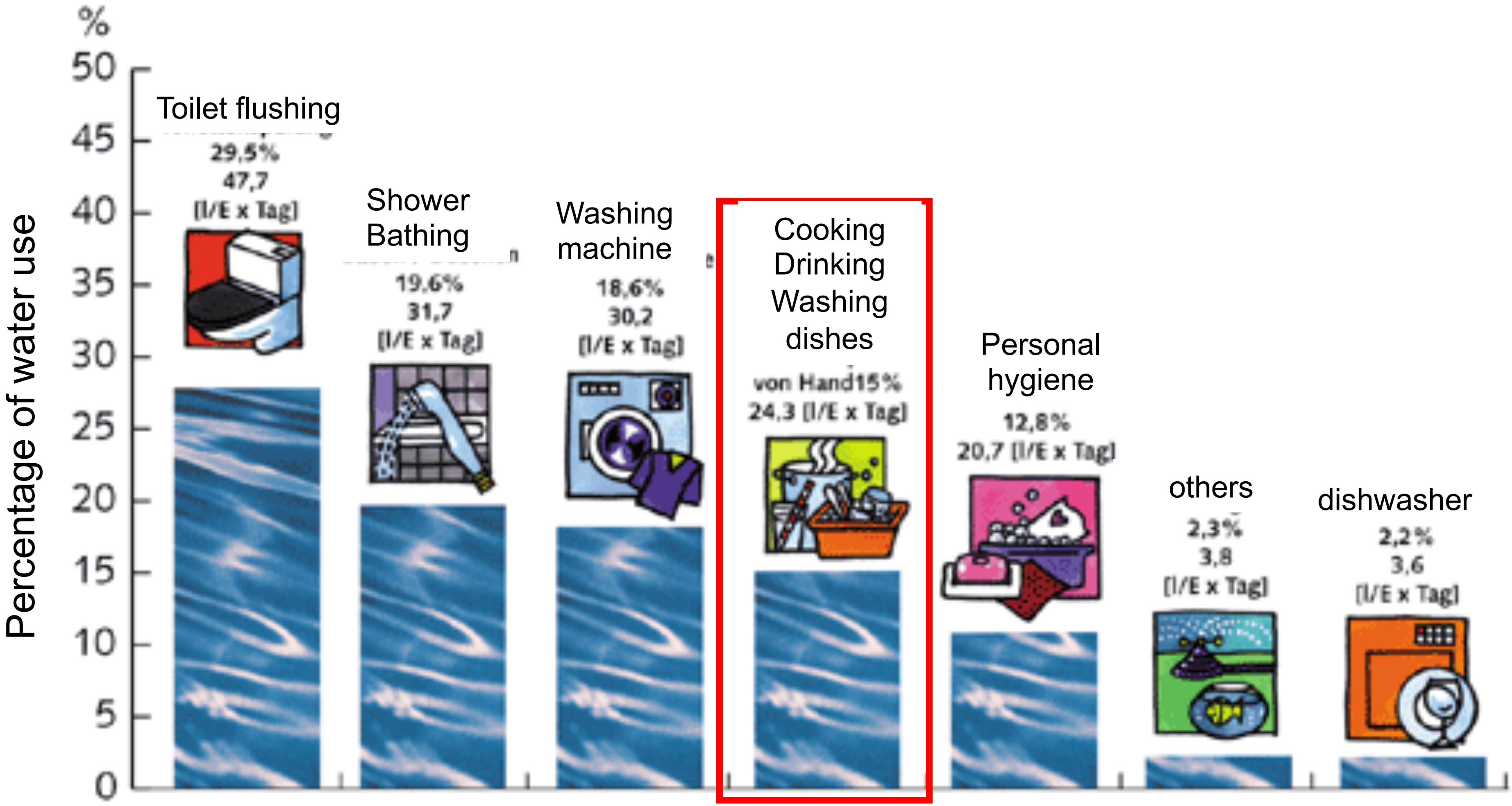
Development of municipal water use in Switzerland



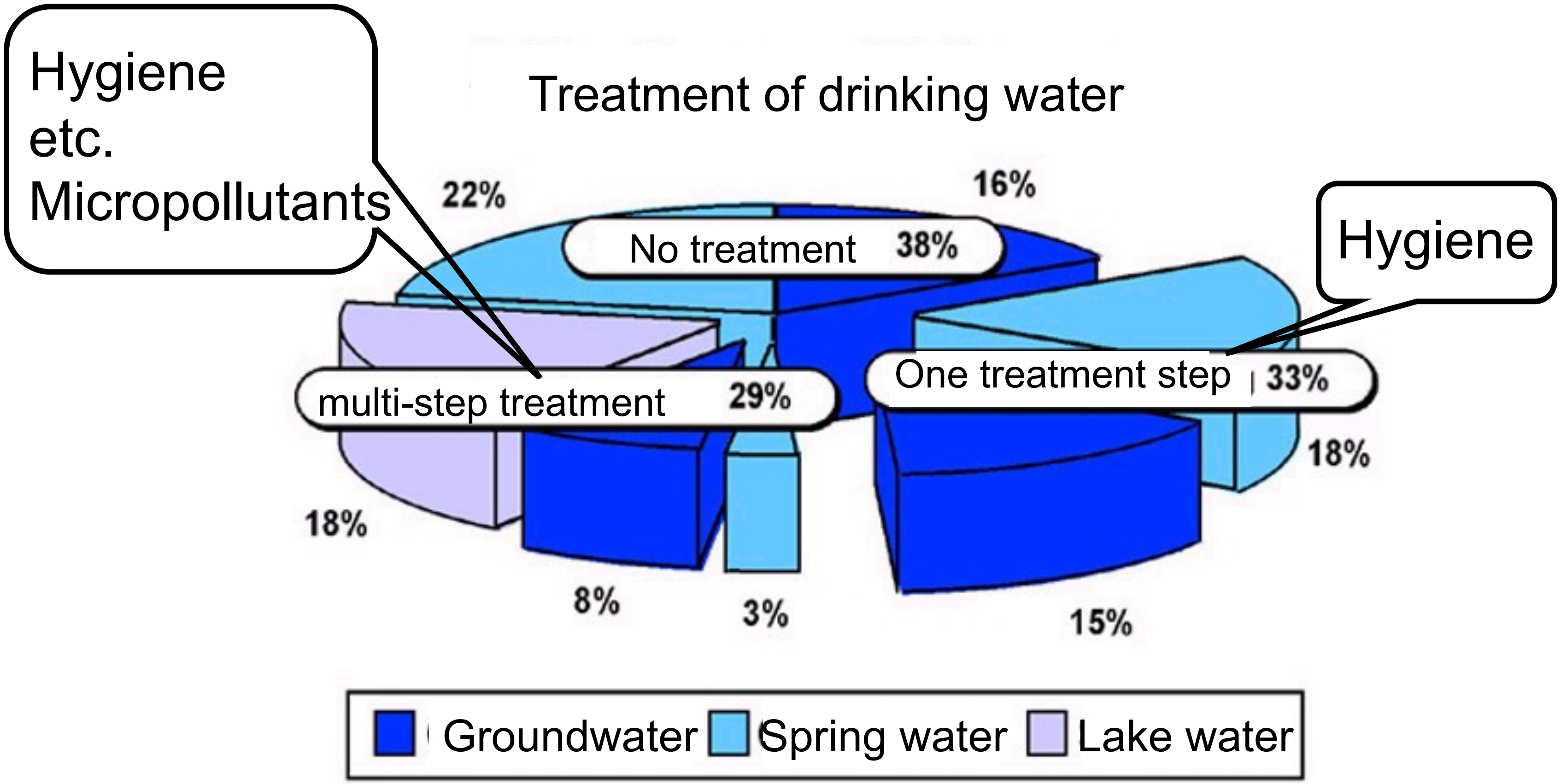
Water production in Switzerland

SVGW – www.trinkwasser.ch

Distribution of water use in private households in Switzerland: 162 liters per inhabitant and day

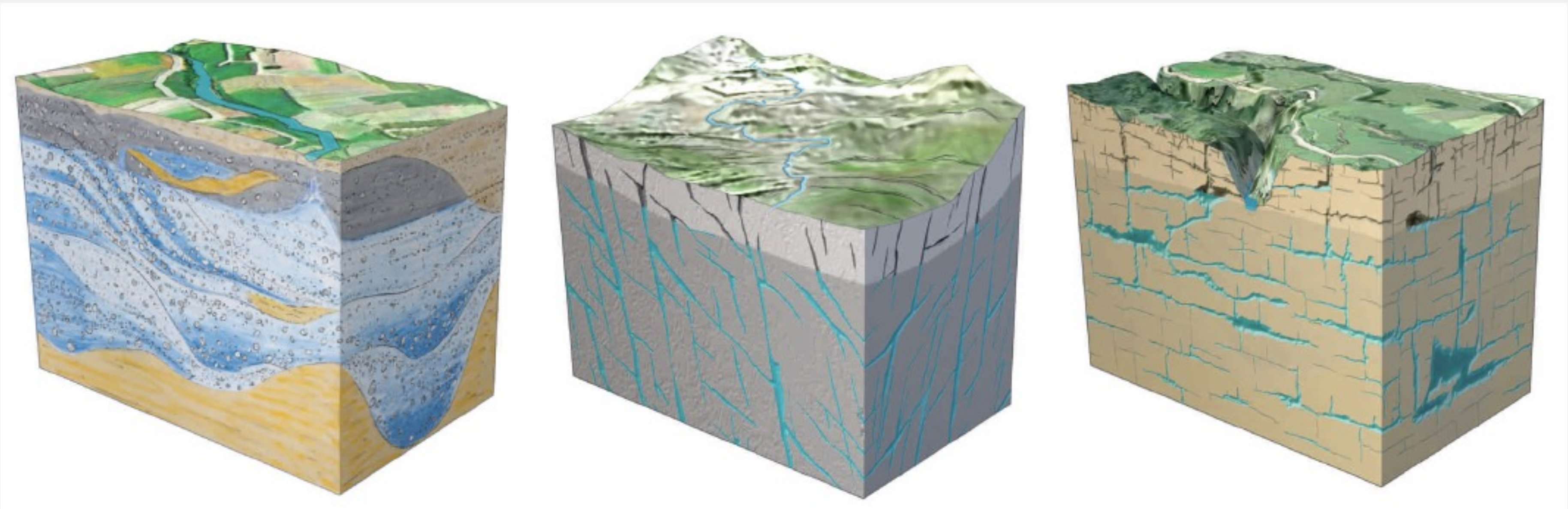


Origin and treatment of drinking water in Switzerland



SVGW-Wasserstatistik

Types of groundwater resources



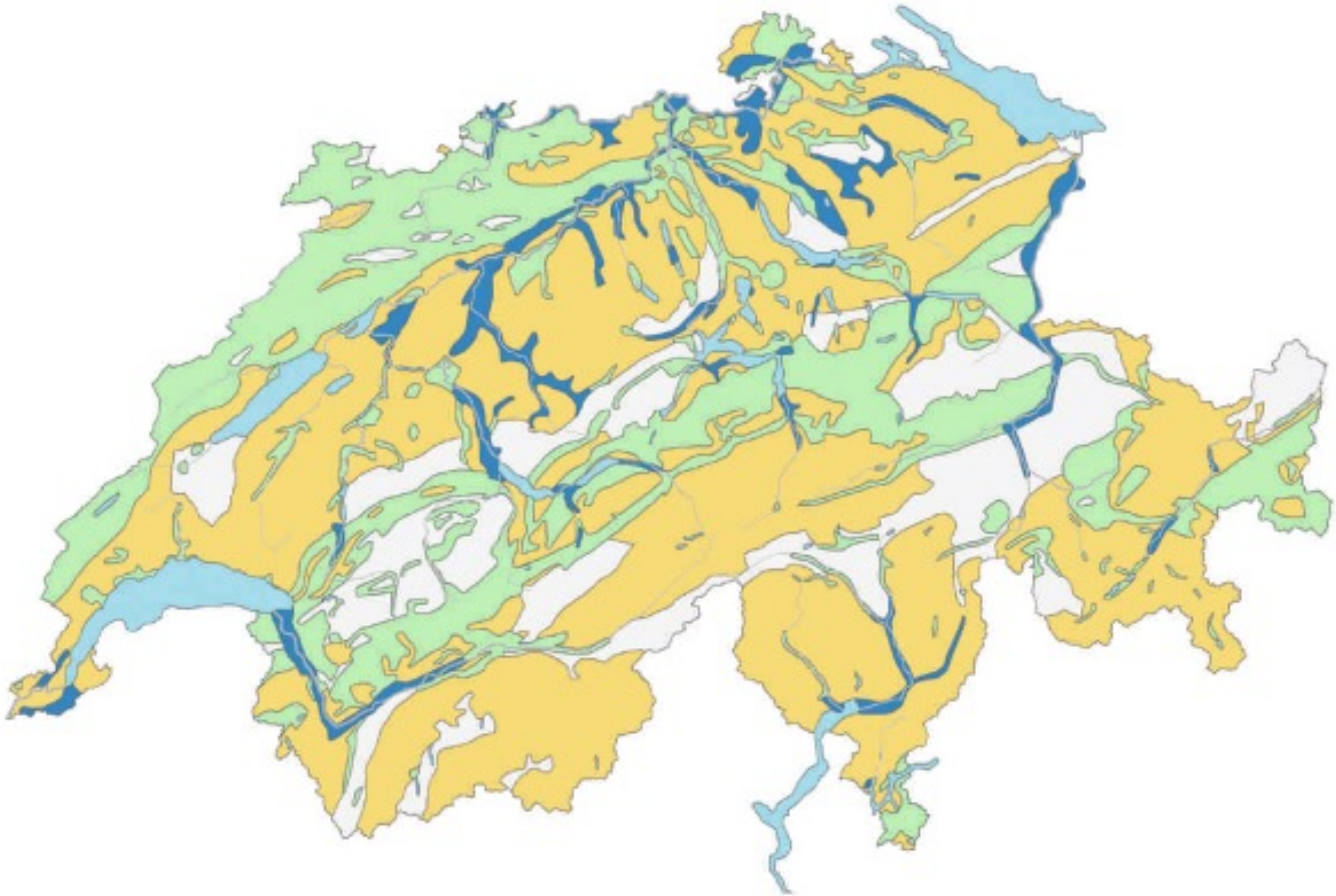
Glaciofluvial or gravel/sandy aquifers

Fractured bedrock aquifers

Karstic groundwater

Sinreich et al. Aqua & Gas, 2012

Groundwater resources in Switzerland



Very productive gravel/sand

Productive gravel/sand & bedrock

Less productive gravel/sand & bedrock

No productive groundwater sources

Sinreich et al. *Aqua & Gas,* 2012

Water composition: Biogeochemical processes in water resources

- weathering of rocks and minerals
- equilibrium of CO_2 between air/water, speciation of carbonate species, equilibria with $CaCO_3$ and $MgCO_3$
- formation of groundwater by aerobic recharge
- formation of groundwater by anaerobic recharge
- redox sequences in anaerobic water resources
- eutrophication of lakes and redox processes
- bio(geo)genic pollutants

Groundwater recharge

- Aerobic groundwater recharge
  - Infiltration of rain water
  - Good aeration (always sufficient oxygen)

    $\Rightarrow$ aerobic respiration ($O_2 + CH_2O \rightarrow CO_2 + H_2O$)

    $\Rightarrow$ Dissolution of limestone (increase of hardness)
- Anaerobic groundwater recharge
  - Hydraulic connection
  - System depletes in oxygen (insufficient aeration)

    $\Rightarrow$ Formation of redox zones

Formation of Hardness: Role of rain water

pH of rain water 4-5, max. 10^{-4} M protons

Dissolution of $CaCO_3$:

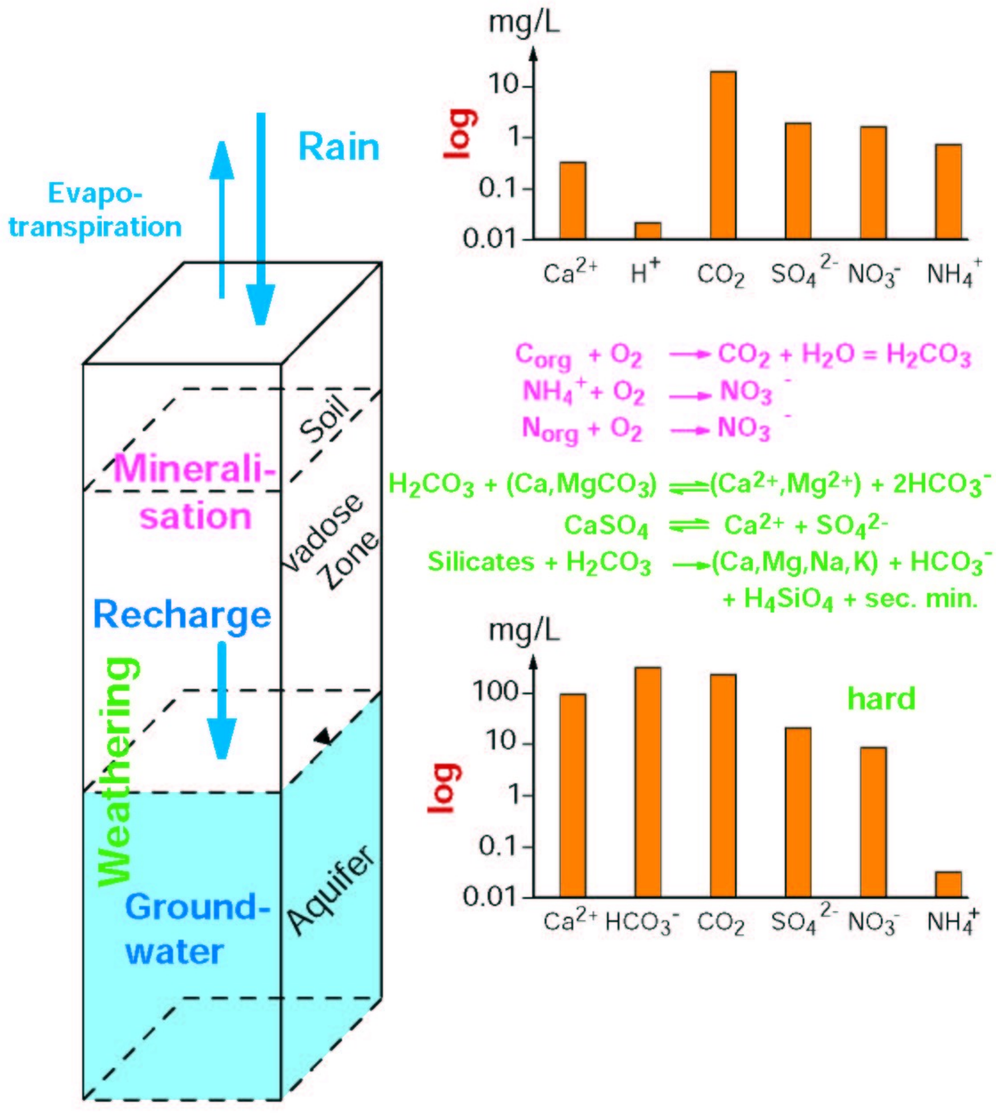
$$CaCO_3 + H^+ \longrightarrow Ca^{2+} + HCO_3^-$$

10^{-4} M H^+ lead to a maximum Ca^{2+} conc. of 10^{-4} M

Typical hardness in Swiss groundwaters is > 10^{-3} M!

Why?

Mineralization of water resources



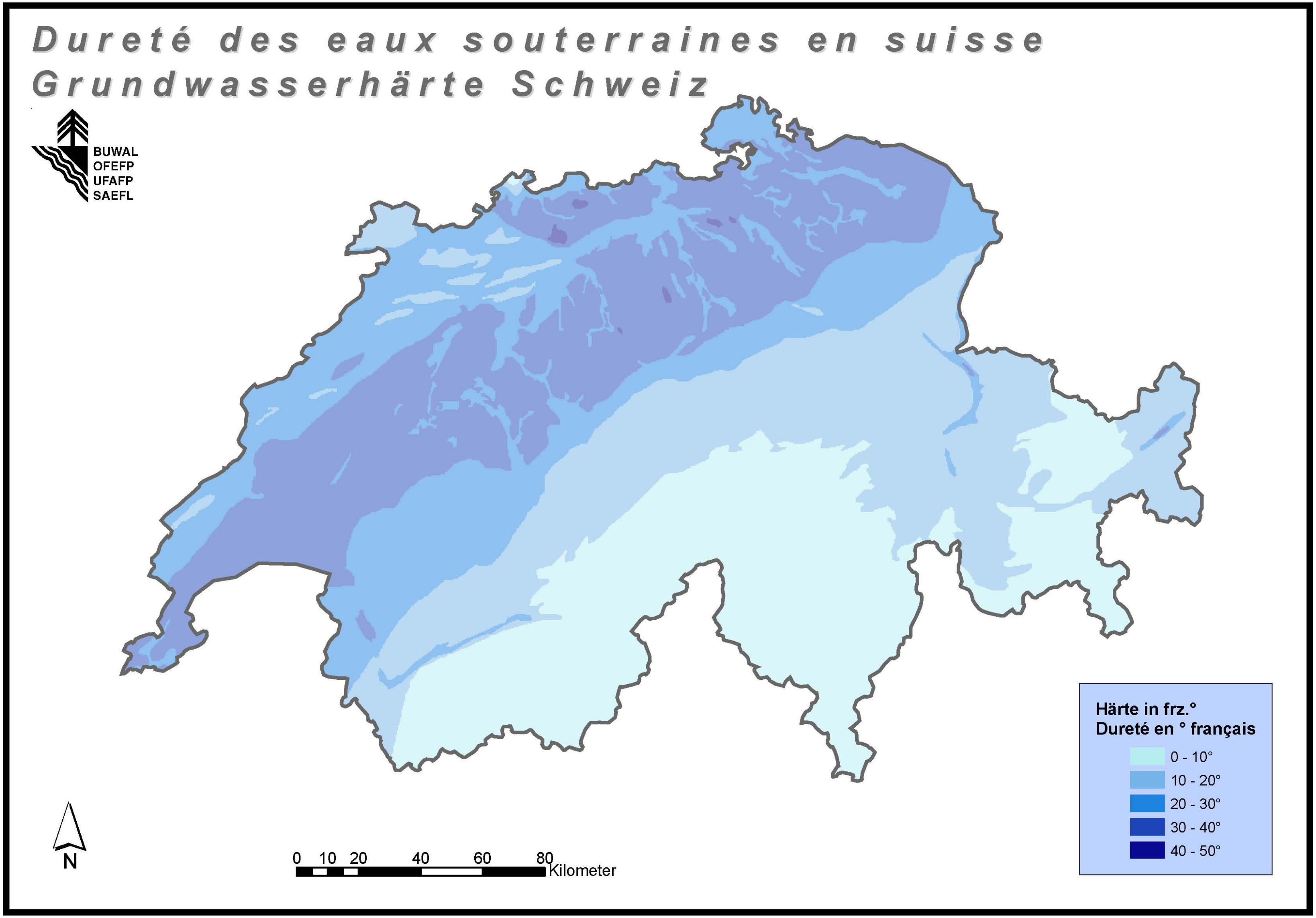
Definitions

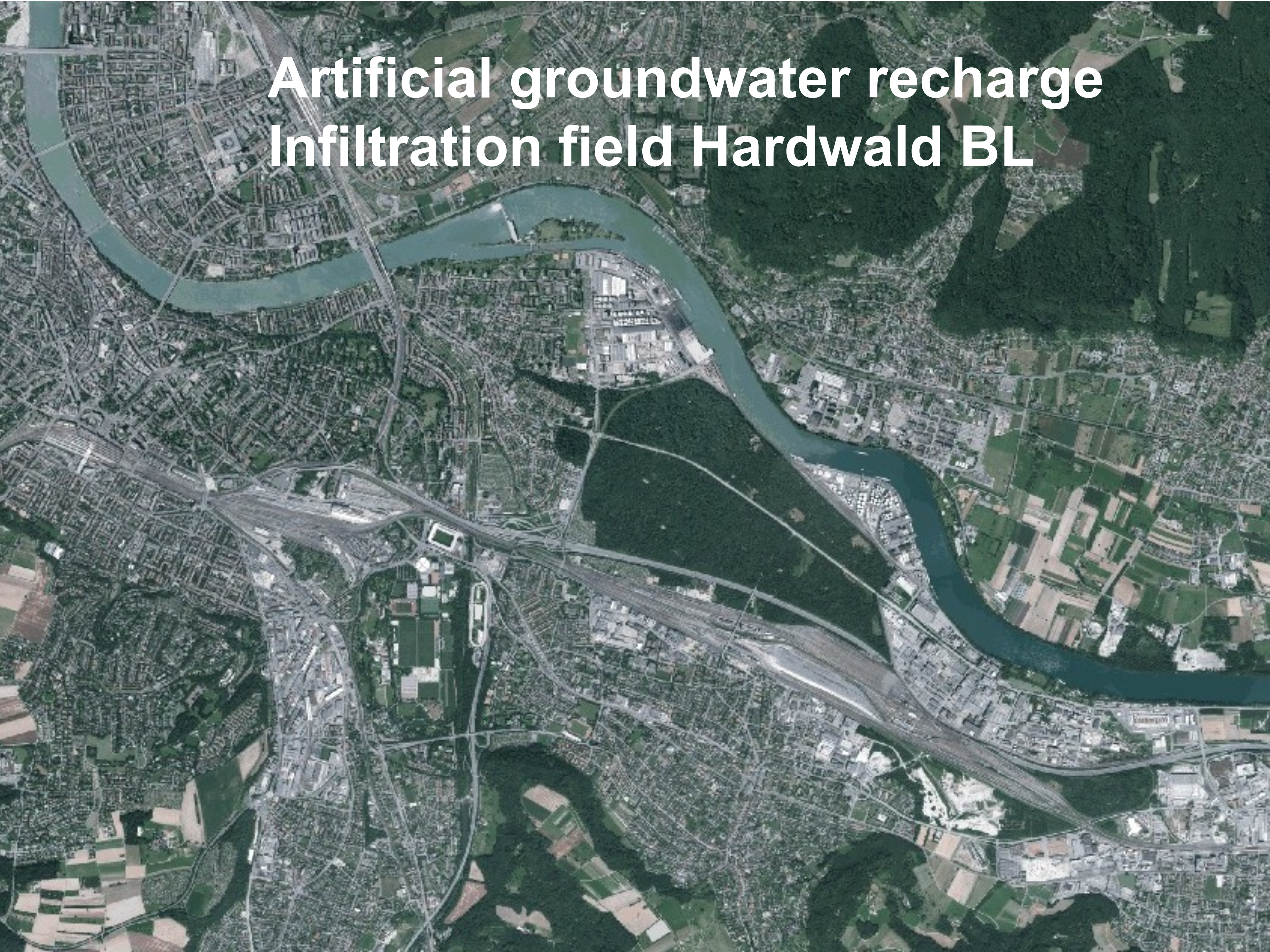
- Milliequivalents (meq, charge units) :
  - – Ca, Mg, SO_4: 1 mmol/L = 2 meq/L
  - – Na, K, NO_3, NH_4, Cl, HCO_3: 1 mmol/L = 1 meq/L
- Degrees of hardness:
  - – **1 fr °H (°F): 10 mg/L $CaCO_3$ (100 g/mol) = 0.1 mmol/L = 0.2 meq/L**
  - – 1 dt °H: 10 mg/L CaO (56 g/mol) = 0.178 mmol/L = 0.357 meq/L

Classification of water hardness

	Total hardness in mmol/L	Total hardness french degrees hardness	Classification
Verzasca	0 - 0.7	0 - 7	very soft
Swiss lakes	0.7 - 1.5	7 - 15	soft
	1.5 - 2.5	15 - 25	medium hard
Groundwater Glattfelden	2.5 - 3.2	25 - 32	quite hard
	3.2 - 4.2	32 - 42	hard
	> 4.2	> 42	very hard

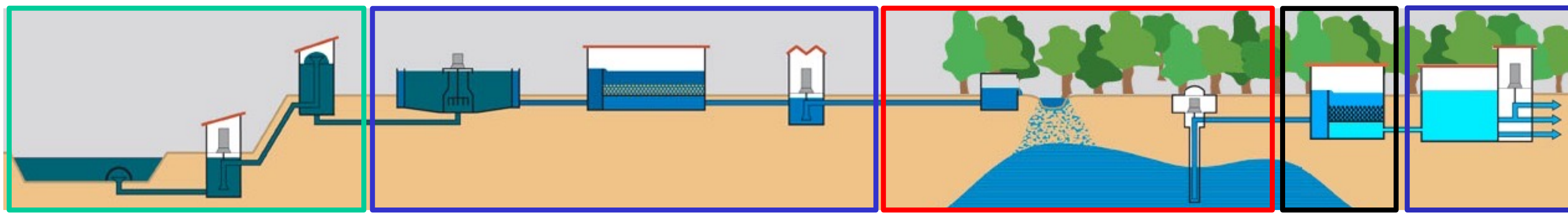
Hardness of groundwaters in Switzerland




Artificial groundwater recharge
Infiltration field Hardwald BL

Infiltration field Hardwald BL

Artificial groundwater recharge: Hardwald, Baselland



1. River Rhine pumping station

2. Pre-treatment
(Sedimentation / Rapid sand filtration)

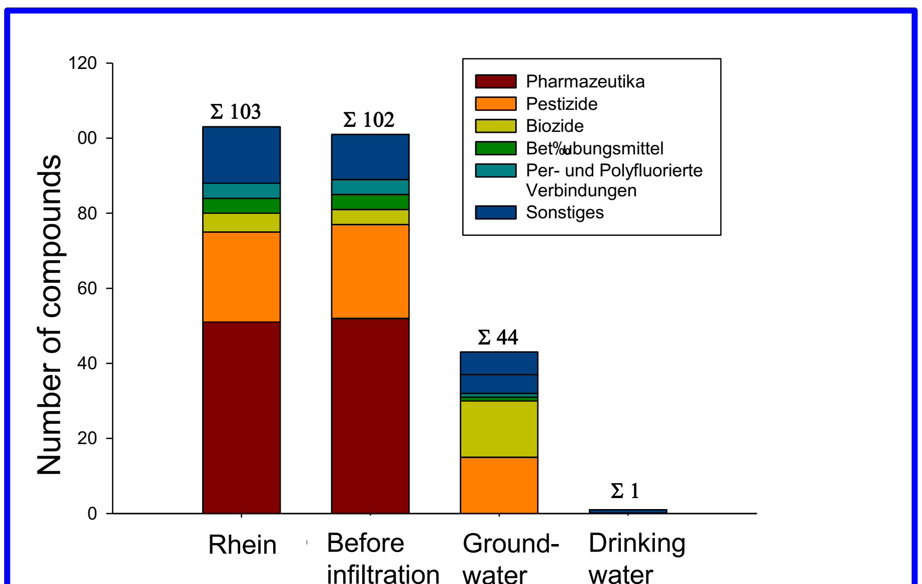
Particle removal

3. Artificial recharge
(Hardwald forest)

Biological treatment

4. GAC Filter UV

5. Distribution



Physical-chemical post-treatment

Rhine river	DOC 1.66 mg/L
Sandfilter	DOC 1.54 mg/L
Groundwater	DOC 0.55 mg/L

Groundwater recharge

- Aerobic groundwater recharge
  - Infiltration of rain water
  - Good aeration (always sufficient oxygen)

  $\Rightarrow$ aerobic respiration ($O_2 + CH_2O \rightarrow CO_2 + H_2O$)

  $\Rightarrow$ Dissolution of limetsone (Increase of hardness)
- Anaerobic groundwater recharge
  - Hydraulic connection
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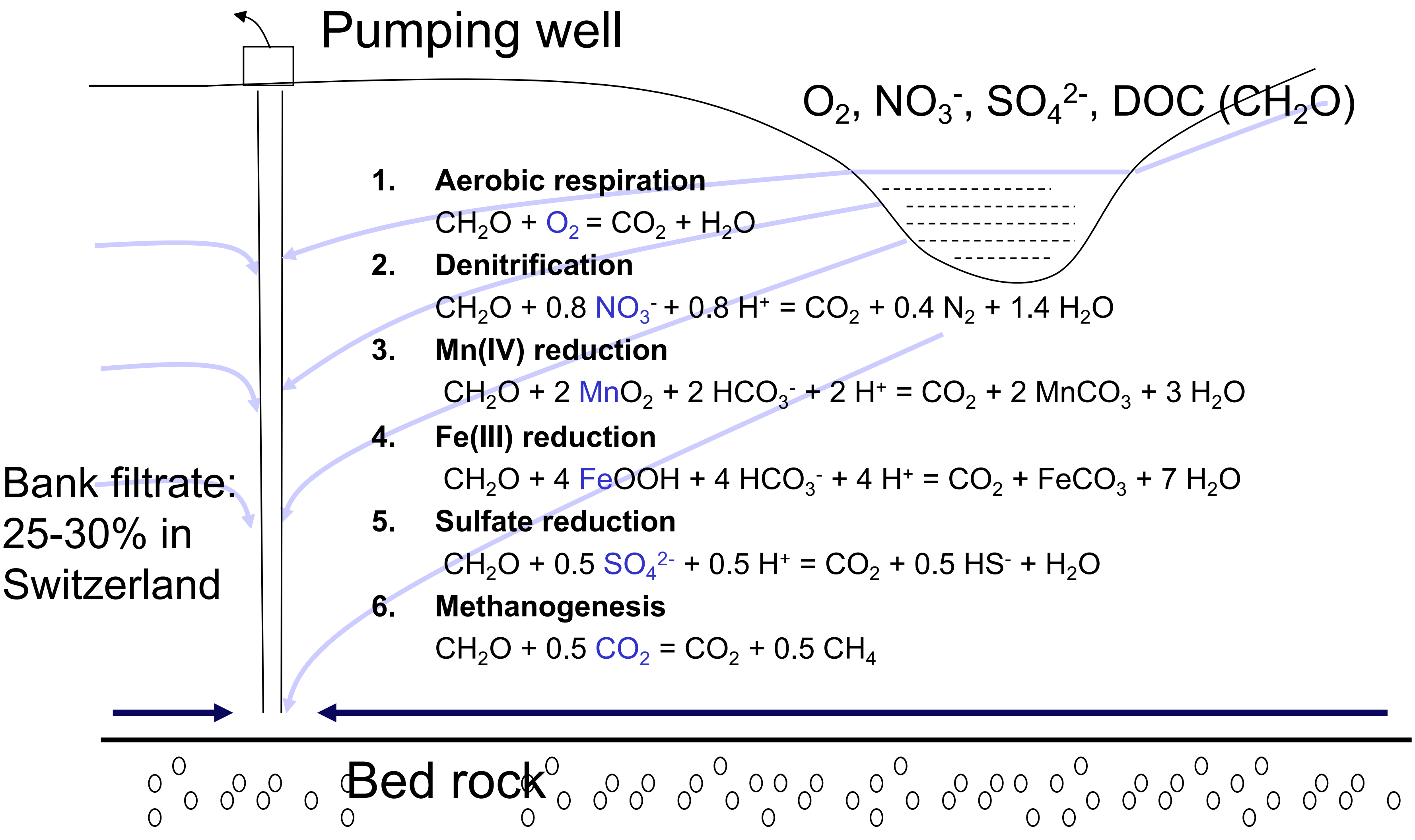
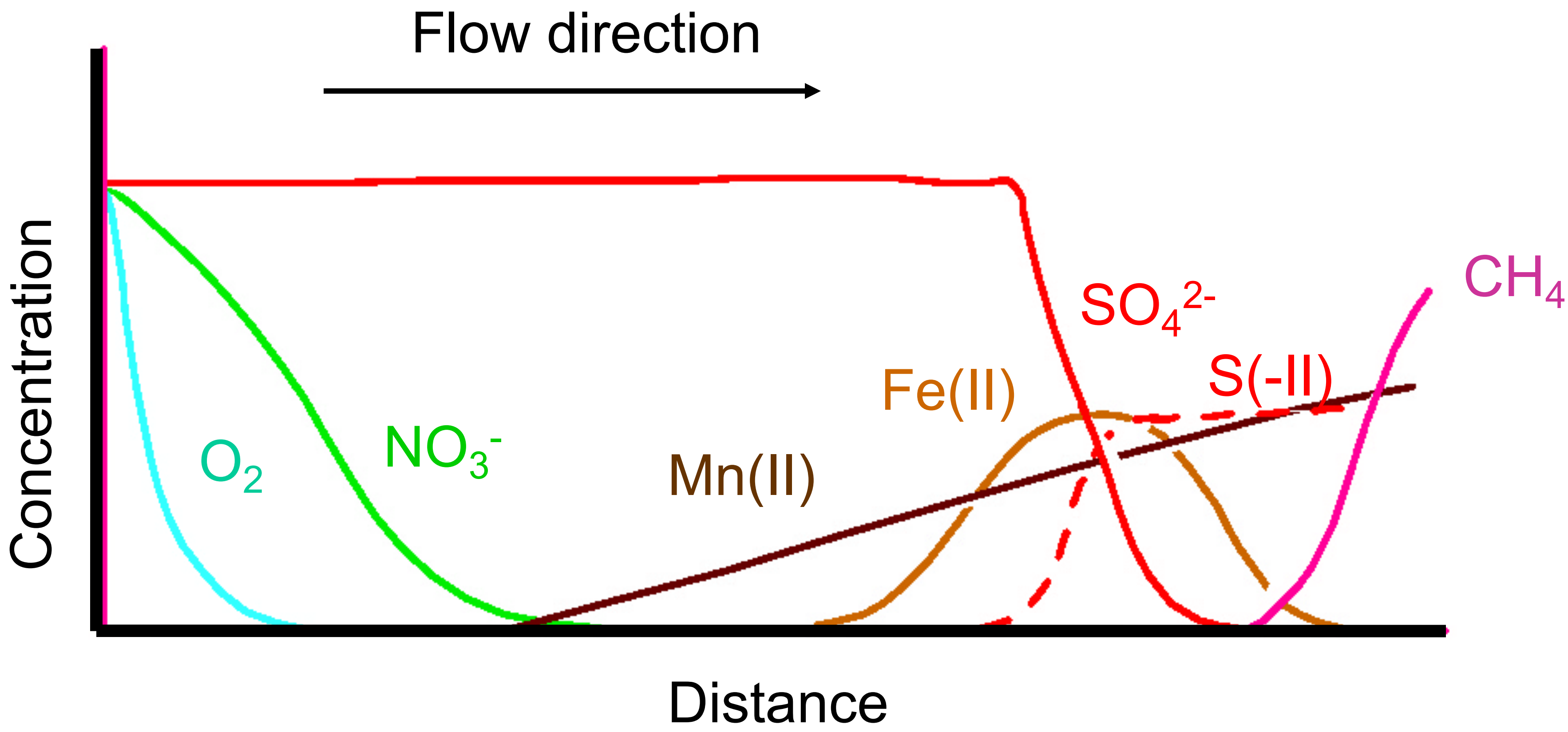
  $\Rightarrow$ Formation of redox zones

Redox processes during riverbank filtration



1. **Aerobic respiration**
   $CH_2O + O_2 = CO_2 + H_2O$
2. **Denitrification**
   $CH_2O + 0.8\ NO_3^- + 0.8\ H^+ = CO_2 + 0.4\ N_2 + 1.4\ H_2O$
3. **Mn(IV) reduction**
   $CH_2O + 2\ MnO_2 + 2\ HCO_3^- + 2\ H^+ = CO_2 + 2\ MnCO_3 + 3\ H_2O$
4. **Fe(III) reduction**
   $CH_2O + 4\ FeOOH + 4\ HCO_3^- + 4\ H^+ = CO_2 + FeCO_3 + 7\ H_2O$
5. **Sulfate reduction**
   $CH_2O + 0.5\ SO_4^{2-} + 0.5\ H^+ = CO_2 + 0.5\ HS^- + H_2O$
6. **Methanogenesis**
   $CH_2O + 0.5\ CO_2 = CO_2 + 0.5\ CH_4$

Infiltration of river water into the subsurface



Reducing conditions: Role of organic matter

A river water infiltrates with a hydraulic connection

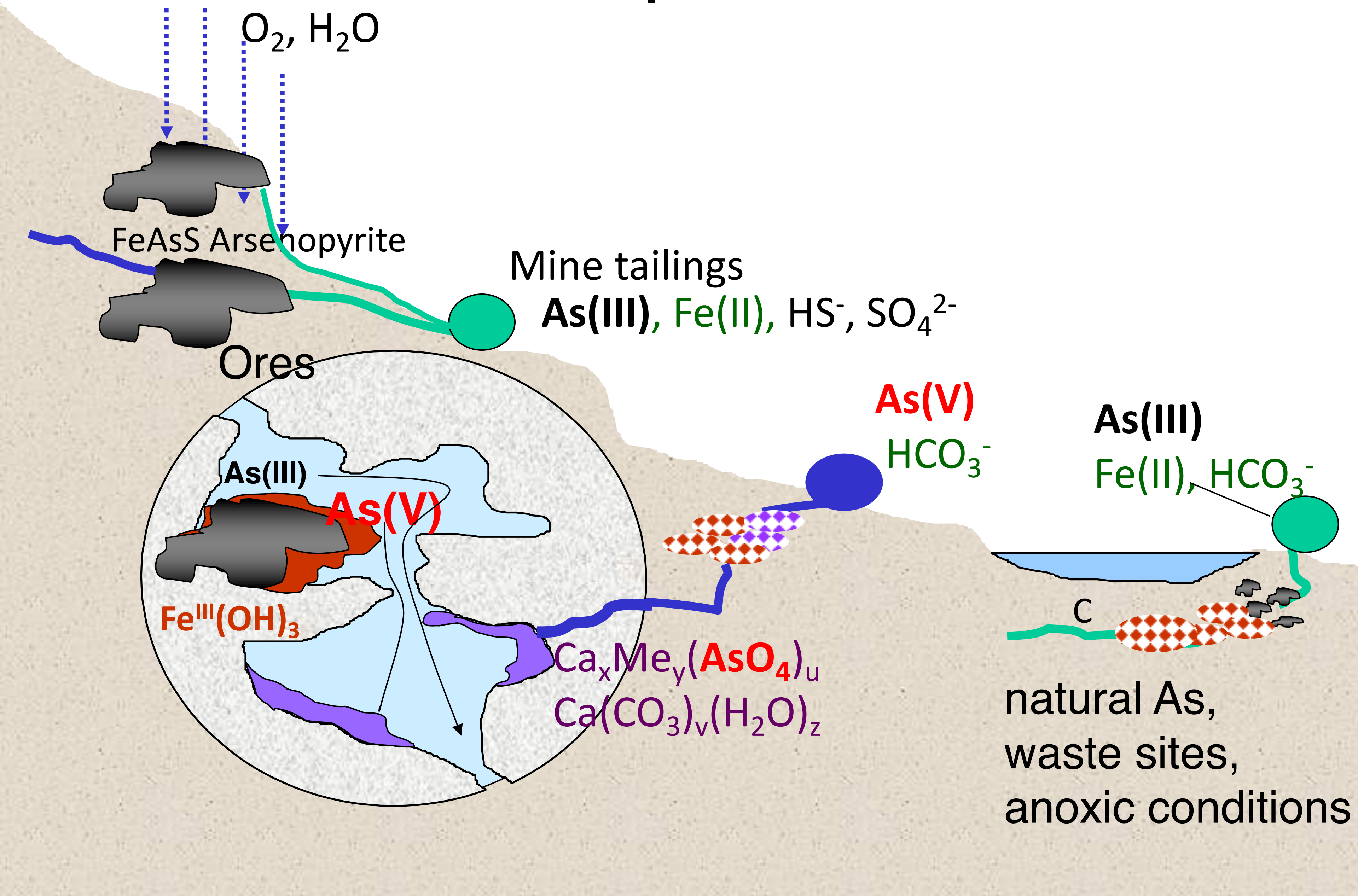
What is the critical concentration of organic matter yielding reducing conditions, if the O_2 concentration in the river is 6 mg/L?

Problematic redox active components (see compilation of drinking water standards)

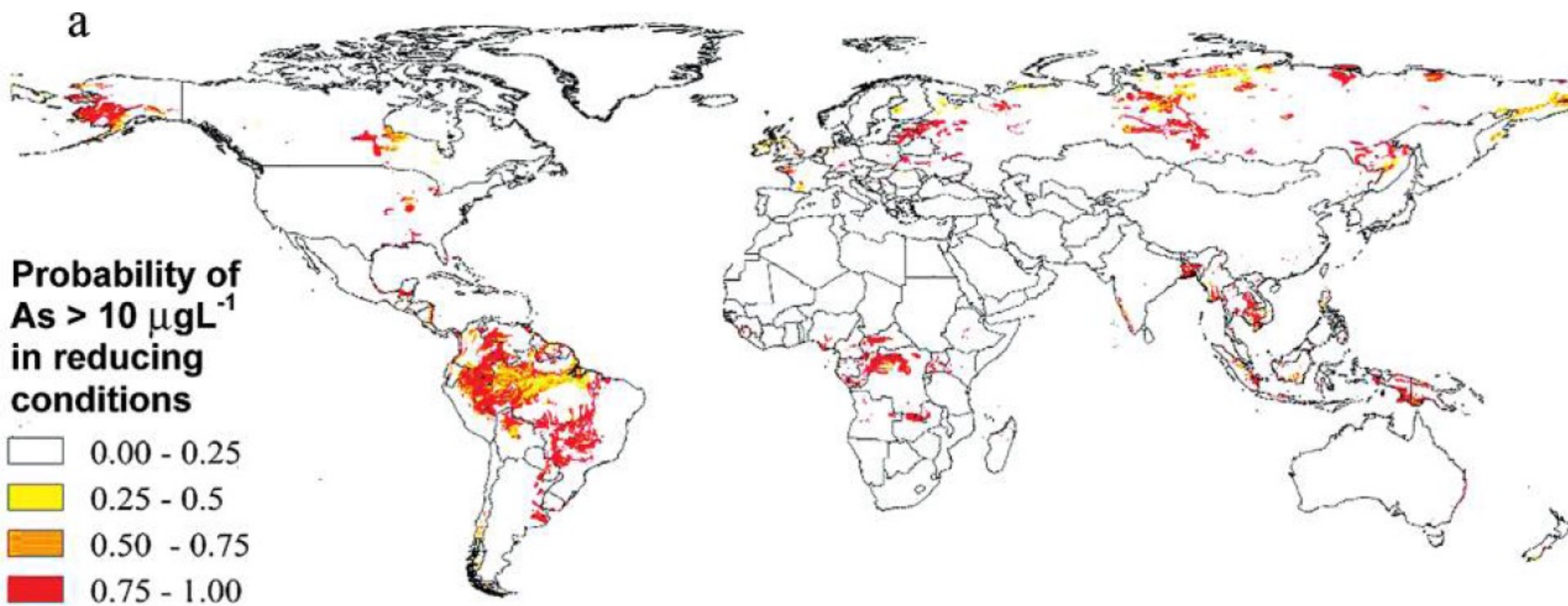
- NO_3^-/NO_2^-: human toxicology
- NH_4^+: Impairment of chlorine disinfection (NH_2Cl formation)
- Mn(II): aesthetics, human toxicology
- Fe(II): aesthetics
- S(-II): aesthetics
- Arsenic: toxicity

Symptoms of Arsenicosis

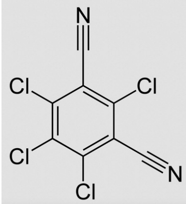
Mobilization of arsenic sources: transformation and transport of arsenic



Arsenic – a widespread geogenic pollutant in groundwater



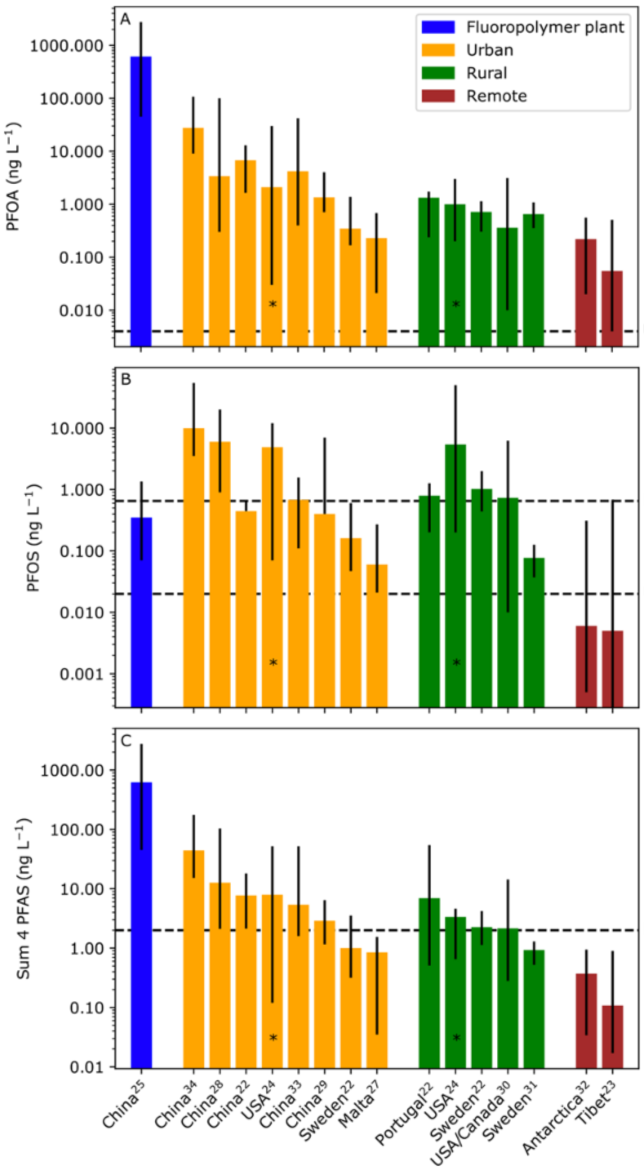
Amini et al. (2008) Environmental Science & Technology 42(10), 3669-3675.



Organic contaminants in groundwater: Chlorothalonil and its metabolites

- Chlorothalonil is a fungicide with widespread application since 1966
- Applied to wheat, grapes, vegetables and flowers
- Chlorothalonil and its metabolites have been recently (2019) detected in many groundwaters in Switzerland (ca. 1 million people are affected in the Swiss Plateau)
- New analytical methods have made this possible
- Often, the concentrations of the relevant metabolites are significantly above the drinking water standard of 100 ng/L
- Some water supplies need to dilute their drinking water with other sources
- Chlorothalonil metabolites are difficult to removed with conventional treatment methods activated carbon or reverse osmosis (RO) are feasible methods, RO produces large volumes of concentrate
- Chlorothalonil has been forbidden end of 2019 as a source control measure, however it will take many years to decades until its metabolites are washed out of the groundwater
- Law suit by Syngenta has been rejected: Drinking water standard of 100 ng/L is legal

PFAS concentrations in rain water

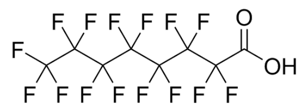


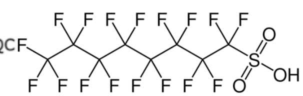
Environmental Science & Technology
pubs.acs.org/est
Perspective

Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS)

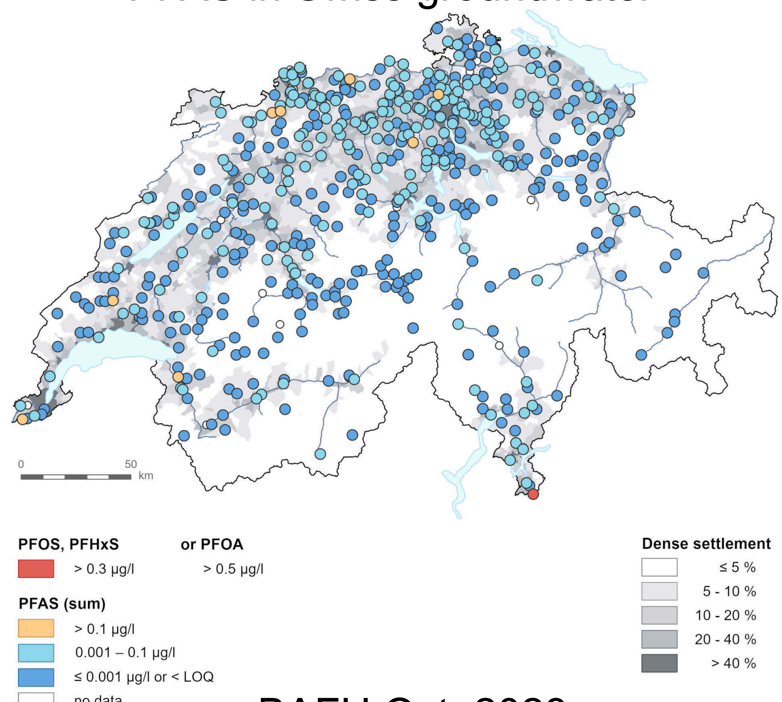
Ian T. Cousins,* Jana H. Johansson, Matthew E. Salter, Bo Sha, and Martin Scheringer

Cite This: Environ. Sci. Technol. 2022, 56, 11172–11179
Read Online





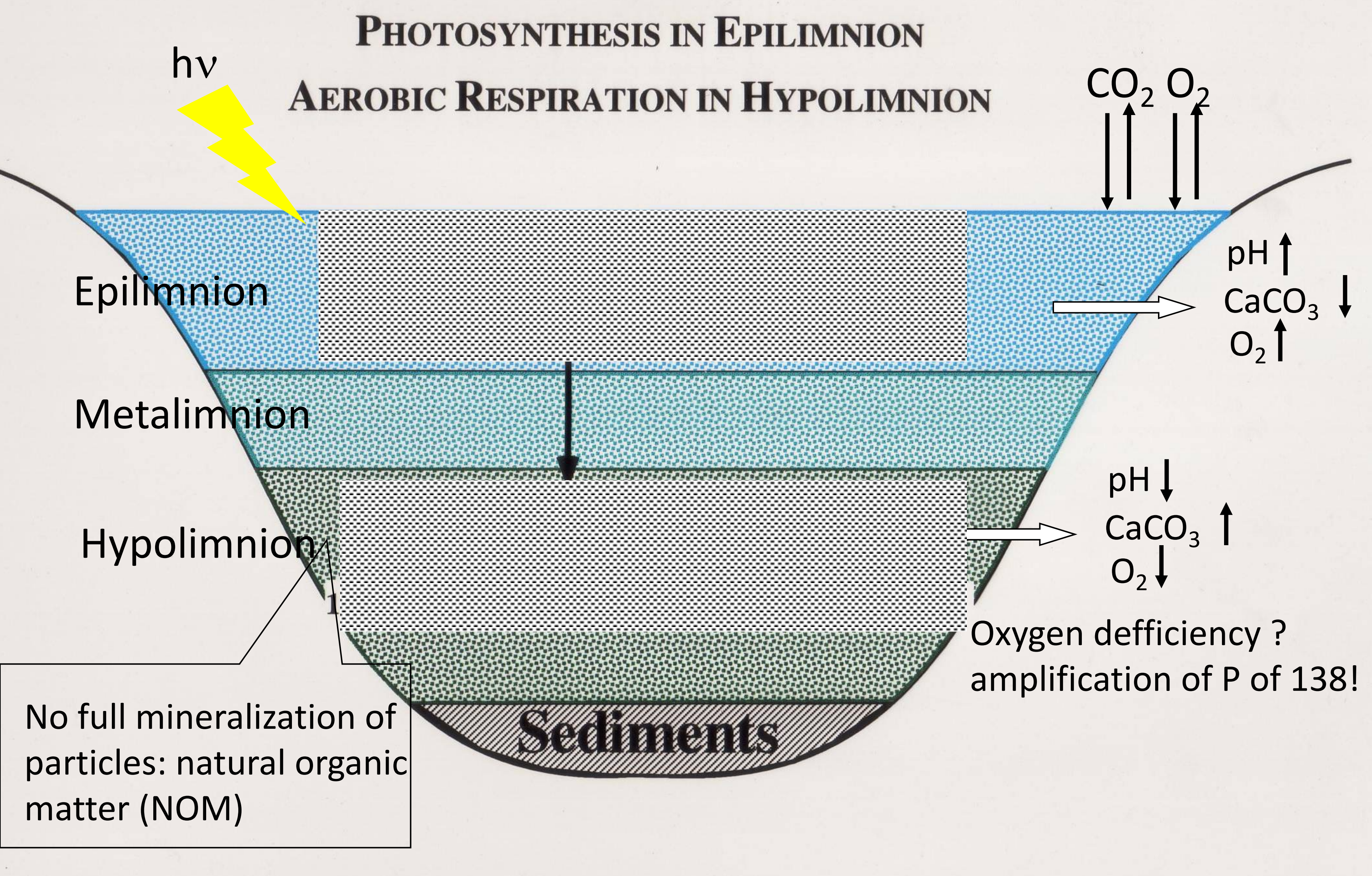
PFAS in Swiss groundwater



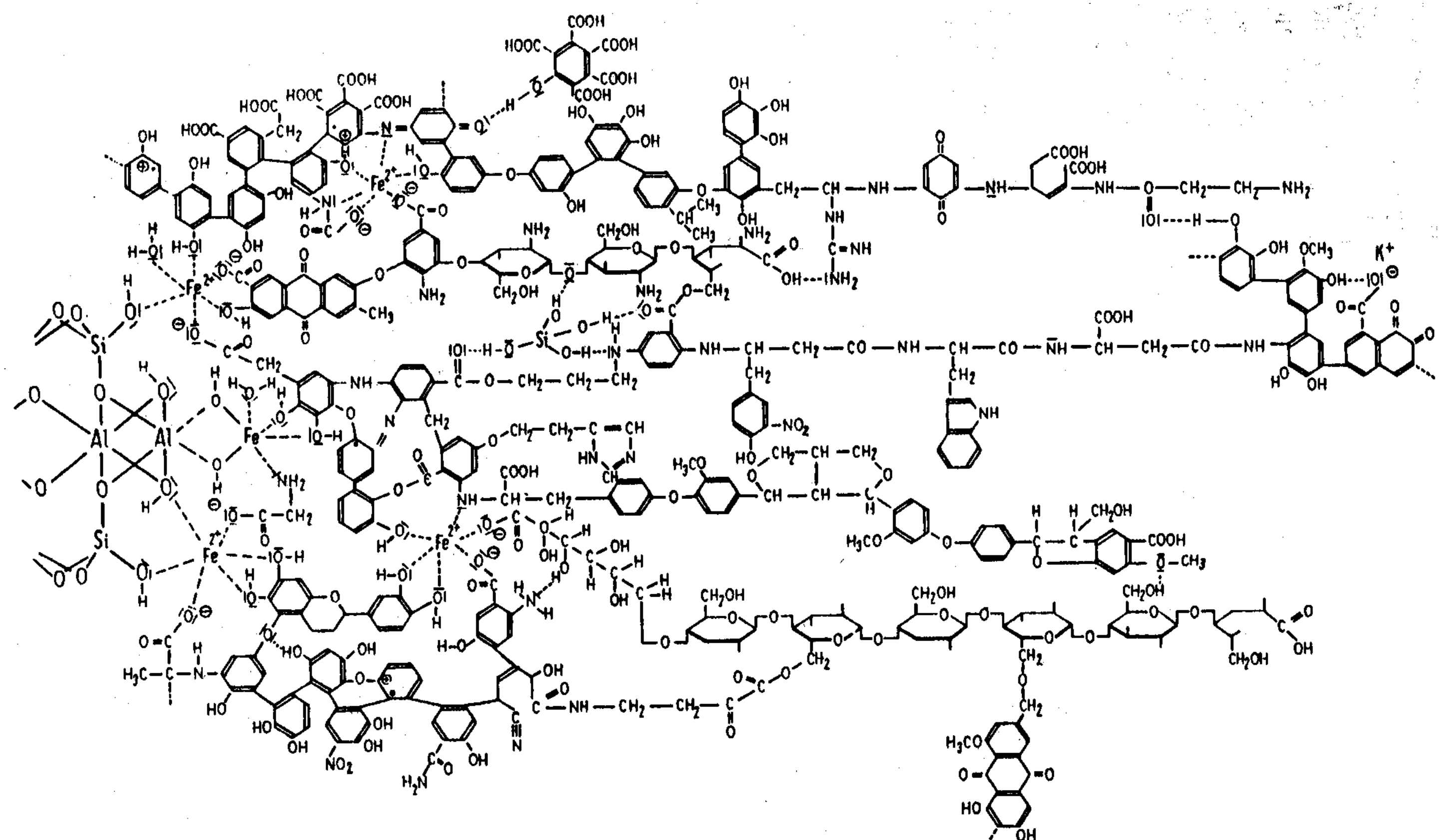
BAFU Oct. 2023

The value of 0.1 µg/l, the EU limit for the sum concentration of 20 PFAS in drinking water, is exceeded at approximately 2% of the NAQUA monitoring sites.
The value of 0.0044 µg/l, which the European Commission proposed as a limit for the (toxicologically weighted) sum concentration of 26 PFAS in groundwater, is exceeded at around 25 % of the NAQUA monitoring sites.

Redox processes in lakes


PHOTOSYNTHESIS IN EPILIMNION
AEROBIC RESPIRATION IN HYPOLIMNION
hν
CO_2 O_2
Epilimnion
Metalimnion
Hypolimnion
pH ↑
$CaCO_3$ ↓
O_2 ↑
pH ↓
$CaCO_3$ ↑
O_2 ↓
Oxygen defficiency ?
amplification of P of 138!
No full mineralization of particles: natural organic matter (NOM)
Sediments

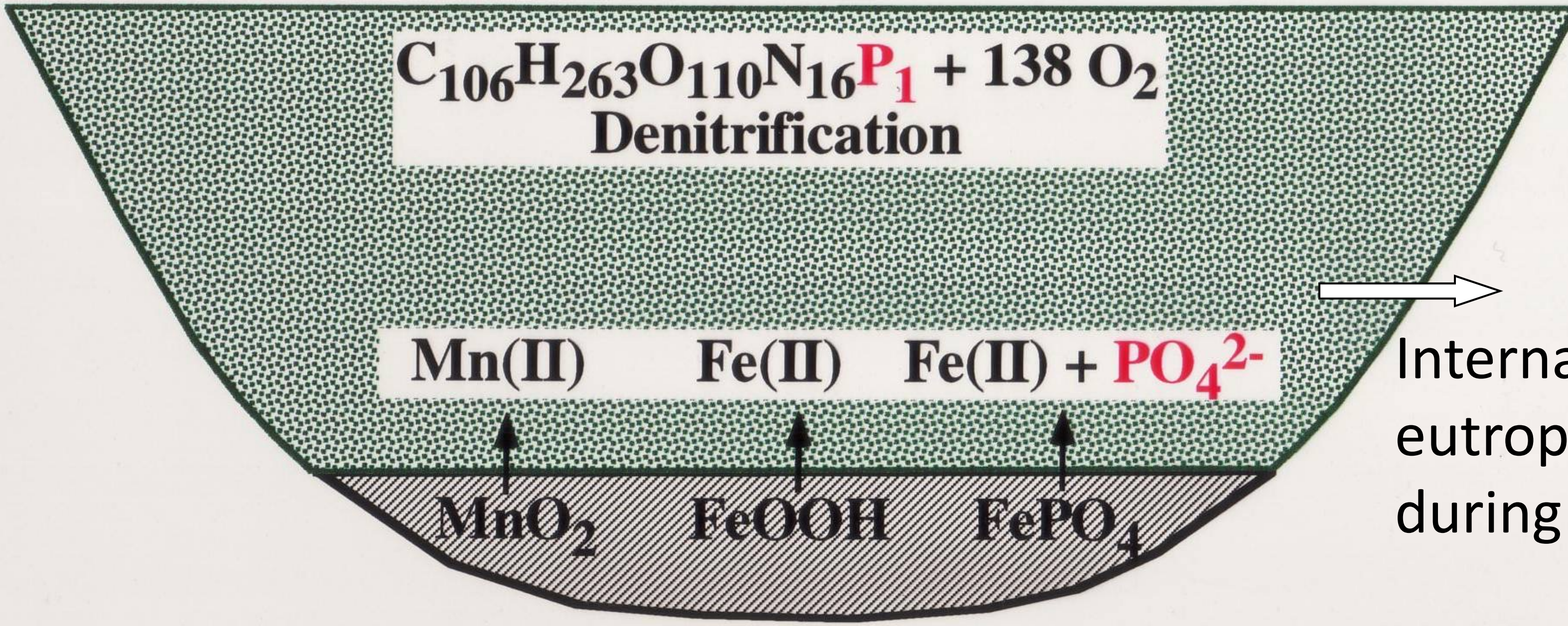
Natural organic matter (NOM)



- Complex mixture of cross-linked organic compounds
- Degradation products/metabolic products of algae/bacteria
- Many different functional groups
- Highly relevant for water treatment

Processes in the Hypolimnion

and at the Sediment-Water Interface



Internal eutrophication during mixing

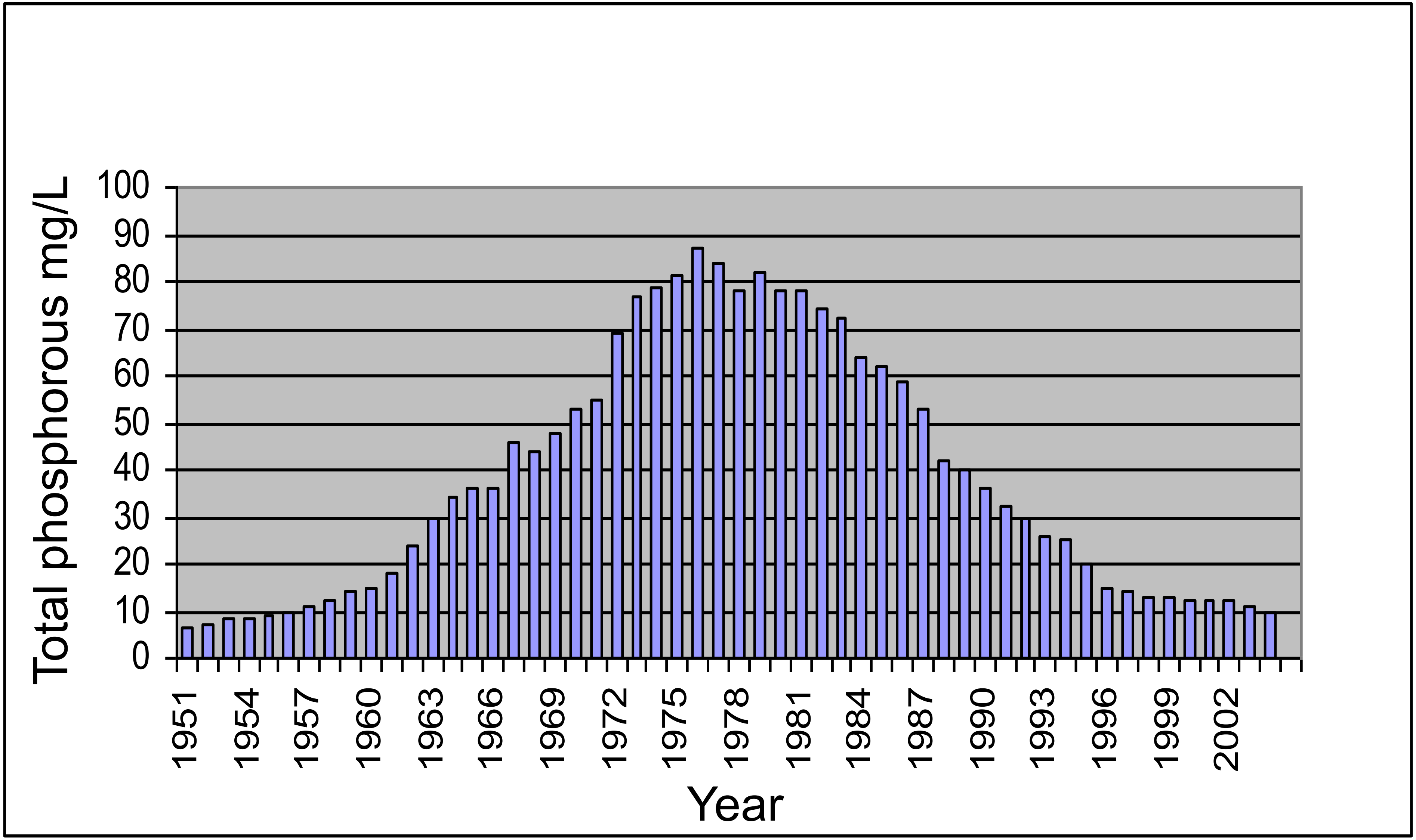
Role of phosphate

- Minimum element for algal growth
- Oxygen consumption in the hypolimnion
- Amplification by P ~ 138!
- Dissolution of Fe and Mn from sediments
- Dissolution of P from sediments
- Internal eutrophication

Measures to restore lakes - external

- No discharge of wastewater (sewer system out of lake basin)
- Phosphate elimination in wastewater treatment plants (legal requirement in CH since 1971)
- Ban of phosphate in textile washing detergents (CH 1986)
- Optimized use of mineral fertilizers

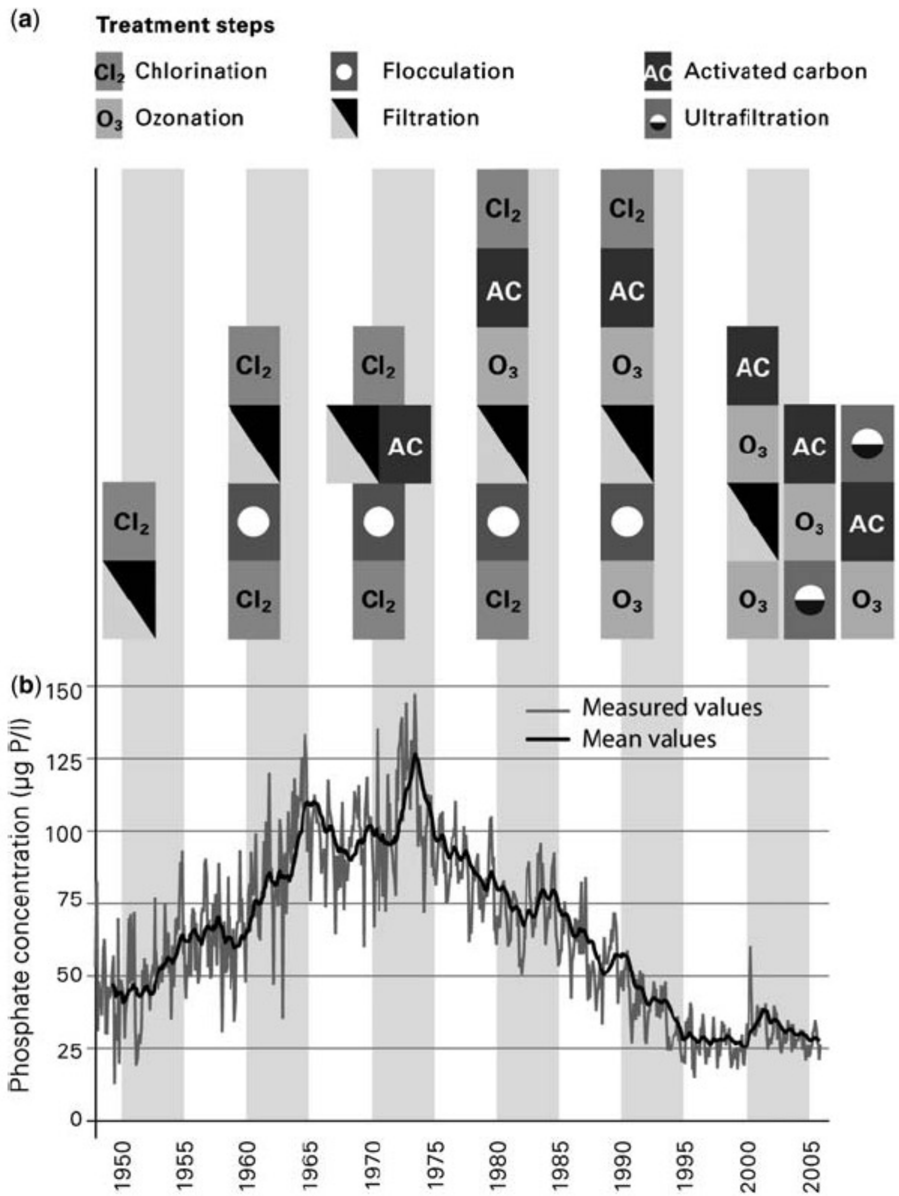
Development of total phosphorous in Lake Constance



Unit processes and process combinations

- Sedimentation
- Filtration
  - Filtration/sand - coagulation (particles-colloids)
  - Membrane filtration (particles – molecules - ions)
  - Activated carbon (particles/adsorption - molecules)
  - Biological filtration (particles/adsorption/degradation)
- Chemical Oxidants
  - Disinfection
  - Chemical Oxidation
- UV-Disinfection
- Process combinations

Development of lake water treatment in Switzerland (Zürich)



Important drivers

Hygiene

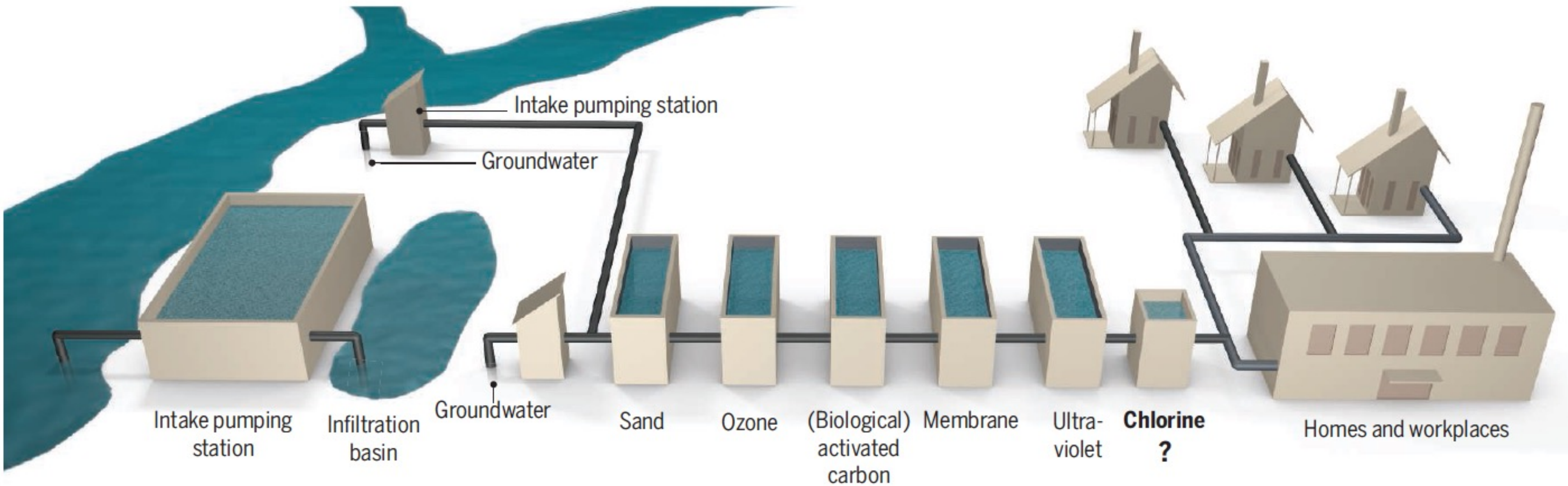
Turbidity

Algal products (e.g. taste and odor, cyano-toxins)

Micropollutants

A. Gmünder, Wabag Water Supply Zurich

Drinking water as a multibarrier system: no or limited residual disinfectant required in distribution system



Protection of water resources
- Active watershed management
- Riverbank filtration
- Artificial recharge
- Groundwater

Water treatment

Multibarrier treatment (ozone, ultraviolet light, advanced oxidation processes, biological filtration, membranes, chlorine)

Distribution system
- Maintain and replace infrastructure
- Water-quality monitoring
- Hydraulic integrity

Article on moodle

Rosario-Ortiz, F., Rose, J., Speight, V., von Gunten, U. and Schnoor, J. (2016) How do you like your tap water? Science 351(6276), 912-914.

Drinking water in Switzerland Multibarrier system

- Water resources protection (Loi sur la protection des eaux, LEaux; Ordonnance sur la protection des eaux, OEaux)
- Water quality and treatment (Loi sur les denrées alimentaires, LDAI; ordonnance sur les substances étrangères et les composants, OSEC; ordonnance sur les denrées alimentaires et les objets usuels, ODAIOUs; ordonance sur l' hygiene, OHyg)
- Maintenance of distribution systems
- Regulations on household materials in contact with drinking water

Regulatory framework

Water resources protection
Ecosystems

CH: LEaux, OEaux (1998)

EU: Water framework directive (2000)

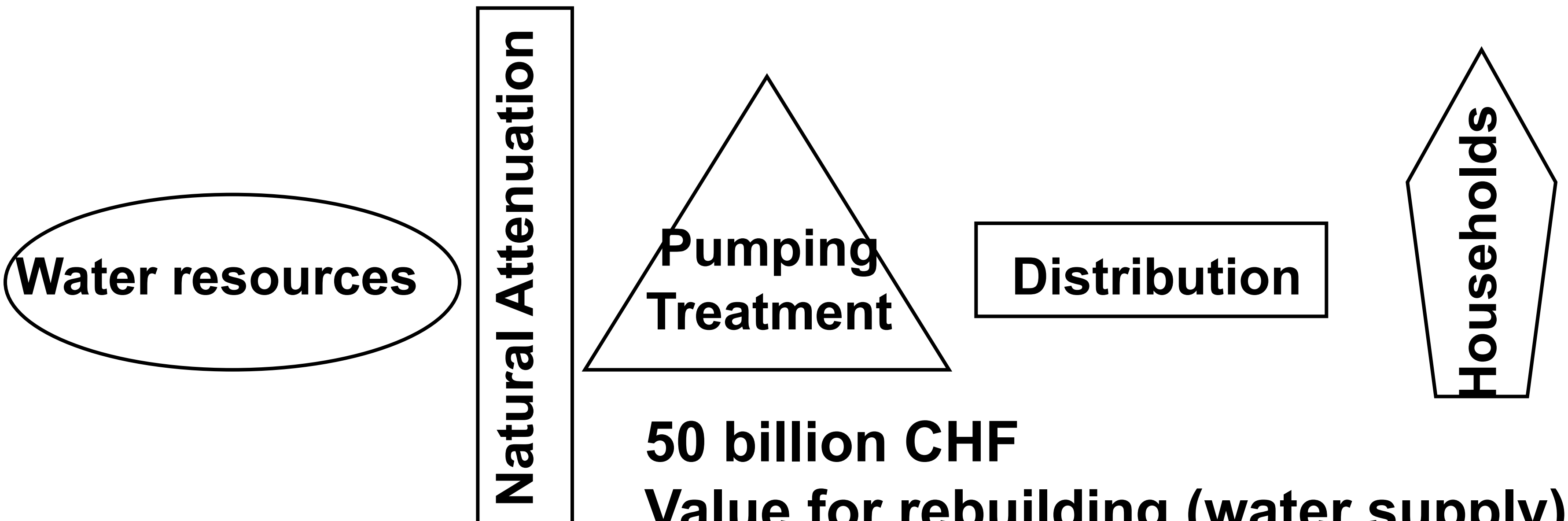
Drinking water regulation
Human toxicology

CH: Ordinance for drinking water

Maximum conc., valeur limit

EU: Drinking water directive (1998)

Parameter-, Indicator values



Drinking water quality

- Hygiene!
- Drinking water has a very high status as food (no free choice)
- Often only small fraction of pollutants from drinking water
- Drinking water standards: Human toxicology/precaution
- 4 pillars: Water resources protection, drinking water treatment, distribution, household
- OECD states: small differences in legislation (Human toxicology vs precaution)