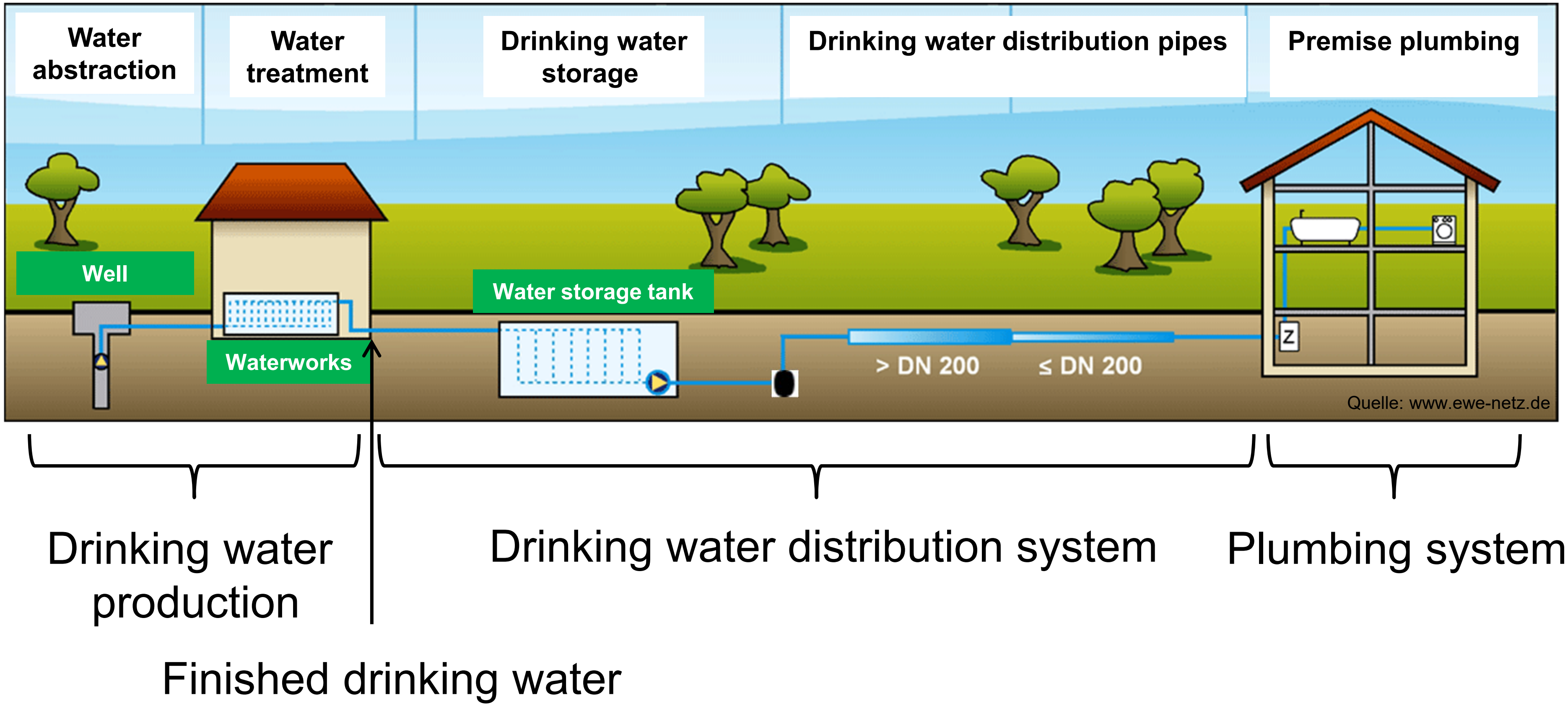
UNIVERSITÄT DUISBURG ESSEN

Open-Minded

From catchment to consumer
Hygienic aspects
(water treatment, disinfection, distribution, biofilms)

Drinking water: from catchment to consumer



Securing microbial safety of drinking water supplies based on the use of sequential, **multiple barriers** from catchment to consumer.

$\Rightarrow$ Prevention of drinking water contamination.

$\Rightarrow$ Minimization of risk to human health.

Drinking water treatment

- **Treatment objectives for the production of safe drinking water from raw water (surface water, groundwater)**

  - Removal of pathogens (high priority)
  - Removal of chemical pollutants
  - Removal of biodegradable compounds $\Rightarrow$ production of biologically stable water, water with low levels of assimilable organic carbon (AOC), that does not promote growth of microorganisms during distribution.

  These processes should be as nearly complete as possible before terminal disinfection!

- **Treatment steps in a waterworks**

  - Because no single treatment process can be expected to remove all of the different types of contaminants, several successive treatment steps are frequently necessary.
  - The number of treatment processes required depend on the quality of the source water.

Schematic overview of a typical community water purification system in the USA (treatment of surface water)

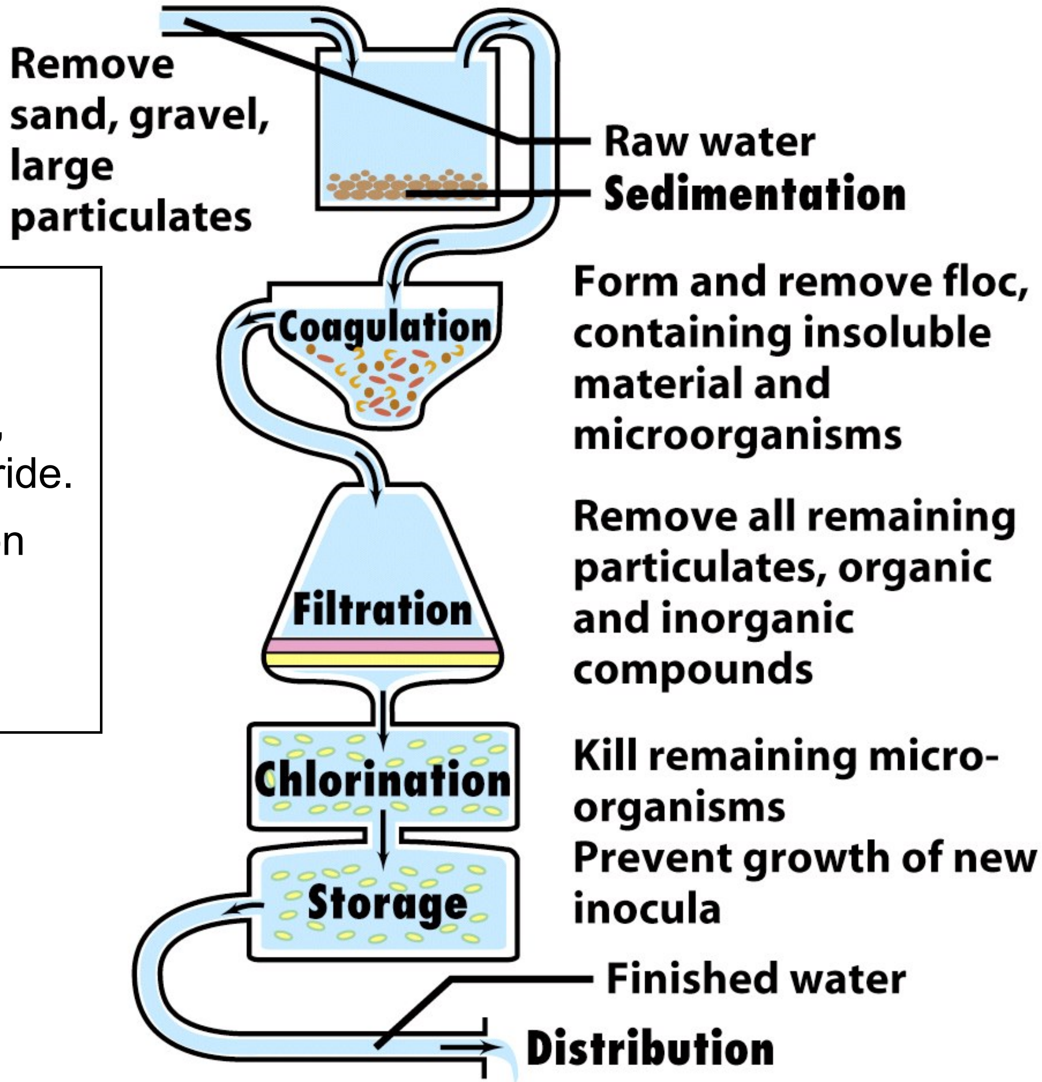


Figure 28-8b Brock Biology of Microorganisms 11/e

Coagulation

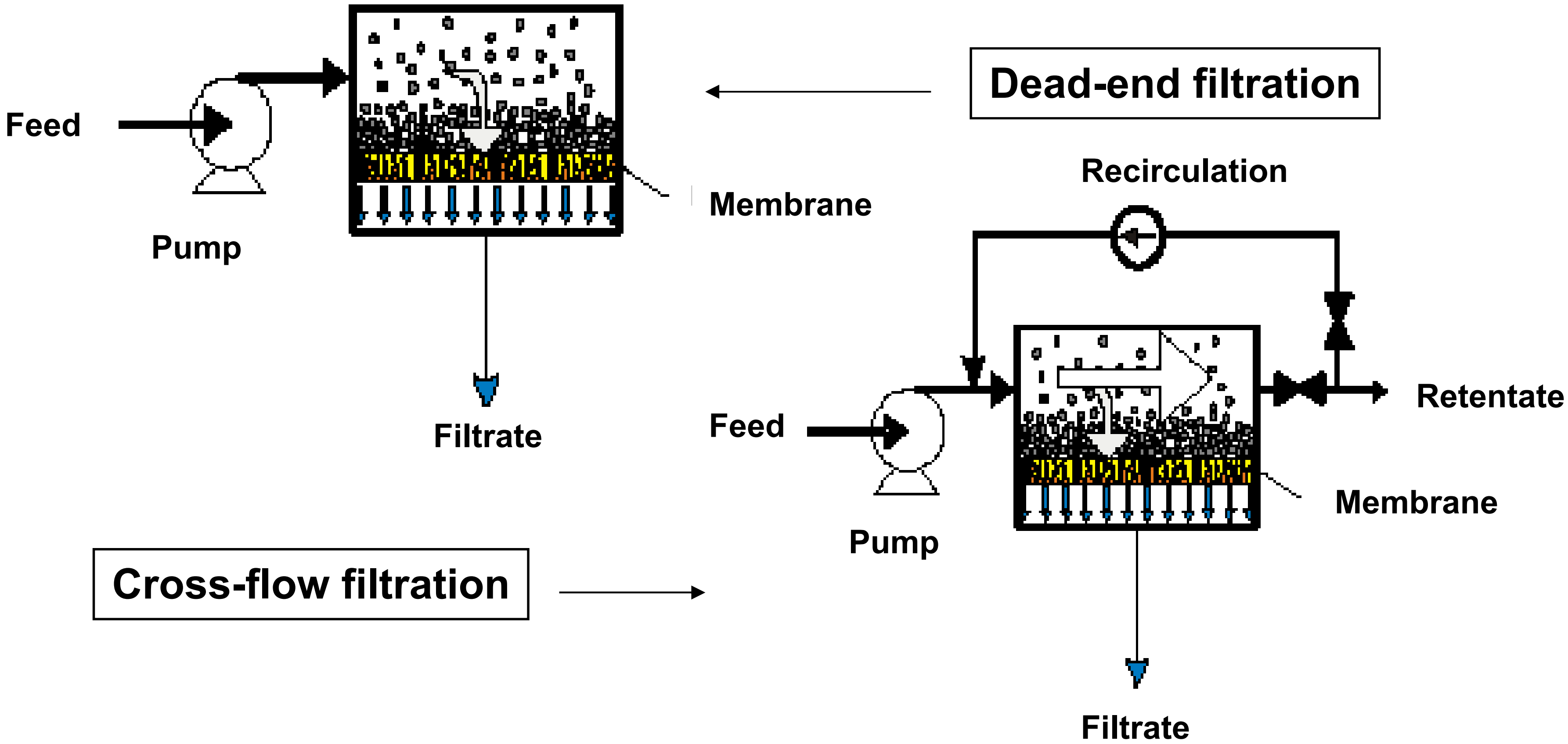
- The most common coagulants are: aluminium sulphate, ferric sulphate, ferric chloride, poly-aluminium chloride.
- Retention of formed flocs by filtration is important because of pathogen accumulation in the flocs to high numbers of hygienic importance.

Filtration

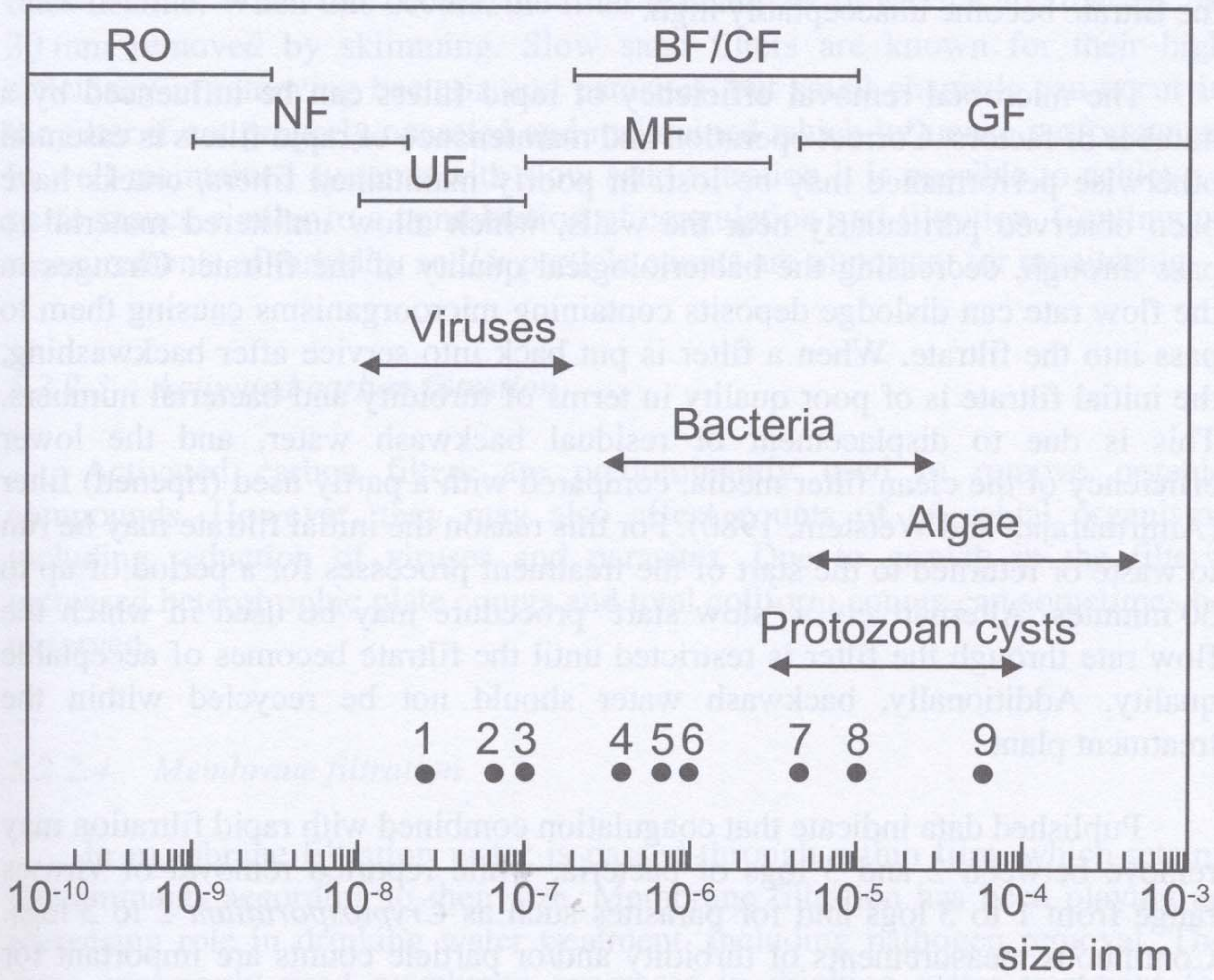
- Slow sand filtration
- Rapid filtration
- Membrane filtration

Membrane filtration

- Water is passed through a membrane, which retains microbial pathogens with sizes greater than membrane pore size.
- Most commonly used membrane processes in drinking water treatment: ultrafiltration and microfiltration.
- Increasingly popular for production of drinking water from groundwater, surface water and seawater.



Filter medium pore sizes and size of microbial particles



Key:
RO: reverse osmosis. NF: nanofiltration. UF: ultrafiltration. MF: microfiltration. BF/CF: bag and cartridge filters. GF: granular filtration including slow sand filtration (slow sand filters have lower pore sizes than rapid-rate filters)
1. MS2 bacteriophage. 2. Rotavirus. 3. PRDI bacteriophage. 4. *Mycobacterium avium* complex (represents smallest size). 5. *Yersinia* spp. 6. Coliform bacteria. 7. *Cryptosporidium* oocysts. 8. *Giardia* cysts. 9. *Balanthidium coli* cysts.

(Stanfield et al., 2003)

Removal of hygienically relevant microorganisms

Treatment step	Removal efficiency
Coagulation and sedimentation	Bacteria: 0.2 – 2 logs (40 – 99 %) Viruses: below 1 log *Cryptosporidium* oocysts: up to 2 logs
Coagulation combined with rapid filtration	Bacteria: 2 – 3 logs Viruses: 1 – 3 logs *Cryptosporidium* oocysts: 2 – 3 logs
Slow sand filtration	Similar to combination of coagulation and rapid filtration
Membrane filtration	Bacteria, viruses, parasitic protozoa: up to 6 logs

Pathogen-elimination barriers in drinking water treatment plants either remove or kill microorganisms.
- Removal: chemical coagulation and flocculation, different types of filtration,
- Killing: disinfection such as chlorination, and ultraviolet (UV) light.

Disinfection

Water treatment preceding terminal disinfection should be capable of producing water of high microbiological quality, so that disinfection becomes a final safeguard.

Disinfection: Elimination of **pathogens** with the aim to prevent the transmission of pathogens.

Sterilization: Killing or removal of **all organisms** and their viruses.

- A limited number of inorganic oxidants are in use for disinfection of drinking water.
- Chlorination (addition of chlorine): widespread method of water disinfection.

Aim of drinking-water disinfection

- Killing or inactivation of **pathogens**, so that risk of infection is excluded during drinking water distribution and during drinking water storage.
  (Target: obligate and facultative pathogens)
- In addition, levels of „unspecific“ microorganisms should be reduced
  $\Rightarrow$ prevention of regrowth in the distribution network.
  (Target: nuisance organisms)

Nuisance organisms

- Non-pathogenic organisms, which are undesirable, because they produce turbidity, taste-, odor- and colour-producing substances (aesthetically objectionable).
- They indicate deficits in water treatment as well as in the state of maintenance and repair of the distribution system.

Relevant chemical disinfectants of drinking water

(Data for dosage and limiting values given for Germany)

Disinfectant	Permissible dosage (mg/L)	Limiting value after treatment (mg/L)	Reaction products (examples)
Chlorine	1.2 (Cl_2)	0.3	THM[1)]
Sodium hypochlorite	1.2 (Cl_2)	0.3	THM[1)]
Calcium hypochlorite	1.2 (Cl_2)	0.3	THM[1)]
Chlorine dioxide	0.4 (ClO_2)	0.2	Chlorite
Ozone[2)]	10 (O_3)	0.05	Bromate

[1)] THM, trihalomethanes (e.g. chloroform $CHCl_3$).

[2)] Use of ozone is limited to oxidation/disinfection during water treatment (ozone decays rapidly in water $\Rightarrow$ no stable residual in water).

Monochloramine (NH_2Cl):

- In some countries (Europe, USA), applied as a drinking water disinfectant.
- In Germany, not permitted as a disinfectant.

Disinfectant concentration and contact time

Inactivation of pathogens by disinfectants increases with time and ideally should follow first-order kinetics.

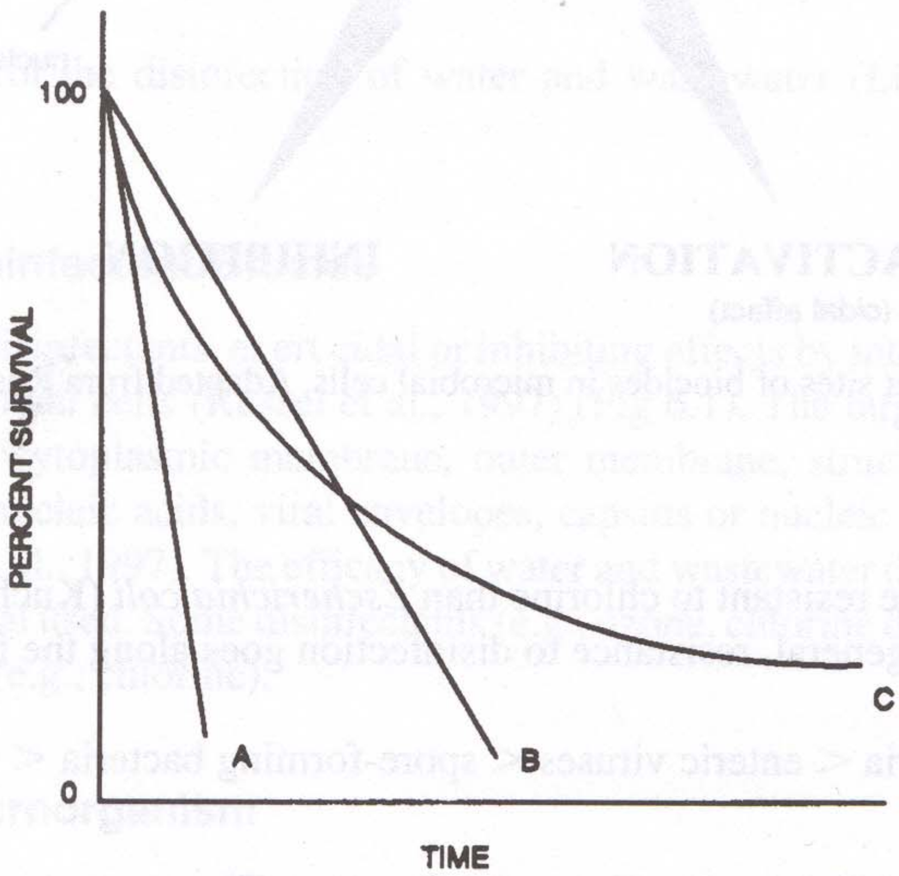


Figure 6.2 Inactivation curves of microorganisms after disinfection. **(A)** Sensitive homogeneous population. **(B)** More resistant homogeneous population. **(C)** Heterogeneous population or partially protected by aggregation. From Hoff and Akin (1986).

Disinfectant concentration and contact time

Relationship between disinfectant concentration and contact time
$\Rightarrow$ Chick-Watson law

$$\mathbf{K = C^n \cdot t}$$

K: Constant for a given microorganism exposed to a disinfectant under specific conditions
C: Residual disinfectant concentration (mg/L)
t: Time required to kill a certain percentage of the population (min)
n: Constant (coefficient of dilution); in most cases n equals 1

$\Rightarrow$ disinfection effectiveness expressed as Ct

Reaction kinetics are affected by

- water temperature
- pH value

Examples for Ct values

TABLE 6.1. Microbial Inactivation by Chlorine: *Ct* Values (Temperature = 5 C°; pH = 6.0)

Microorganism	Chlorine Concn (mg/L)	Inactivation Time (min)	*Ct*
Escherichia coli	0.1	0.4	0.04
Poliovirus I	1.0	1.7	1.7
Entamoeba histolytica cysts	5.0	18	90
Giardia lamblia cysts	1.0	50	50
	2.0	40	80
	2.5	100	250
Giardia muris cysts	2.5	100	250

Adapted from Hoff and Akin, 1986.

Ct values for virus inactivation (USEPA, 1999)

Disinfectant	Units	Inactivation 2-log	3-log	4-log
Chlorine[1]	mg min/l	3	4	6
Chloramine[2]	mg min/l	643	1 067	1 491
Chlorine dioxide[3]	mg min/l	4.2	12.8	25.1
Ozone	mg min/l	0.5	0.8	1.0
UV	mW s/cm^2	21	36	not available

1. Values based on a temperature of 10 °C, pH range 6 to 9, and a free chlorine residual of 0.2 to 0.5 mg/l.
2. Values based on a temperature of 10 °C and a pH of 8.
3. Values based on a temperature of 10 °C and a pH range of 6 to 9.

Chlorine

- **Chlorine chemistry**

  Chlorine gas introduced in water: $Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^-$
  Sodium hypochlorite in water: $NaOCl + H_2O \leftrightarrow HOCl + OH^- + Na^+$
  Dissociation of HOCl in water: $HOCl \leftrightarrow H^+ + OCl^-$

  HOCl: hypochlorous acid; OCl^-: hypochlorite ion

- **Role of pH value**

  pH controls the amount of HOCl and OCl^- in solution; HOCl is 80 times more effective than OCl^- for *E. coli*.

  For disinfection with chlorine, Ct increases with pH, while chlorine dioxide is generally more efficient at higher pH value.

Chlorine

Toxicological aspects of chlorine by-products

- Trihalomethanes (THM; chloroform, bromodichloromethane, dibromochloromethane, bromoform), halogenated acetonitriles and certain chlorohydroxyfuranones: suspected mutagens or carcinogens.

- Evidence of an association between chlorination of drinking water and increased risk of colon and bladder cancer (association is stronger for consumers who have been exposed to chlorinated water for more than 15 years).

- Possible association of water chlorination with increased risk of cardiovascular diseases.

Chlorine dioxide

Chlorine dioxide must be generated at the site of application:

$2\ NaClO_2 + Cl_2 \rightarrow 2\ ClO_2 + 2\ NaCl$

In alkaline solution, it forms chlorite and chlorate:

$2\ ClO_2 + 2\ OH^- \rightarrow ClO^{2-} + ClO^{3-} + H_2O$

Chlorite and, to a lesser extent, chlorate are of health concern, since they combine with hemoglobin to cause methemoglobinemia.

Chloramination

- **Chloramination**: disinfection of water with chloramine; several benefits such as lower THM concentrations, lower coliform regrowth in distribution pipes, improved maintenance of disinfectant residual; although less effective than chlorine, more effective in controlling biofilm microorganisms.

- **Chloramine chemistry**

Monochloramine formation:	$NH_3 + HOCl \rightarrow NH_2Cl + H_2O$
Dichloramine formation:	$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$
Trichloramine formation:	$NHCl_2 + HOCl \rightarrow NCl_3 + H_2O$

Chloramination

- The proportion of the three forms of chloramines depends on the pH of the water.
- Monochloramine is the predominant chloramine at the pH range of drinking water (pH 6 – 9).
- Toxicological aspects:
  Formation of mono-chloramine is desirable because di- and trichlor-amines cause unpleasant taste and odor; chloramines cause hemolytic anemia in kidney hemodialysis patients.

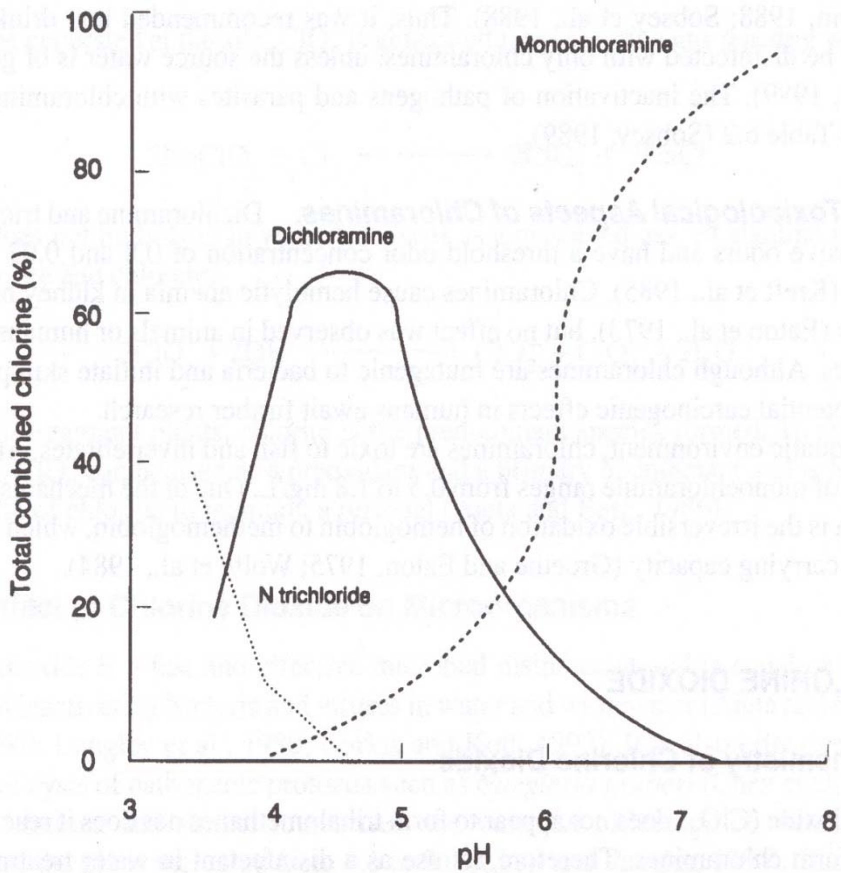


Figure 6.10 Distribution of chloramine species with pH. From Wolfe et al. (1984). (Courtesy of the American Water Works Association.)

UV (ultraviolet) disinfection of drinking water

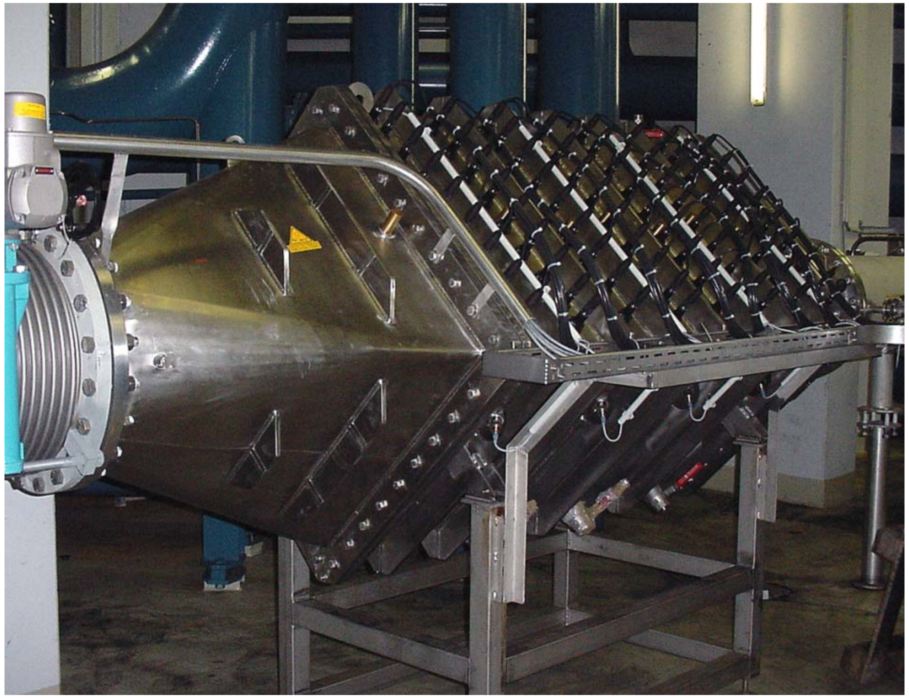
- UV irradiation disinfection systems:

  - Low-pressure mercury lamps enclosed in quartz tubes, immersed in flowing water.

  - Transmission of UV by quartz decreases upon continuous use; quartz lamps must be regularly cleaned, using mechanical, chemical and ultrasonic cleaning methods.

- Mechanism:

  UV irradiation damages microbial DNA at a wavelength of 254 nm.



UV water treatment device,
Waterworks Styrum-Ost,
Mülheim an der Ruhr
Source: Bundermann, 2005

UV (ultraviolet) disinfection of drinking water

Advantages:

- Efficient inactivation of bacteria and viruses in drinking water,
- No production of undesirable mutagenic/carcinogenic or toxic by-products,
- No taste and odor problems,
- No need to handle and store toxic chemicals.

Disadvantages:

- No disinfectant residual in treated water (in contrast to chemical disinfection such as chlorination),
- Problems in maintenance and cleaning of UV lamps,
- UV-treated bacteria can undergo repair after UV irradiation.

Factors that determine survival of microorganisms in the presence of disinfectants

- Type and state of microorganism (tolerance/resistance properties)
  - group and physiological state of microorganism
  - physical state (planktonic, cell aggregates, biofilms)
- Choice of disinfectant
- Contact time
- Concentration of disinfectant
- Abiotic factors
  - water temperature
  - pH value
  - redox potential
  - turbidity
  - inorganic and organic substances

Relative microbial susceptibility to chemical disinfectants

least resistant

- Enveloped virus
- Gram-positive bacteria
- Non-enveloped virus
- Fungi
- Gram-negative bacteria
- Prokaryotic-eukaryotic interactions
- Mycobacteria
- Spores
- Cysts
- Oocysts
- Prions

- Free cells
- Aggregates
- Attached cells
- Biofilms

most resistant

Biofilms are 100- to 1000-fold more tolerant or resistant compared to planktonic cells.

Morató et al., 2003

Elimination of microorganisms from water

Procedure	Microorganisms Inclusive Pathogenic Agents					
	Single, Freely Suspended			In Particles of Fecal Origin **Cellular aggregates, biofilms**		
	Bacteria	Viruses	Parasites	Bacteria	Viruses	Parasites
Filtration*	+	+	+	+	+	+
Disinfection						
Chlorine, chlorine dioxide	+	+	–	–	–	–
Ozone	+	+	(+)∅	–	–	–
UV light	+	+	(–)°	–	–	–
Thermal (>90 °C)	+	+	+	+	+	+

\+ Microorganisms including causative agents of diseases can be eliminated reliably.

– Elimination of microorganisms including causative agents of diseases not guaranteed.

* Filtration is hygienically sufficient, if the colony count in the filtrate is $<100\ mL^{-1}$ and *E. coli* as well as coliform organisms are not detectable in 100 mL.

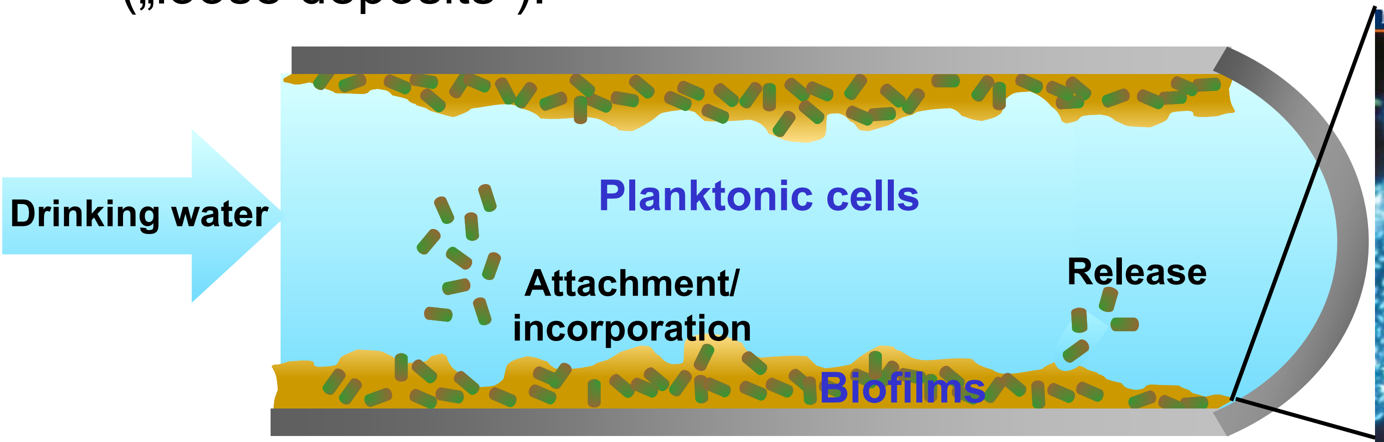
∅ Ozone has shown a quite good effect against parasites in laboratory examinations when the concentration was high and the contact time was long. Experiences in practice is still missing for a final judgement.

° UV light may possibly kill parasites as well as bacteria and viruses as early investigations show (SCHOENEN et al., 1997).

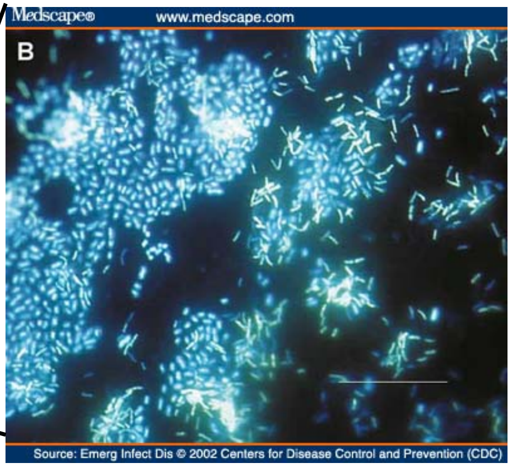
Source: Schoenen, 2000

Distribution of microorganisms in drinking water systems

- Finished drinking water is not sterile.
- Distribution of microorganisms: about 2 % to 5 % of all cells are in the bulk water, and the vast majority live in biofilms and attached to particles („loose deposits“).



Source: M. Moritz, Biofilm Centre, UDE



Drinking water biofilm on steel surface

Phase	Total cell count (microscopy, flow cytometry)	Fraction of viable cells	Fraction of culturable bacteria (HPC)
Water	10^3 - 10^5 cells/ml	up to 98 %	0.001 - 1 %
Biofilms	10^4 - 10^8 cells/cm²	up to 80 %	0.001 - 1 %

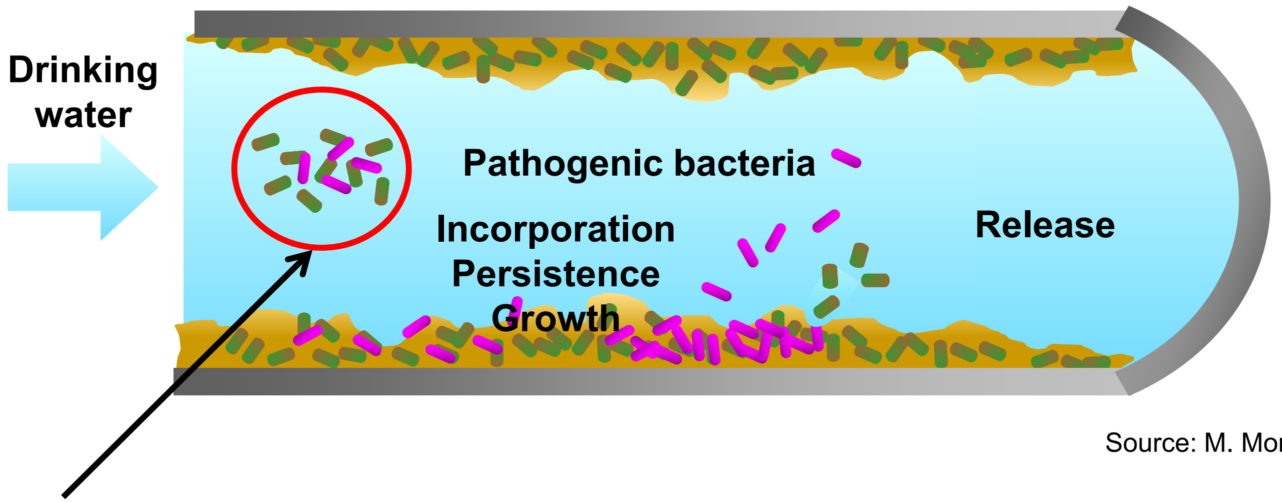
Diversity: drinking water microbiomes

Microbiome: The total of all microorganisms and their collective genetic material present in a distinct environment.

Quantification and characterization of microbiomes are mainly based on molecular methods: Fluorescence in situ hybridization, analysis of clone libraries, qPCR, high-throughput sequencing (next-generation sequencing)

Categories	**Commonly found bacteria in drinking water distribution systems (water, biofilms)**
Predominant phyla	Proteobacteria, Actinobacteria, Firmicutes, Verrucomicrobia, Nitrospirae, Bacteroidetes
Predominant genera	*Acinetobacter*, *Aeromonas, Alcaligenes, Aquabacterium*, *Arthrobacter, Corynebacterium*, *Bacillus*, *Burkholderia*, *Citrobacter*, *Enterobacter*, *Flavobacterium*, *Klebsiella*, *Methylobacterium*, *Moraxella*, *Pseudomonas*, *Serratia*, *Staphylococcus*, *Mycobacterium*, *Sphingomonas*, *Xanthomonas*
Facultative (opportunistic) pathogens	*Mycobacterium*, *Legionella* spp. including *L. pneumophila*, *Pseudomonas aeruginosa*, *Klebsiella*, *Aeromonas*

Pathogenic bacteria in drinking water systems



Source: M. Moritz, Biofilm Centre, UDE

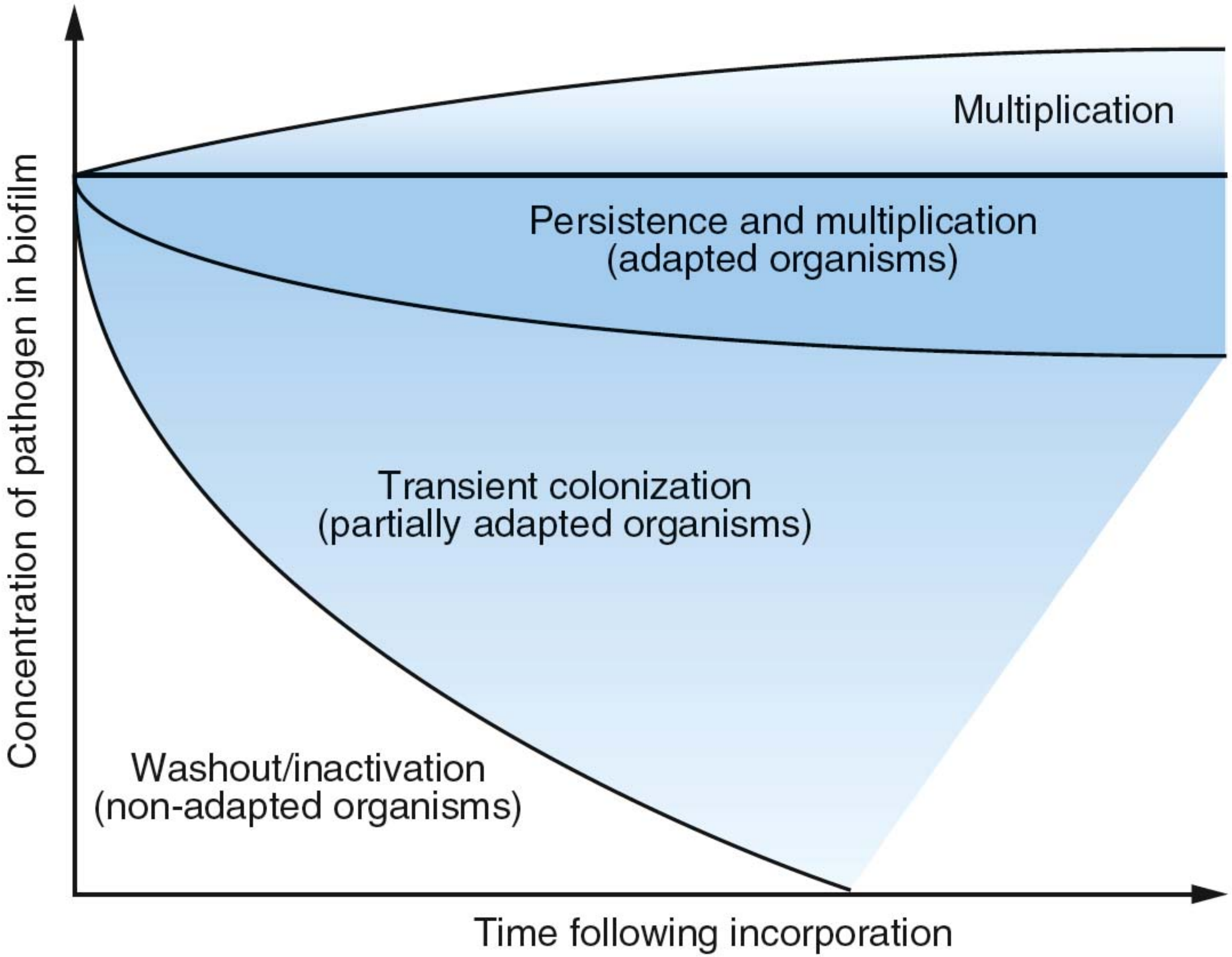
Microbiological examination of drinking water systems:

Routinely, sampling of water phase, and determination of target organisms (bacteria) using culture methods.

Predominant microorganisms: environmental bacteria and protozoa, **without any significant risk to human health**.

Pathogenic microorganisms introduced through contamination events

Fate of pathogens in drinking water biofilms after incorporation (contamination)



Pathogens

Environmental

Legionella spp.,
Mycobacterium spp.,
Pseudomonas aeruginosa

Faecally derived

Escherichia coli,
coliform bacteria,
Salmonella enterica,
Campylobacter spp.,
Helicobacter pylori

Enteric viruses,
Cryptosporidium spp.

Source: Wingender, 2011

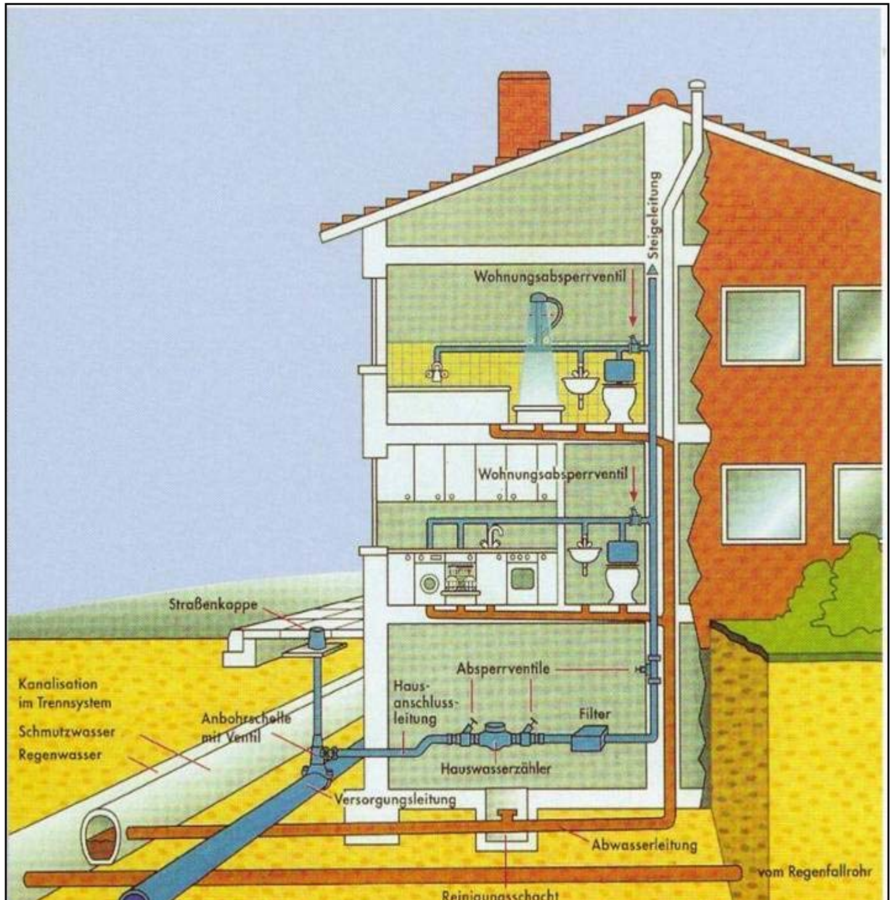
Hygienic and technical problems caused by biofilms in drinking water systems

- Reservoir of pathogenic microorganisms, contamination of water by biofilm microorganisms (regrowth, release of microorganisms with pathogenic properties).
- Enhanced tolerance against disinfectants, consumption of disinfectants and formation of disinfection by-products.
- Formation of odours (e.g., caused by actinomycetes).
- Source of discoloration and turbidity of drinking water (e.g., caused by iron and manganese oxide depositing bacteria).
- Microbially influenced corrosion (biocorrosion).
- Increase in flow resistance.

Premise plumbing in buildings

Characteristics of premise plumbing

- Small pipe diameters ⇒ large surface area for biofilm formation.
- Long stagnation periods.
- Cold and hot water temperatures (fluctuating).
- Diverse materials (copper, steel, plastic such as polyethylene and polyvinyl chloride, elastomers).
- Multiple connections.
- Multiple water outlets at different locations.



Source: Hamburger Wasserwerke GmbH

Premise plumbing - the last meters/centimetres to the tap

From the perspective of hygiene: critical component along the drinking water supply from the waterworks to the consumer‘s tap.

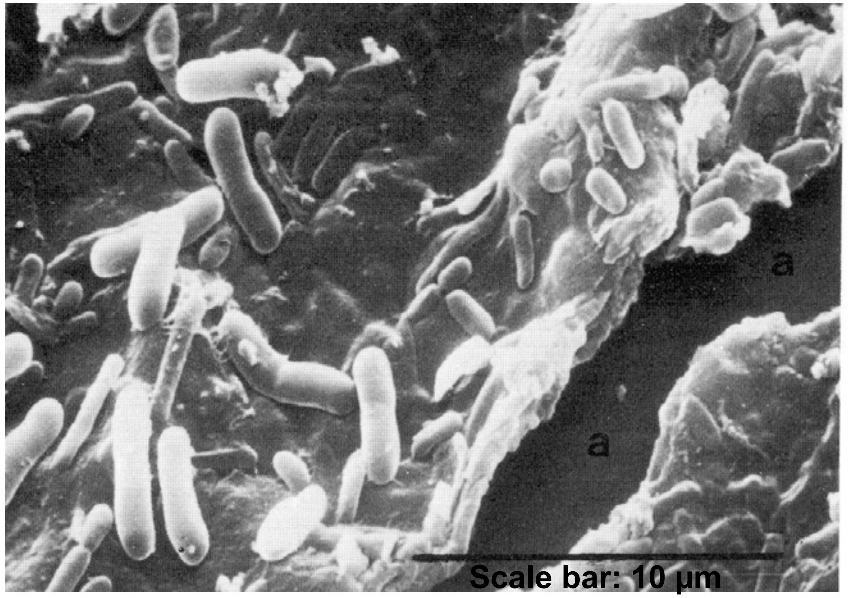
L. pneumophila and *P. aeruginosa*: most important pathogens relevant in premise plumbing

- *L. pneumophila* and *P. aeruginosa* are epidemiologically and clinically important bacterial pathogens that can contaminate plumbing systems of buildings, and can be involved in water-related outbreaks.
- Detected more frequently in plumbing systems compared with drinking water distribution systems.
- Causing recurrent, sometimes years long contaminations in premise plumbing of buildings.
- In particular, critical in hospital water systems.

Non-compliance to action levels - survey of data from German health authorities from over 4,400 public buildings (2003 – 2009; Kistemann et al., 2010)

Parameter	Action level	Number of samples	Non-compliance absolute (%)
Legionella sp.	100 cfu/100 mL	22 786	2 908 (12.8)
P. aeruginosa	0 cfu/100 mL	3 468	102 (2.9)

Water biofilms in health-care facilities



Biofilm on the inner surface of a silicone tube from a dental unit.
(Exner and Tuschewitzki, 1984)

Biofilm on corroded faucet flow straightener.
(Trautmann et al., 2005)

Biofilms in dental waterlines can harbour opportunistic pathogens such as *Legionella pneumophila* and *Pseudomonas aeruginosa*.

Biofilms in water outlets can act as important infection sources of *Pseudomonas aeruginosa* for hospital patients.

Water-associated pathogens in premise plumbing of health-care facilities

- Health-care facilities
  Hospitals, health centres, residential care facilities, nursing homes, dental offices, dialysis centres.
- Potential of nosocomial infections in patients (especially neonates, infants, the elderly, individuals with weakened immune system).
- Hospital water supply, including biofilms, can be a source of infection.
- Drinking water may not be suitable for all uses and for all patients such as severely immunosuppressed persons.
- Potential risk of infection:
  - by water used to wash burns or wounds,
  - by water used to wash medical devices such as endoscopes, respiratory equipment and catheters,
  - by water used for renal dialysis.

  $\Rightarrow$ Use of sterilized water may be required.

Pathogens involved in water-associated infections in health-care facilities

Organisms	**Sites of infection**
Bacteria	
Legionella spp.	Lungs, other organs
Pseudomonas aeruginosa	Blood, lungs, urinary tract, skin, wounds
Mycobacterium spp. (*M. avium*, *M. chelonae, M. fortuitum*, *M. kansasii*, *M. xenopi*)	Disseminated, respiratory tract, wounds, blood, stomach
Stenotrophomonas maltophilia	Blood, respiratory/urinary tract, skin
Acinetobacter baumannii	Skin, wounds
Aeromonas hydrophila	Blood
Serratia marcescens	Eyes
Elizabethkingia meningoseptica	Respiratory tract
Fungi	
Aspergillus fumigatus	Lungs
Exophiala jeanselmei	Disseminated
Fusarium solani, *F. oxysporum* and other *Fusarium* species	Disseminated

WASH IN HEALTH CARE FACILITIES

Global Baseline Report 2019

World Health Organization

WHO UNICEF JMP

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Routine microbial monitoring of water quality
The indicator concept

Recognition that the majority of pathogens in drinking water are faecally derived resulted in the concept to measure general levels of faecal contamination by means of representative micro-organisms (**indicator organisms**).

- Originally developed as measures of faecal pollution of source waters.
  Later also used to measure efficiency of water treatment, post-treatment contamination and deterioration of drinking water quality.

- **Index** and **indicator** organisms
  - **Index organisms**: point to the presence of pathogenic organisms.
  - **Indicator organisms**: used to measure the effectiveness of a process, e.g., filtration, disinfection, distribution.

Monitoring of drinking water quality

- Microbiological drinking water quality: routinely monitored by water suppliers and public health authorities.
- Routine microbiological parameters and requirements according to the Council Directive 98/83/EC of 3 November 1998 and the German Drinking Water Ordinance (2017):

Parameter	Function	Parametric value
Escherichia coli	Microbiological parameter (index organisms)	0 cfu or MPN/100 ml
Enterococci	Microbiological parameter (index organisms)	0 cfu or MPN/100 ml
Coliform bacteria	Indicator parameter	0 cfu/MPN/100 ml
Colony count 22 °C	Indicator parameter	No abnormal change or 100/ml
Colony count 36 °C	Indicator parameter	No abnormal change or 100/ml
Clostridium perfringens	Indicator parameter	0 cfu/100 ml

Cfu: colony-forming units; MPN: most probable number

Water safety plan (WSP)

WSPs: Management plans developed by water suppliers.

Approach for comprehensive risk assessment and risk management that encompasses all steps in water supply from catchment to consumer.

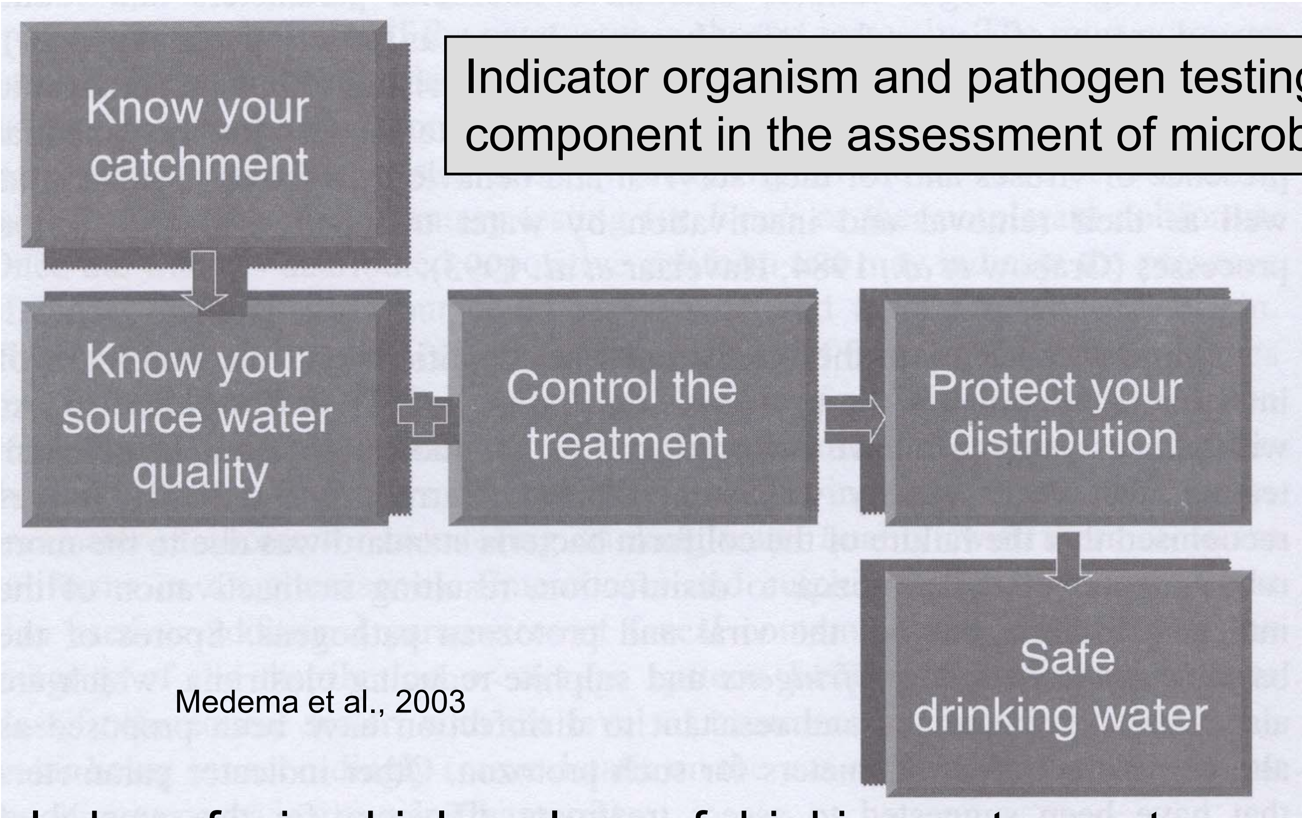
The WSP approach involves five components:

- Definition of water quality targets based upon public health protection and disease prevention.
- System assessment to determine whether the water supply chain (up to the point of consumption) as a whole can deliver water of a quality that meets the defined targets (risk analysis).
- Monitoring of the steps in the supply chain that are of particular importance in securing safe drinking-water.
- Management plans documenting the system assessment and monitoring and describing action to be undertaken from normal conditions to extreme events.
- Systematic independent surveillance that verifies that the above are operating properly.

"Catchment to consumer" approach to risk management of drinking water safety

Today, water agencies focus on the whole system approach

- assessment of all types of physical, chemical and microbiological risks,
- development of water safety plans.



Indicator organism and pathogen testing is an important component in the assessment of microbiological risk.

Medema et al., 2003

Knowledge of microbial ecology of drinking water systems can contribute significantly to effective control strategies (microbiome and biofilm management).

Exam (Water Science, TWM)

Applied Microbiology
Hygiene

22 July 2019, 10:00 – 12:00, S03 V00 E33
(19 September 2019, 12:00 – 14:00)