



(waste) Water treatment

Wastewater treatment (purpose → improve hygienic quality of water)

- separation and removal
 - (bio)degradation
- of potentially harmful substances or organisms from water
- disinfection (chlorine and chlorine compounds, UV radiation, ozone)

In some cases → chemical treatment of water or transformation (oxidation, reduction) of potentially harmful substances (e.g. in in-situ groundwater remediation)

Wastewater treatment utility

- purpose: collection, treatment of wastewater and disposal of associated pollutants / risk materials (sludge, etc.)
- municipalities (cities) are also responsible for the collection and disposal of runoff, which consists of stormwater, misplaced or excessive irrigation, domestic car washing, etc.
- runoff collects in gutters or holding ponds; then goes to storm sewers; and is dumped into a nearby river or, in coastal cities, directly into the ocean.
- this (runoff) water often carries a variety of pollutants: fertilizers, animal waste, oils, tire dust, etc.
- for municipalities that do not have combined storm and sanitary sewers, this runoff is dumped without treatment.

Wastewater – important parameters (properties)

- color, turbidity, odor
- pH, Eh (redox potential), electrical conductivity (mS cm^{-1}), dissolved oxygen
- chemical oxygen demand – COD: the amount of oxygen consumed in the reactions with species dissolved in the water solution
- biochemical oxygen demand – BOD_5 : the amount of oxygen consumed by the (micro)organisms that degrade organic C in the water (for 5 days)
- presence/activity of pathogens (*Giardia lamblia*, enteric viruses, *Cryptosporidium* – oocysts)
- nitrate/nitrite, phosphorus contents
- potentially toxic/risk elements and heavy metals
- others...

Wastewater – important parameters (properties)

color vs. turbidity

- color is caused by amount and nature of species dissolved in water
- the more intensive the color is → the more light is absorbed
- turbidity (on other hand) is caused by light scattering; the light is scattered by undissolved components in suspension
- the water often contains dissolved as well as dispersed components
- appearance of apple juice in the bottle on the right is affected by both turbidity as well as the color (but turbidity is more visible)
- the appearance of the juice in the bottle on left is caused mainly by color as most suspended components were filtered

solution → all species are dissolved

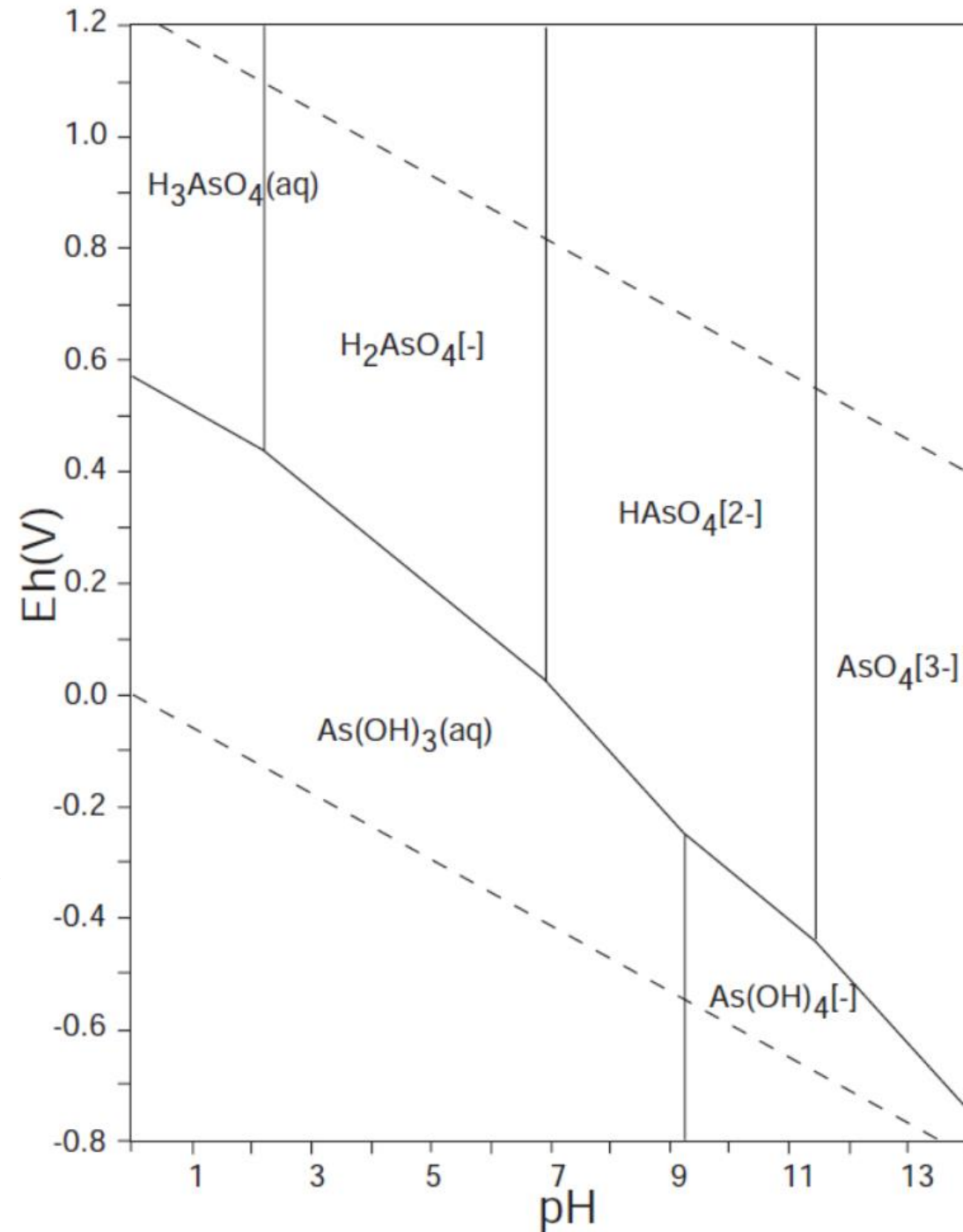


suspension = solution + colloids + small particles

Wastewater – important parameters

- Eh (redox potential → units of voltage, V): higher values indicate oxidizing environment and lower reducing
- why Eh (redox) is important? → because the elements (may) differ in toxicity based on their oxidation number
- examples of differing toxicity:
 - As (III) > As (V)
 - Cr (VI) > Cr (III)
 - Hg (II) > Hg (I)
 - Mn (III) > Mn (II)
 - Mn (III) > Mn (IV)
- based of Eh – pH values we can predict the chemical speciation of element(s) in the water solution

As in water changing speciation according to pH – Eh variation →



Wastewater treatment (techniques and processes)

physical processes:

- sieving
- sedimentation (centrifugation)
- flotation
- aeration
- filtration and membrane processes (reverse osmosis)

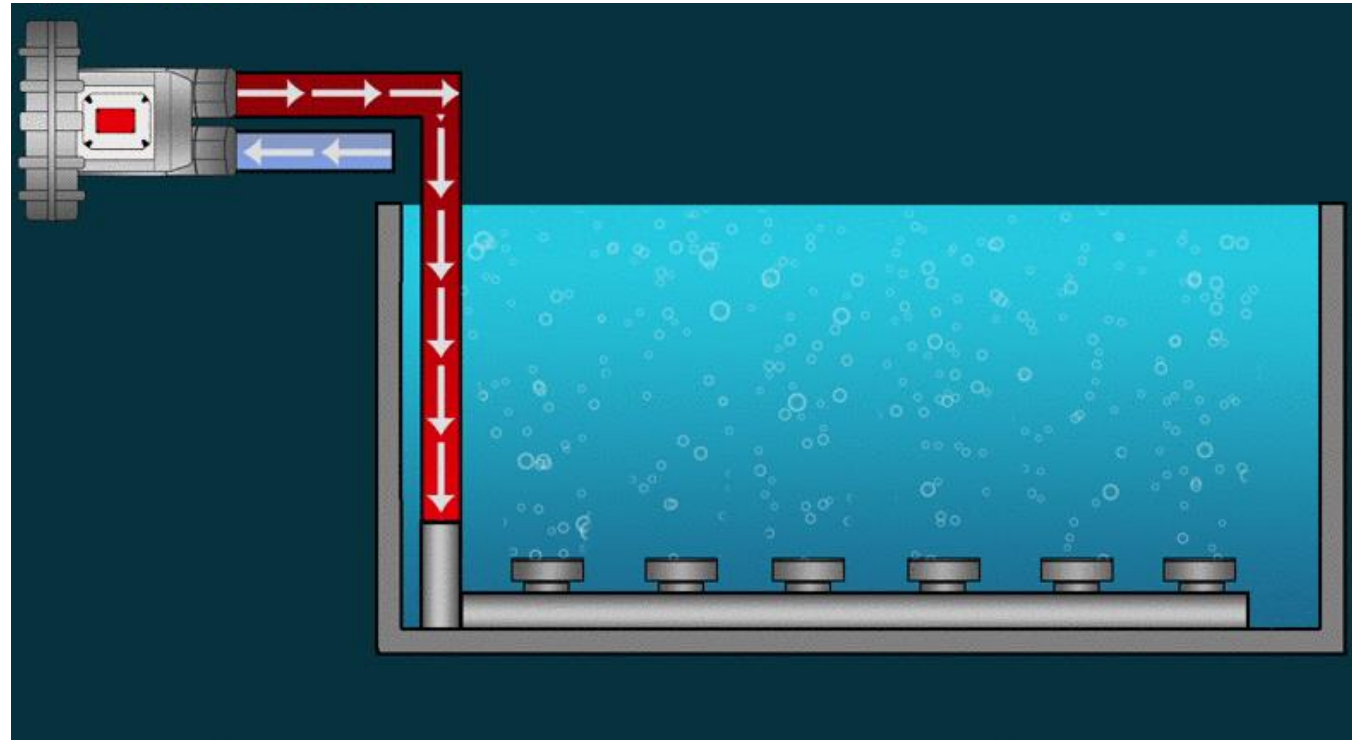
chemical and biochemical processes:

- ion exchange
- coagulation
- denitrification/nitrification
- respiration (including anaerobic)
- decomposition (ammonization)

Wastewater treatment (techniques)

flotation

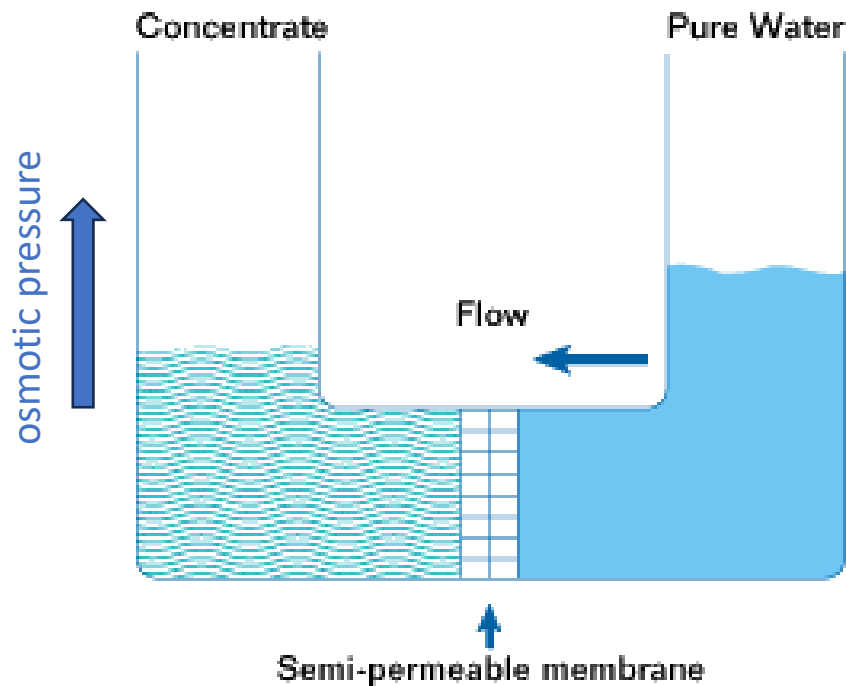
- simple principle with broad application – pumping the gas (air) into suspension to achieve separation
- the goal typically is to trap nonpolar (hydrophobic) components/particles into air bubbles and to collect them subsequently from the surface
- heavier/polar components on the other hand remain in the solution (suspension) or settle to the bottom



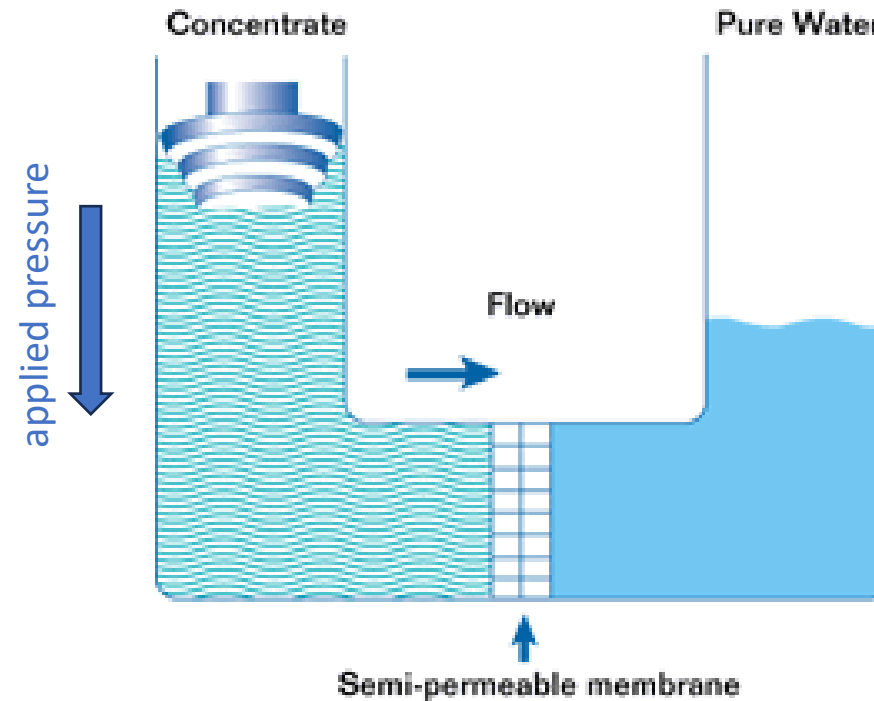
Wastewater treatment (techniques)

reverse osmosis (the filtration under pressure): the principle is widely used in water treatment and demineralization

osmosis:



reverse osmosis → applied pressure app. 100–800 psi:

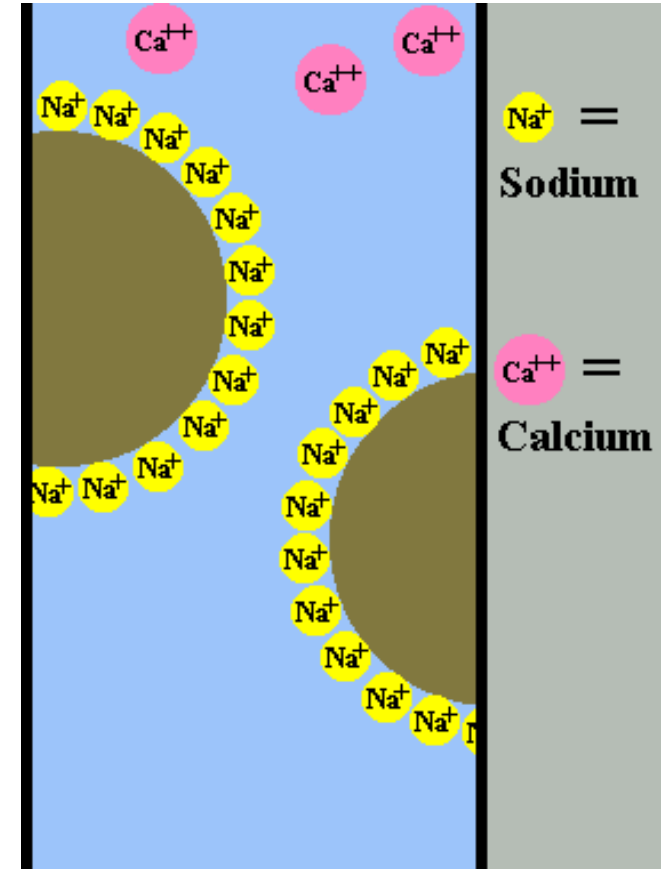


Desalination of sea water is often carried out through reverse osmosis. Energy demand is ranging between 3 and 12 kW per m³.

Wastewater treatment (techniques)

ion exchange principle is widely used for water treatment

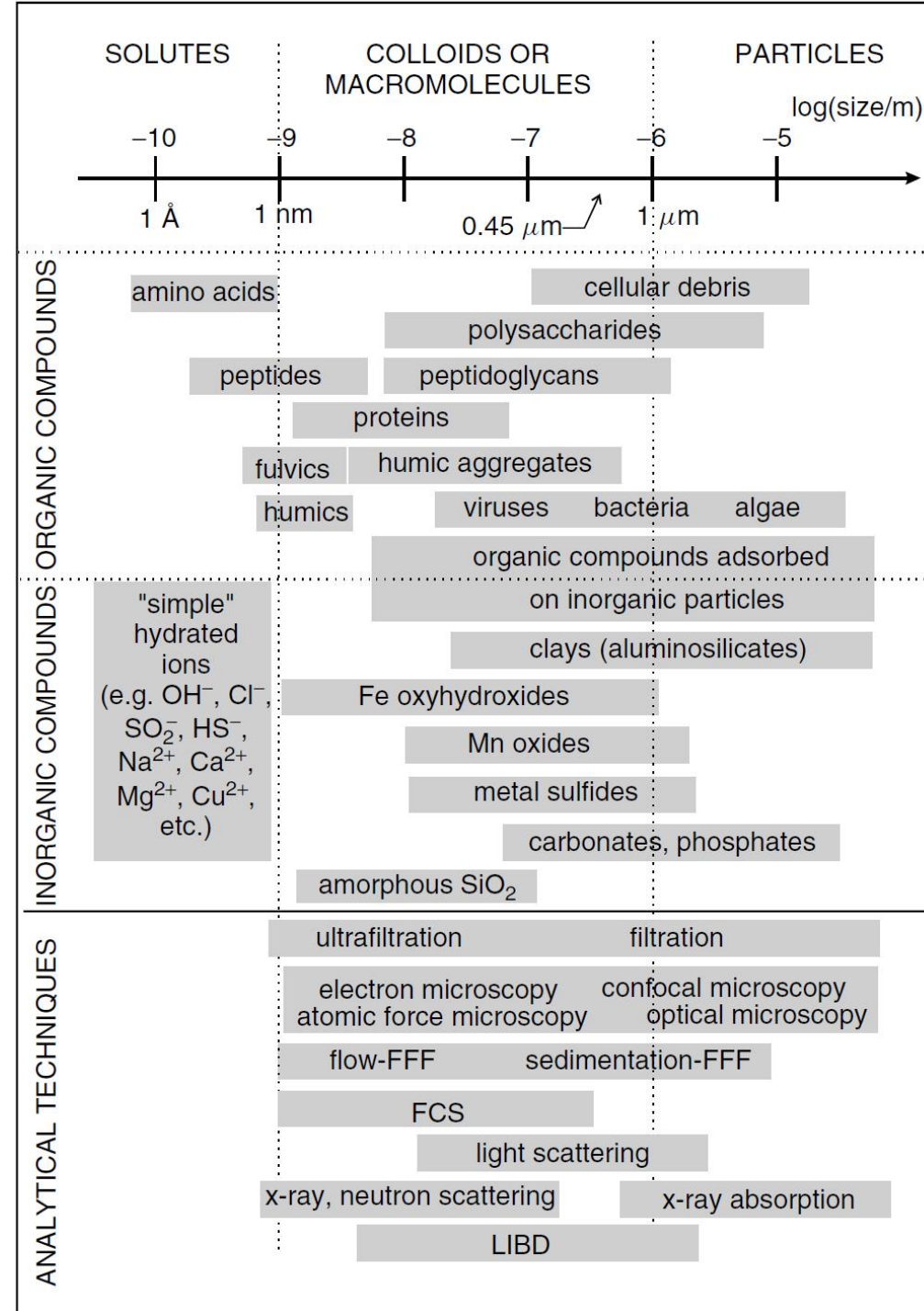
- it is based on exchange reactions between charged solid surface and ionic species with opposite charge
- the most reactions proceed between cations and negatively charged surface
- nowadays various synthetic ion exchangers are available including gels, resins or zeolites
- stoichiometry applies to ion exchange → net change in charge should be zero
- important aspect of many ion exchangers is that they can be recovered and reused → many exchange reactions are reversible



Approximate size of the components commonly found in the (waste)water →

Filtration processes slow down significantly as the size of components decreases

larger components are usually removed before smaller ones



General stages of water treatment

- preliminary: purely physical, such as screening and gravity, and is intended to protect the plant equipment (sieving/screening, flotation, sedimentation)
- primary: removal of suspended solids and organic matter, often by the addition of chemicals; chemical/physical process, whereby small particles agglomerate (flocculate)
- secondary: biological process in which microbes consume the dissolved and suspended organic matter (and sometimes nitrogen and phosphorus)
- tertiary: removes remaining suspended solids by fine filtering, and may include disinfection and nutrient removal

General stages of water treatment

it depends on the wastewater properties

- domestic/municipal (organic pollution and pathogens are the main problem)
- industrial – variable properties/composition of wastewater (food, metallurgy, chemical, pharmaceutical, etc. – each has its own specifics)

example of simple water treatment sequence:

1. screening/sieving, 2. coagulation, flocculation (aggregation), 3. sedimentation, 4. filtration, and 5. disinfection

- if the wastewater contains organic pollution in higher amount, it should be removed prior possible treatment of inorganic components (which is not always possible)

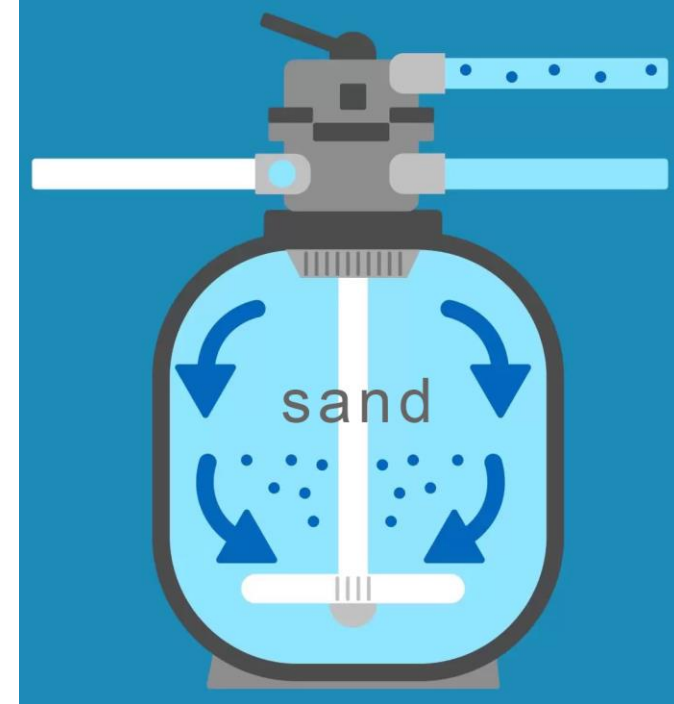
Processes involved in water treatment

- Large particles are removed first by screening and/or settling. Next are particles that will float or settle with some assistance, such as air floatation or mixing with coagulants. Colloids and dissolved materials are removed last. Disinfection of water is carried out in the end.
- The coagulation operation consists of the addition and flash mixing of chemicals (aluminum sulfate $\text{Al}_2(\text{SO}_4)_3$, ferric chloride FeCl_3) to remove the charge on colloids and suspended solids so that they will aggregate in the flocculation step. Flocculation is slow mixing that increases the rate of collisions between particles whose electrostatic repulsive forces have been neutralized in the coagulation step. Now the particles will stick together into sizes that will settle.
- Flotation is often applied in wastewater treatment and not so much in treatment of groundwater. The reason is that wastewater contains more hydrophobic components, such as fats, oils, and grease.

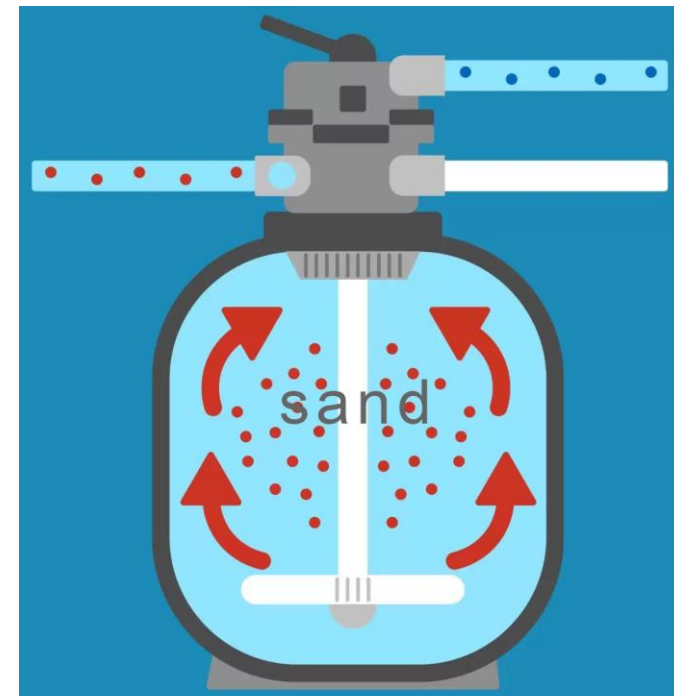
Processes involved in water treatment

- filtration can be carried out using sand filters (with backwashing for purpose of clearing).
- sand filter: simple device that is essentially a tank filled with sand with water introduced at the top and removed at the bottom. Sometime after the filter is started up (a few days to a few weeks), the upper layer of sand becomes coated with a gelatinous biological layer made up of algae, bacteria, protozoa, and small invertebrates. This sticky layer is biologically active and converts organic matter in the water to water, carbon dioxide, and harmless salts. It is even effective in removing Giardia and Cryptosporidium oocysts, which are nearly unaffected by chlorination.

filtering



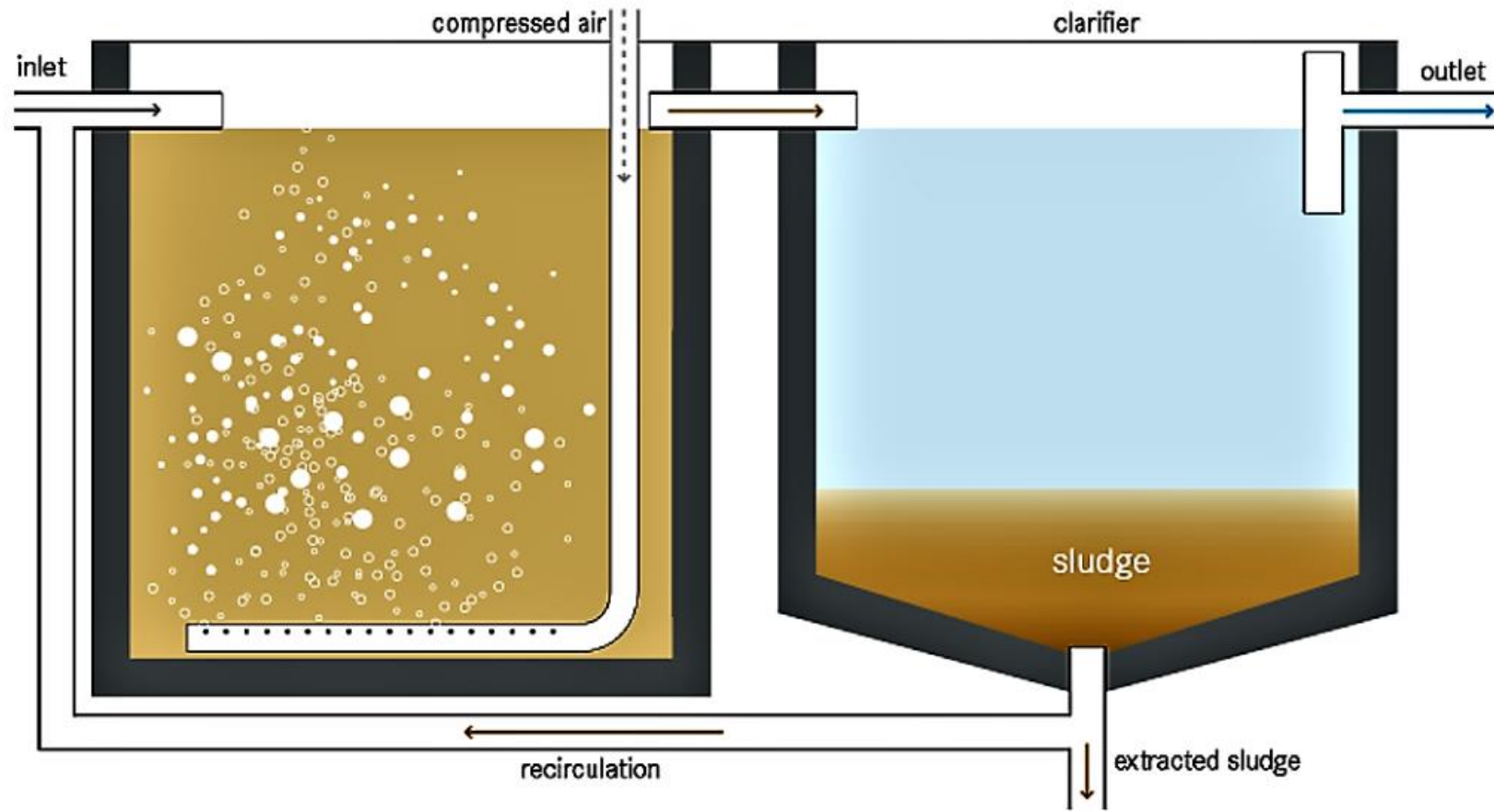
backwash



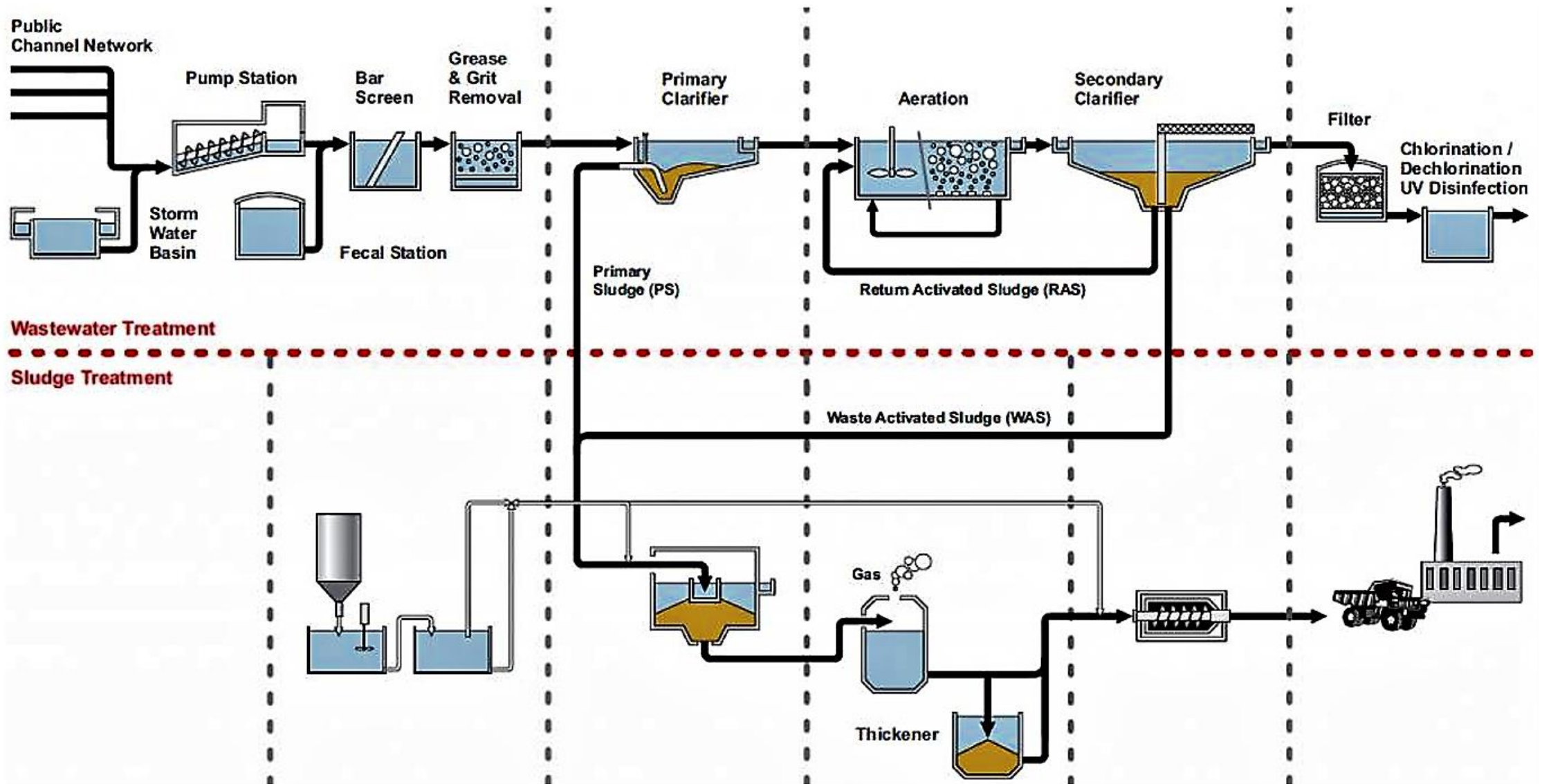
Activated sludge

- activated sludge process refers to a multi-chamber reactor unit that makes use of highly concentrated microorganisms to degrade organics and remove nutrients from wastewater
- **aerobic** process → continuous and well-timed supply of oxygen is required
- pumping the air into the reactor not only provides oxygen for the microorganisms, but also keeps the sludge in suspension and prevents it from settling
- aerobic bacteria are the most common organisms but facultative anaerobic bacteria (prefer oxygen, but can survive without it) along with higher organisms can be present; Protozoa – up to 3% (Amoebae, Flagellates, Ciliates) or even some Metazoa organisms (Rotifera, Nematoda, Tardigrada) – however they don't contribute to water treatment, and their larger portion indicates that the sludge is old
- different configurations of the activated sludge process can be employed. In general, the processes that occur are effective at **removing soluble, colloidal and particulate organic matter**. The reactor can be designed for biological **nitrification** and **denitrification**, as well as for biological **phosphorus removal**.
- although the processes cause significant decrease in organic matter and nutrients contents, as well as removal of pathogens, the water from the outlet doesn't meet the standards for drinking

Activated sludge (basic concept)



Activated sludge (application in municipal wastewater treatment)

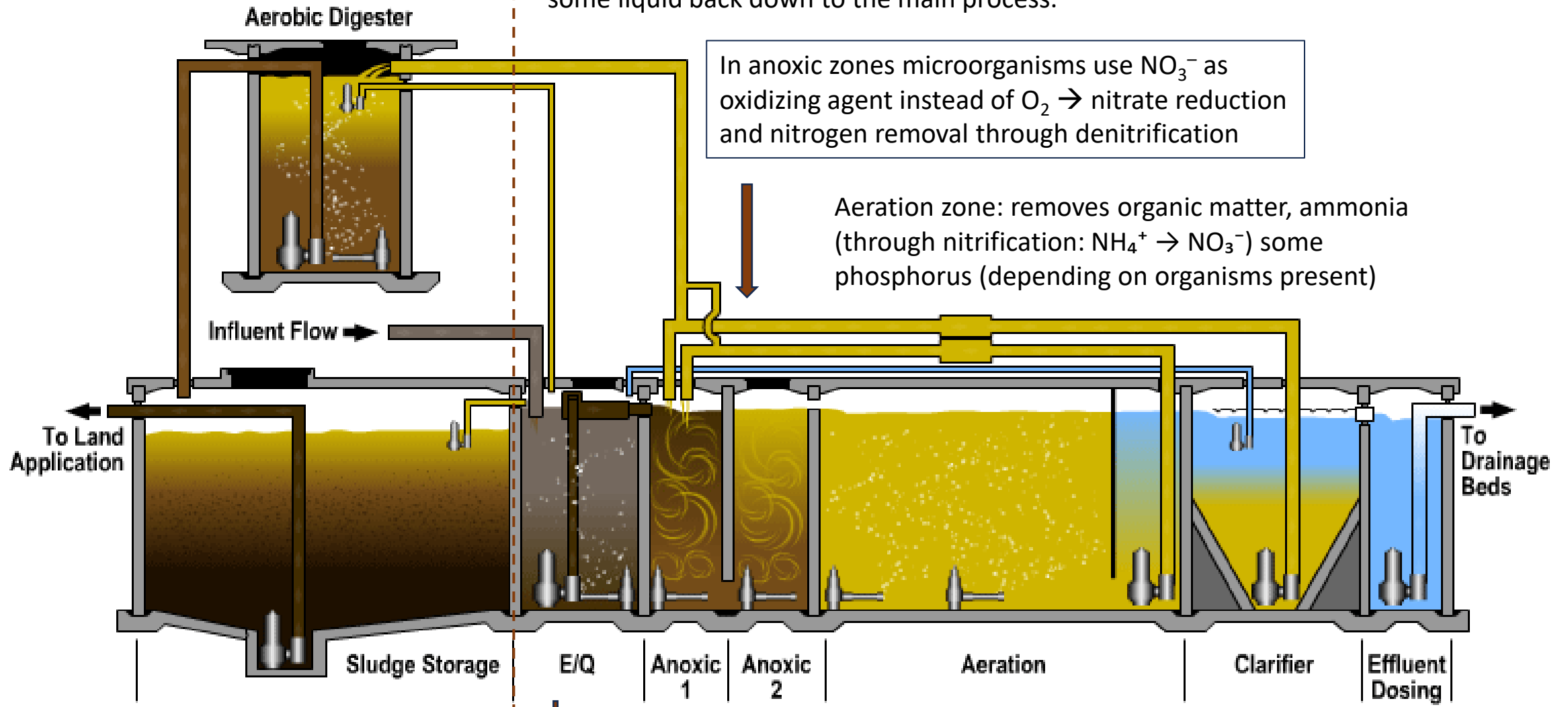


sludge handling

This unit stabilizes organic solids using aerobic bacteria. Air is supplied to oxidize organic matter. Reduces odor and pathogens. This digested sludge loop often returns some liquid back down to the main process.

In anoxic zones microorganisms use NO_3^- as oxidizing agent instead of $\text{O}_2 \rightarrow$ nitrate reduction and nitrogen removal through denitrification

Aeration zone: removes organic matter, ammonia (through nitrification: $\text{NH}_4^+ \rightarrow \text{NO}_3^-$) some phosphorus (depending on organisms present)



The settled solids from the clarifier accumulate here before further treatment.

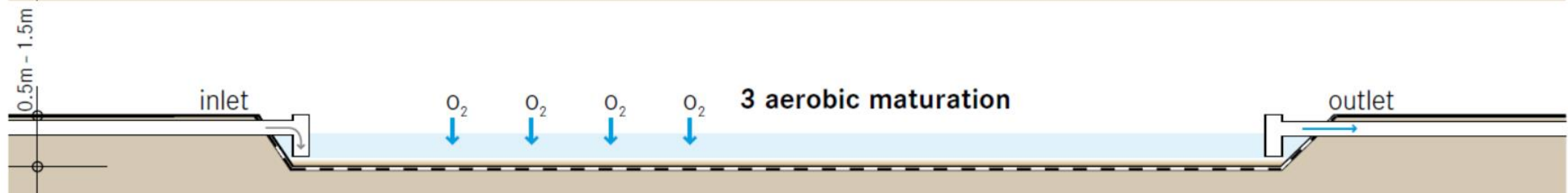
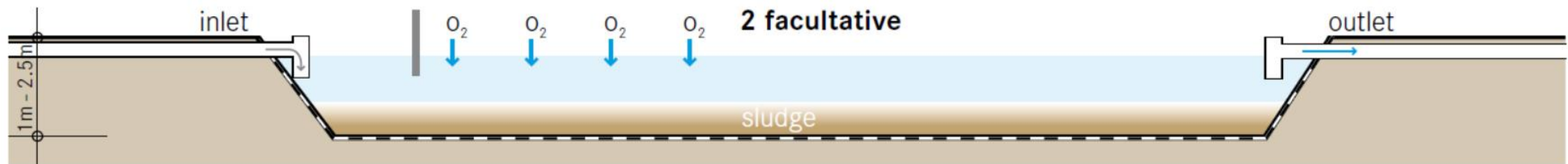
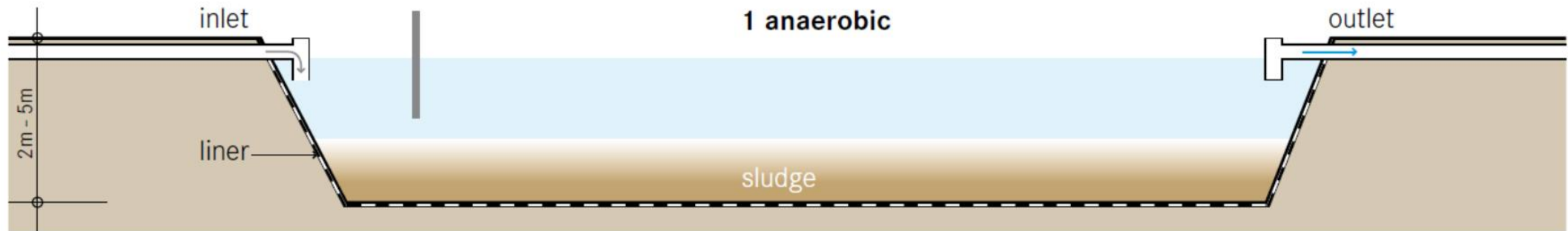
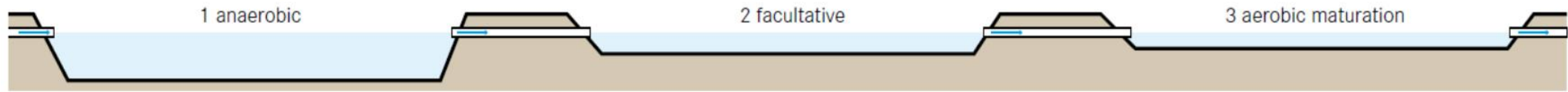
This tank smooths out fluctuations in flow and concentration (prevents hydraulic shocks). Helps mix incoming wastewater into a consistent quality.

Biomass flocs settle by gravity.

Wastewater stabilization ponds

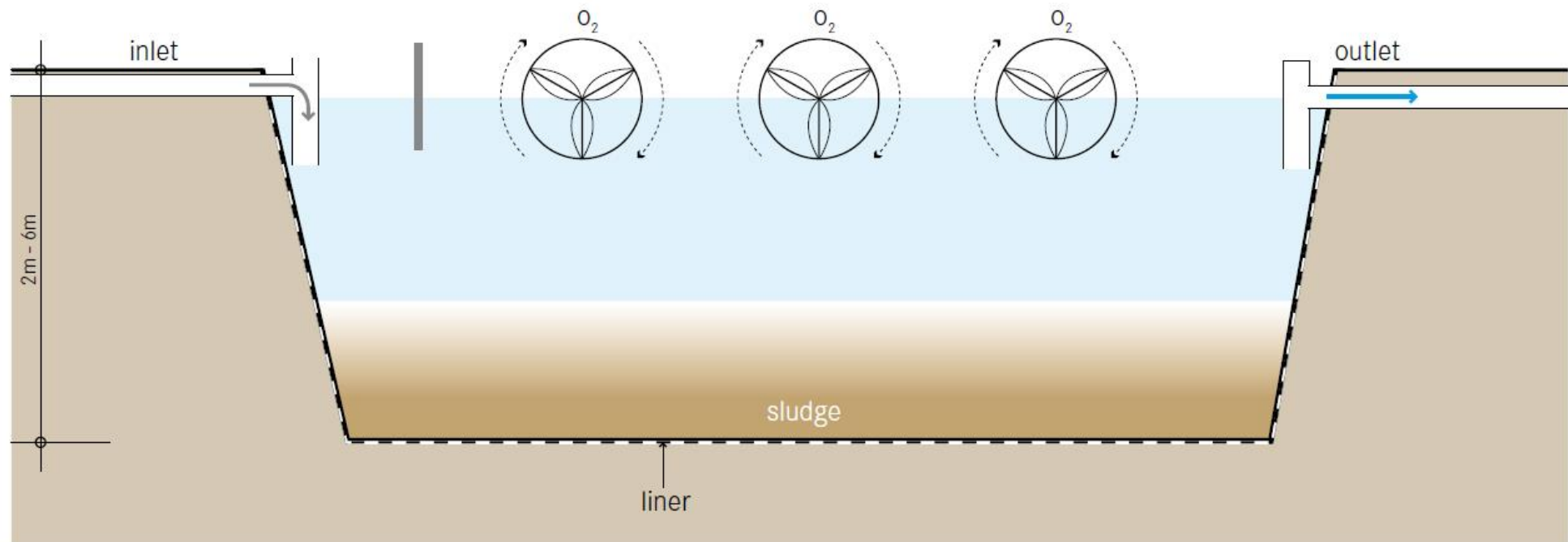
- larger water bodies – ponds (doesn't require electricity but the climate shouldn't be too cold)
- there are three types: (1) anaerobic, (2) facultative and (3) aerobic (maturation)
- WSPs are (should be) linked in a series of three or more with effluent flowing from the anaerobic pond to the facultative pond and, finally, to the aerobic pond
- the anaerobic pond is the primary treatment stage and reduces the organic load in the wastewater (it can remove up to 60% of the BOD) → CH_4 is produced
- the effluent from the anaerobic pond is transferred to the facultative pond, where further BOD is removed. The top layer of the pond receives oxygen from natural diffusion, wind mixing and algae-driven photosynthesis. The lower layer is deprived of oxygen and becomes anoxic or anaerobic. The aerobic and anaerobic organisms achieve BOD reductions of up to 75%.
- anaerobic and facultative ponds are designed for organic matter removal, while aerobic ponds are designed for pathogen removal` additionally, the algae release O_2 into the water and at the same time consume CO_2 produced by the respiration of bacteria.

Wastewater stabilization ponds



Aerated ponds

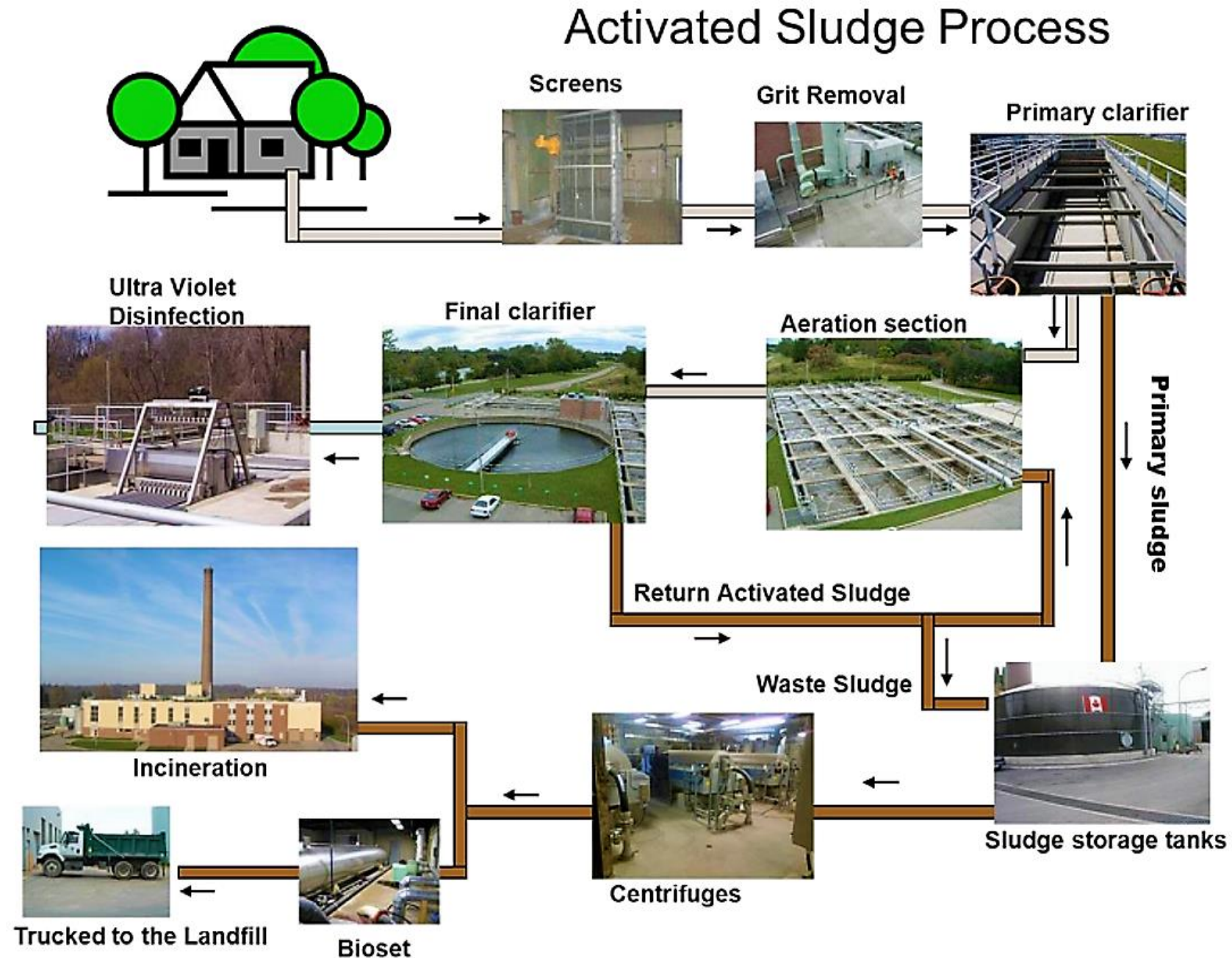
- aerators provide oxygen and keep the aerobic organisms suspended and mixed with water to achieve a high rate of organic degradation
- the increased aeration allows for increased degradation and increased pathogen removal. As well, because oxygen is introduced by the mechanical units and not by light-driven photosynthesis, the ponds can function in relatively colder climates



Activated (sewage) sludge – disposal

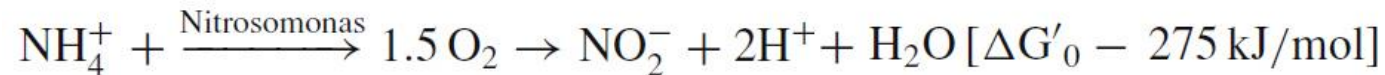
- the sludge itself requires special treatment as it contains various pathogens
- the sludge should be composted long enough (2 to 4 months) under thermophilic conditions (55 to 60 °C) in order to be sanitized sufficiently for safe agricultural use
- in many countries the application of sewage sludge to the soil is regulated by law; chemical and microbiological properties of the sludge must be known before the application into the soil (org. matter content, nutrient amounts, content of risk elements, microbial parameters)
- increasing pH of sludge helps, as many pathogenic (micro)organisms prefer acidic conditions and slightly alkaline conditions stabilize sludge also from chemical viewpoint
- dewatering through centrifugation
- combustion in the incinerator

Activated sludge
(sequence in wastewater
treatment in London)

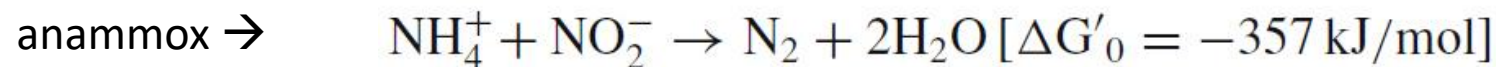
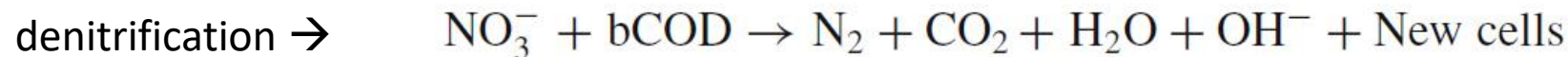
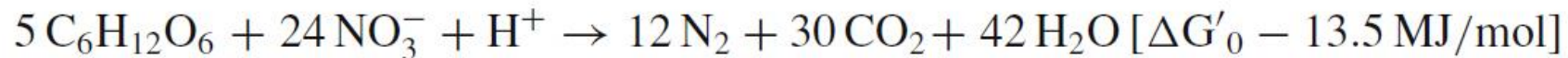


Activated sludge (nitrogen processes; NO_3^- and NO_2^- are hazardous)

- biochemical reactions of N in wastewater are significantly affected by O_2 and organic matter (carbon) concentrations
- N is present in various forms: organic N, NH_3 , NO_2^- , NO_3^- , NH_4^+
- aerobic conditions: organic C is converted into CO_2 and organic N into NH_3 and (at the same time) new (living) cells are produced; additionally, nitrification takes place:



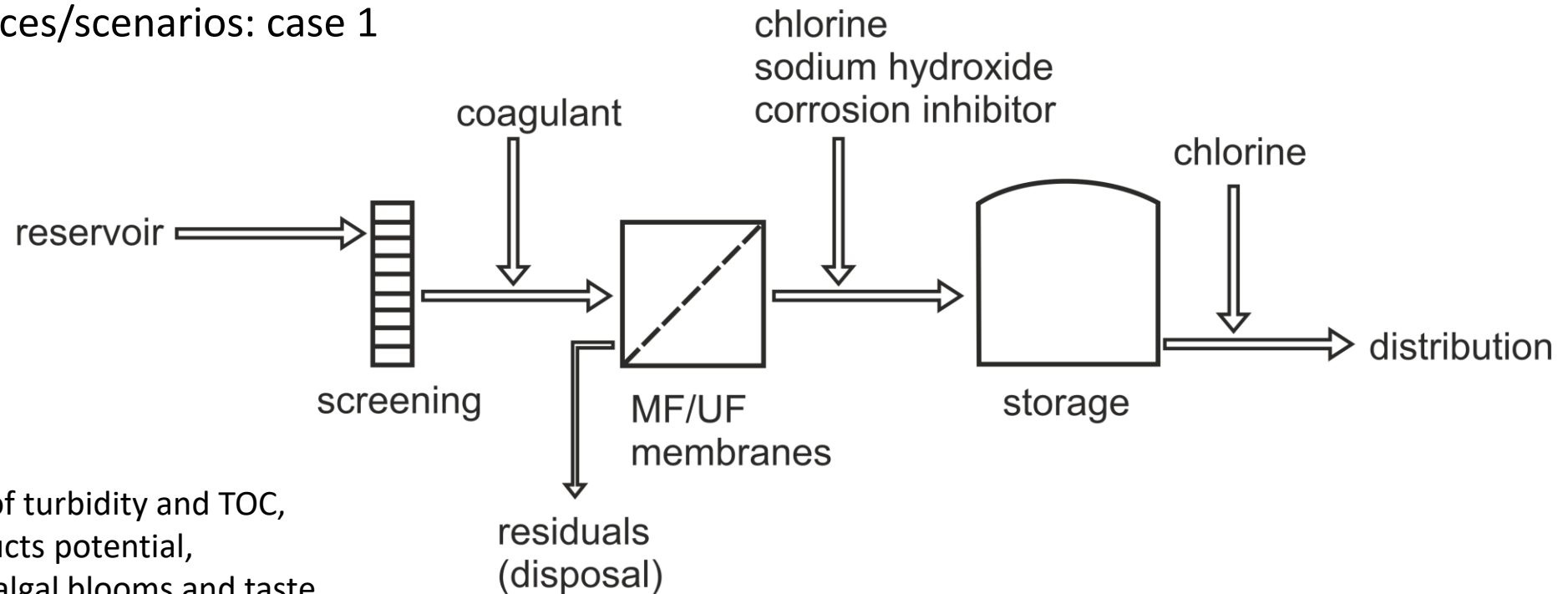
- anaerobic conditions: denitrification and anammox processes proceed – these are important, as they remove NO_2^- and NO_3^-



Water treatment – inorganic components/contaminants

- the aim often is to stimulate precipitation or coagulation; for example, solubility of certain metals change (decrease) as a result of oxidation ($\text{Fe}^{\text{II}+}$ precipitates as $\text{Fe}^{\text{III}+}$ is oxidized)
- inorganic solutes can be removed through ion exchange, (ultra/nano)filtration, reverse osmosis or via electrolysis
- during electrolysis cationic and anionic species dissolved in water solution accumulate on the electrodes based on their charge

Water treatment sequences/scenarios: case 1

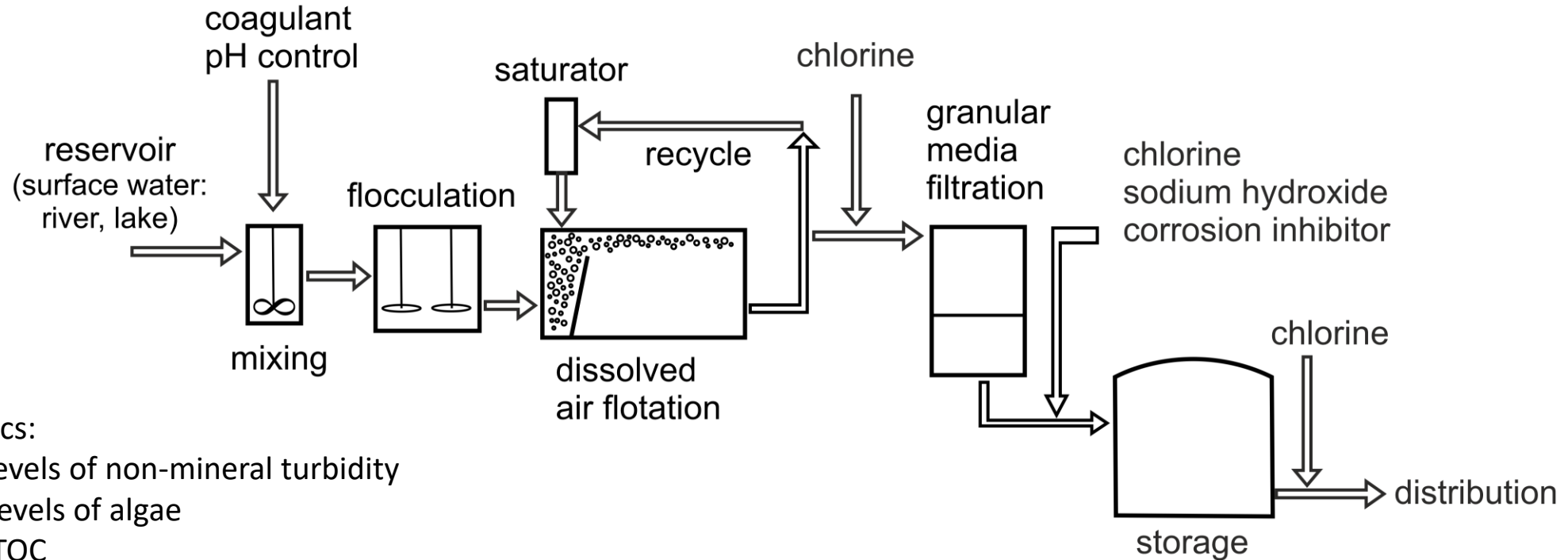


Reservoir characteristics:

- little or no Fe and Mn,
- low to moderate levels of turbidity and TOC,
- low disinfection byproducts potential,
- no history of significant algal blooms and taste and odor episodes

Let's say that we have a water reservoir of fairly good quality, and the goal is to remove dissolved chemicals (mainly organic) and certain pathogens. Since dissolved organic materials are not removed effectively from water using micro- or ultrafiltration (MF/UF), one of the ways to approach this problem is **to add a coagulant** before applying membrane processes. On the other hand, MF/UF membrane filtration can be used to trap certain pathogens (*Giardia* cysts, *Cryptosporidium* oocysts). To reduce the risk of spreading the pathogens it is convenient to apply additional disinfection in end (chlorine or UV radiation).

Water treatment sequences/scenarios: case 2

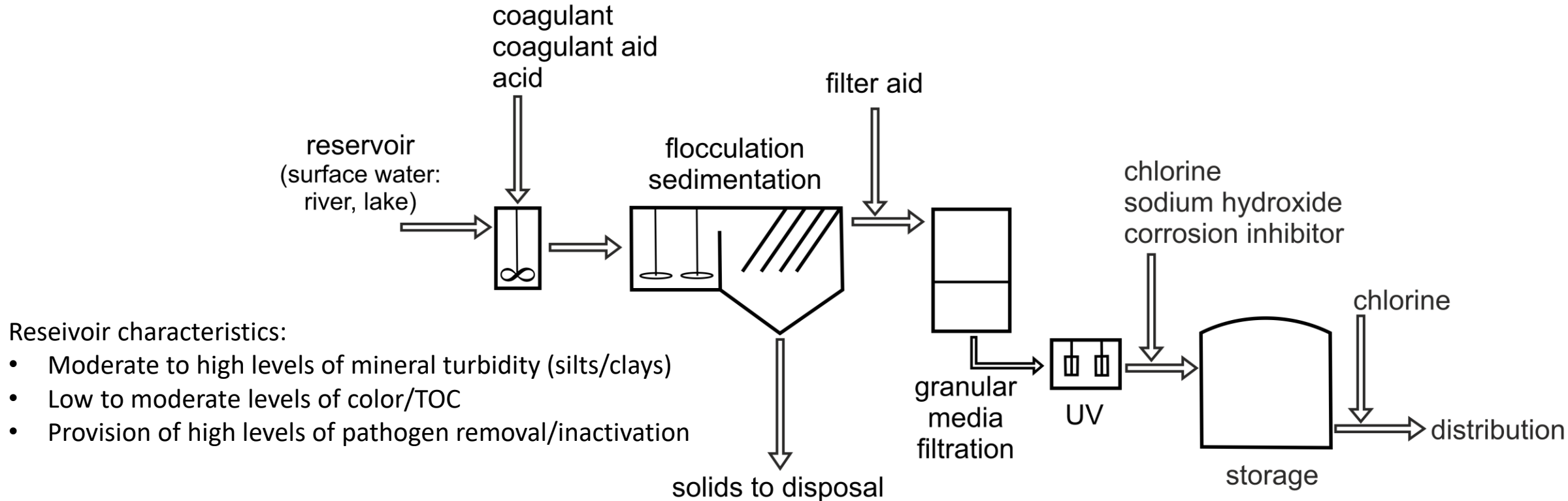


Reservoir characteristics:

- Low to moderate levels of non-mineral turbidity
- Moderate to high levels of algae
- Low to high color/TOC
- Provision of high levels of pathogen removal/inactivation
- Iron and manganese may or may not be present

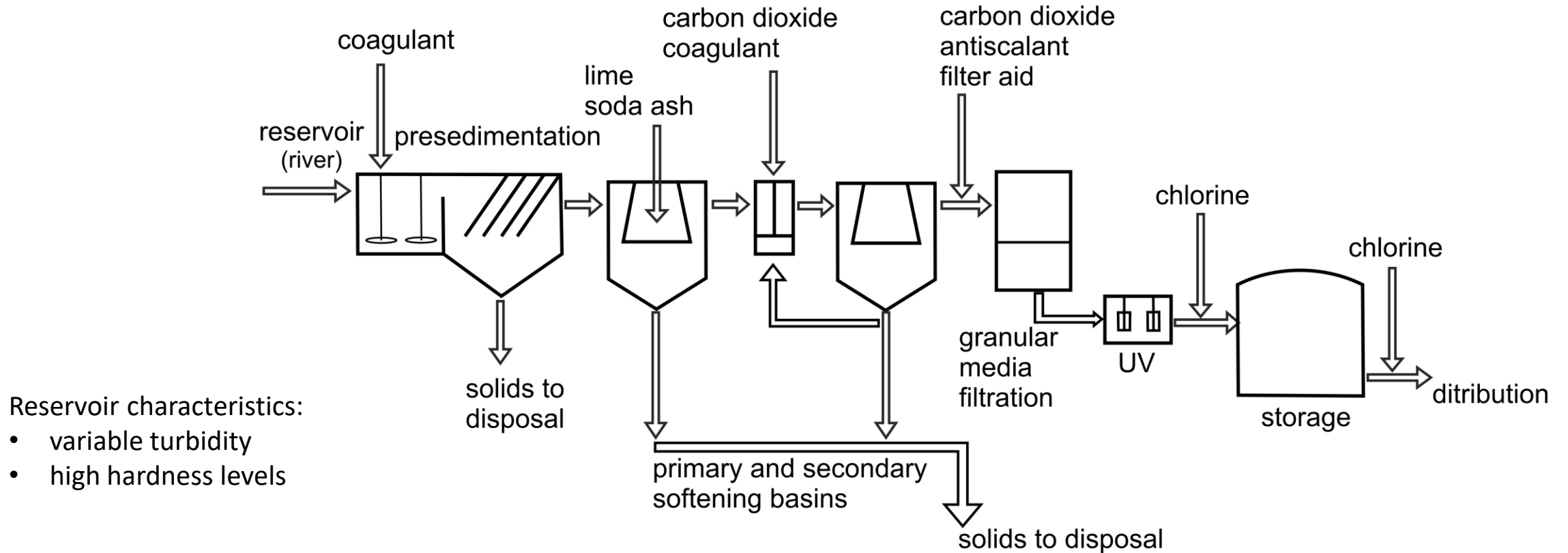
The procedure could be applied for treatment of surface water reservoir, which contains elevated content of organic carbon, higher amount of algal biomass, both causing turbidity of water. Air flotation to provides effective removal of organic carbon occurring mainly in suspended form. Proposed approach can trap also some Mn and Fe and decrease their contents by filtration.

Water treatment sequences/scenarios: case 3



Water treatment for a reservoir or river supply when reduction of hardness is not required. This process is appropriate to address the following water quality conditions: 1) moderate to high levels of mineral turbidity (caused by silts/clays), 2) low to moderate levels of color/TOC, 3) the need of high levels of pathogen removal/inactivation. Silt/Clay turbidity is reduced by flocculation/sedimentation procedure. Optimization of coagulation pH is achieved through the addition of acid and the pH is adjusted after filtration and UV treatment using NaOH.

Water treatment sequences/scenarios: case 4

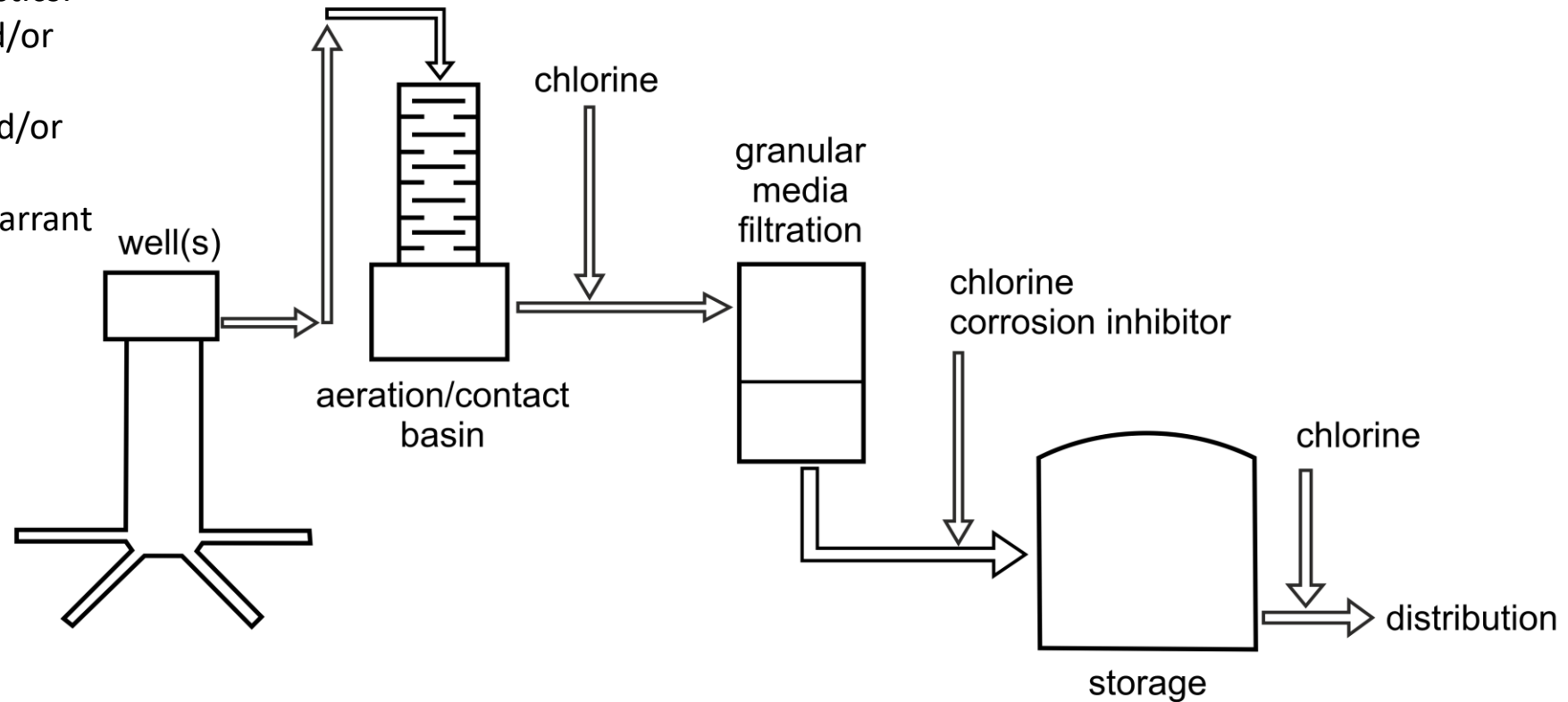


Let's say that the reservoir is a river with "hard" water. The treatment process is appropriate when both clarification and softening of a river supply with highly variable turbidity and high hardness levels are required. The treatment incorporates presedimentation with inclined-plate sedimentation basins to reduce turbidity and color before softening. Subsequently, two-stage lime softening/recarbonation process takes place. The disinfection with UV radiation is carried out after filtration.

Water treatment sequences/scenarios: case 5

Reservoir – groundwater characteristics:

- Higher concentration of iron and/or manganese
- Presence of hydrogen sulfide and/or radon
- Hardness at levels that do not warrant softening treatment

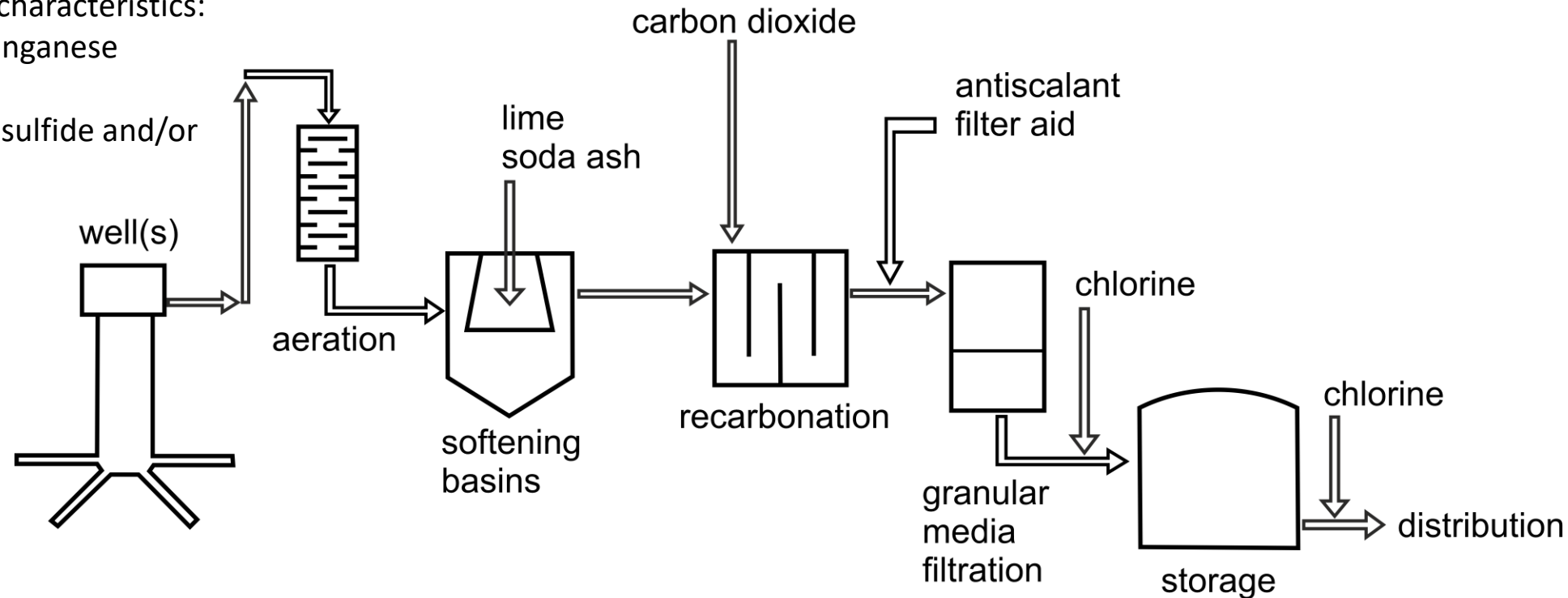


Groundwater with elevated iron and manganese concentrations that contains also dissolved hydrogen sulfide and/radon (gases). Let's assume that hardness is not a issue. Forced- or induced-draft cascade aeration is provided to initiate the oxidation of Fe and Mn and to remove hydrogen sulfide, radon, possibly also other dissolved gases. Chlorine is added to speed up the oxidation of Mn. Aeration serves mainly for removal of gases, whereas most of Fe and Mn is separated via filtration.

Water treatment sequences/scenarios: case 6

Reservoir – groundwater characteristics:

- Higher iron and/or manganese contents
- Presence of hydrogen sulfide and/or radon
- High hardness level



A process configuration for a groundwater supply with the following treatment requirements: 1) removal of iron and/or manganese, 2) removal of hydrogen sulfide and/or radon, 3) reduction of hardness. Besides stripping sulfide and radon, aeration also reduces CO_2 concentrations, thereby reducing both the lime dosage and the associated chemical solids production. Following single-stage lime softening, a recarbonation basin with a detention time of at least 20 minutes is typically provided to ensure adequate stabilization of softened water pH before adding an antiscalant and subsequent filtration. Antiscalant is a dispersing agent that prevent filter pores from clogging.

Water treatment (used material/chemicals)

- activated carbon – has huge specific surface area, which makes it very effective/efficient sorbent, it is widely used in various filters, cleanup mechanisms and environmental applications
- zeolites – belong to tectosilicates, which means they have complex 3D structure, which contain “cavities” that can trap various ions; have high specific surface area, its chemical structure enable selective adsorption of different chemical species (heavy metals, risk element), there are natural as well as synthetic zeolites
- iron with valency of 2 or 0. Fe^0 or Fe^{II+} has high tendency to oxidize (to lose electrons) and therefore it can be used as reducing agent (donor of electrons). This can be used if some species dissolved in water are less toxic in state with lower valency (chromium), or if some compounds precipitate as a result of decreasing their valency → precipitates can be separated more easily from the solution (via filtration)
- hydrogen peroxide (H_2O_2) – oxidant → used in removal (oxidation) of organic matter from water
- chlorine and its compounds: besides being used in disinfection, they are used also as oxidizing agents (similarly as H_2O_2)
- many others (coagulants, dispersing agents, acids, bases,...)

Water disinfection

- chlorine or chlorine compounds: for > 50 years main form has been the Cl_2 (dissolved gas, with minimal concentration of 0.05 mg/L)
- if water contains organic matter → there is a risk that the reaction between Cl_2 and organic compounds will result in toxic organochlorines formation, therefore organic matter should be removed / degraded before chlorination
- the use of other Cl forms is preferred such as chlorine dioxide ClO_2 (or chloramine), that doesn't cause the formation of toxic products
- ozone is effective oxidizing agent (even more effective than Cl), however, also in case of O_3 , there are however some concerns regards possible formation of hazardous products (similarly as in case of Cl)
- UV radiation ($\lambda = 260\text{-}265\text{ nm}$) → causes either death or sterilization of microorganisms in water; it applied mainly in beverage industry; in case of potable water its application is problematic mainly in case of wider distribution systems → risk of microbial recontamination of water