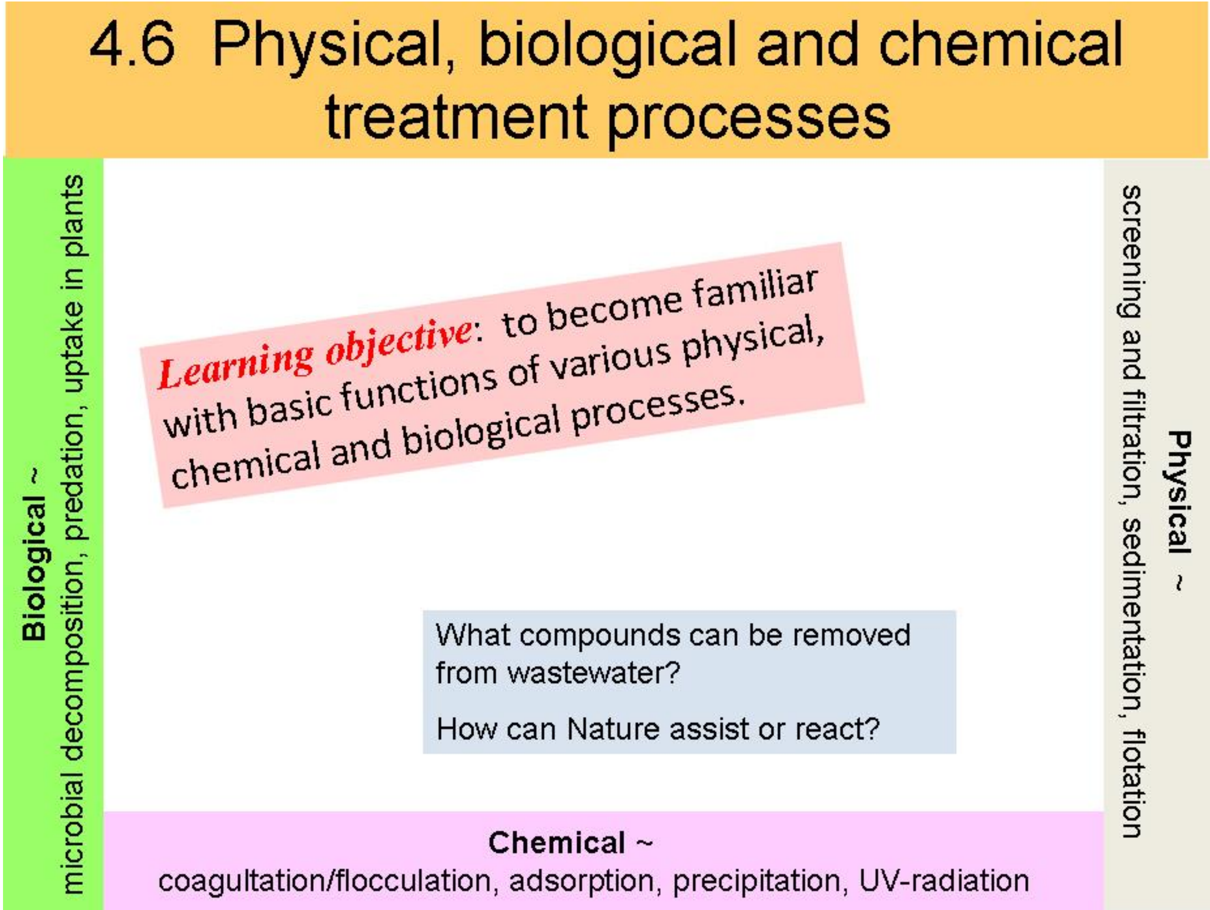


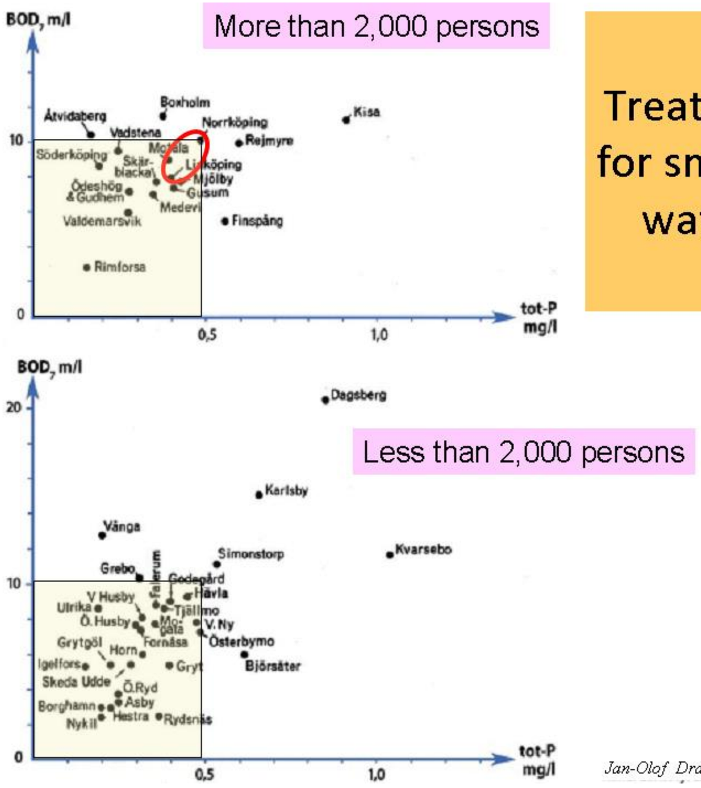
A focus in this sourcebook is on managing greywater from households. Common groups of contaminants in wastewater are suspended solids (dirt, clay, colloidal materials, silt, dust, insoluble metal oxides and hydroxides), dissolved organics (humic acids, fulvic acids, trihalomethanes, synthetic organic chemicals, etc.), dissolved ions (heavy metals, silica, arsenic, nitrate, chlorides, sulphates, etc.), microorganisms (bacteria, viruses, protozoa, helminths, fungi, algae, moulds, yeast cells), and gases (hydrogen sulphide, methane, radon, carbon dioxide)

In Module 4.5 the focus is on reducing wastewater volumes and reducing the concentration of unwanted components through source control measures. In this module the focus is on treatment processes to reduce the amounts of undesirable ingredients in the wastewater that reaches the final water body or soil. We describe each basic physical, chemical and biological process and why they can reduce undesirable components in wastewater and sludge. The aim is to deliver an effluent and sludge of a quality that does not endanger the receiving environment. Module 5.1 provides information on ways to recycle water and nutrients back to agricultural and other uses..

In the next Module 4.7 we combine different basic processes to treat a large spectrum of pollutants. Examples of treatment technologies and management systems are discussed.

The objective is to provide information on the treatment of greywater and wastewater from individual households as well as from smaller communities and towns. The basic processes are the same in both situations but the sophistication of the application may differ, and so may the combinations of processes. The good news is that small systems can be as effective as or more effective than large-scale ones when it comes to effluent and sludge quality. We begin this module with an illustrative example.

4.6- 2



Treatment results for small and large water utilities

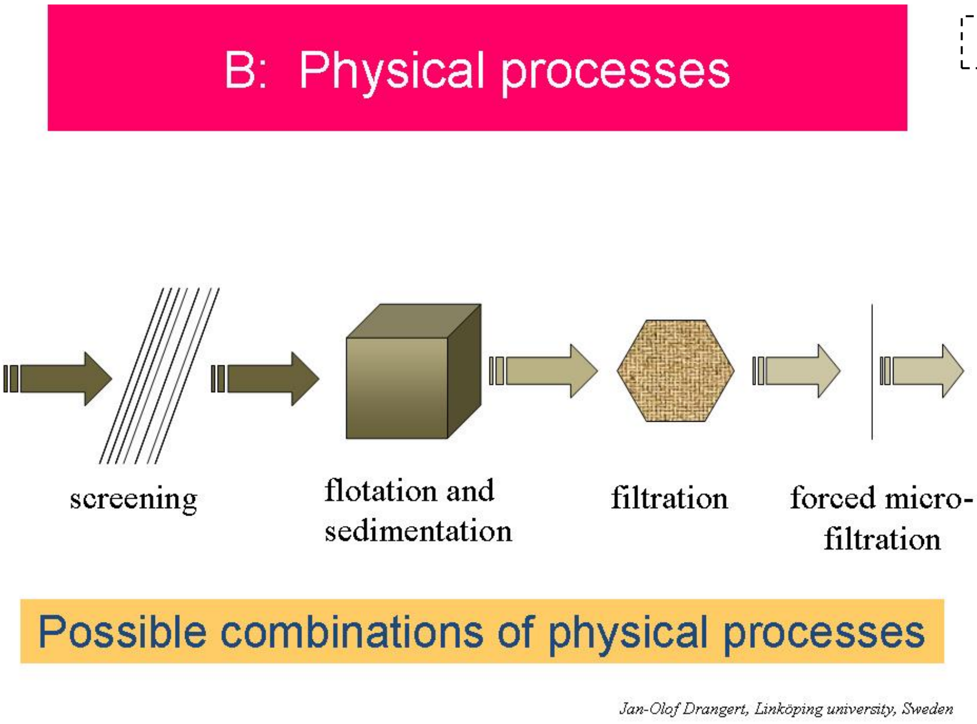
Jan-Olof Drangert, Linkoping university, Sweden

A powerful standard argument in favour of centralised networks is that a large-scale utility will use the latest technology, has better trained staff to operate and maintain the system, and can provide cheaper services for its customers. Research and development of wastewater treatment has focussed on large units, and household options such as septic tanks attract almost no R&D. Yet, there are indications that the large units do not provide better effluent quality than small systems.

In 1987 a county board compared treatment results for small and large wastewater treatment units in Sweden (Drangert and Löwgren, 2005). Two important indicators of effluent quality were selected. BOD (measure of organic content) and total phosphorus (TP) levels were measured and the findings are presented in the above graphs for communities with more than 2,000 persons and for those with less than 2,000 person equivalents (picture). The only two cities in the study, Linköping and Norrköping, each had BOD levels in their effluent of about 10 mg/l, and total P levels of 0.4 and 0.5 mg/l respectively (in red oval). Ten achieved better results than the cities (inside the coloured rectangle), while only one community, Kisa, had higher value of P.

The communities with less than 2,000 inhabitants also exhibit better treatment results than the two cities with three exceptions (far outside the rectangle). The good performance of small and middle-sized communities is not because all industries are located in the two cities. That could have been the case for other compounds but not for BOD concentrations and amounts of P. The conclusion is that bigger treatment plants do not guarantee better treatment results. Since then, more research has gone into small treatment units down to the household level and today, treatment quality is not an argument in favour of centralised solutions.

In the future, when households are acknowledged partners in managing the waste flows, it will be easier still for residents to make more meaningful contributions in a small system than in a large one. They can refrain from disposing non-degradable and toxic substances.
This contribution is likely to have a crucial bearing on the quality of effluent and sludge, and on reuse/ recycling management.



4.6- 3

Physical treatment processes use particle size or relative density to sort out certain components from the wastewater. A treatment unit may contain all the physical processes shown in the picture above, or only a few of them. The sequencing of processes may vary, but the one above is common. Debris and larger items are trapped in a screen. However, small particles and suspended material such as non-biodegradable fibres from clothing, powdered detergents, soaps and grease go through the screen and may be trapped by sedimentation, flotation, or media filtration and manufactured-membrane filtration. Physical processes reduce the amounts of microorganisms and chemical compounds to varying degrees. The trapped material always has to be removed regularly in order for the physical treatment process to function at full capacity.

Generally, it is easier and less expensive to sort items at the source and not discharge them in the wastewater. This is obvious for a household arrangement or a small group of households with a joint system. The household members can easily wipe food remains and fat from plates and cooking utensils, and they know that the more they allow into the water, the messier the job of emptying their grease trap will be. However, in a city sewerage the householder does not see the connection, and they do not know that cleaning (preventable) grease crusts from pipes is one of the operator´s tasks they pay for through their water bills.

Screening of debris and other solid items

4.6- 4

Solids trapped by a screen in a city wastewater treatment plant

Organics from kitchen pipe sorted out in a plastic screen

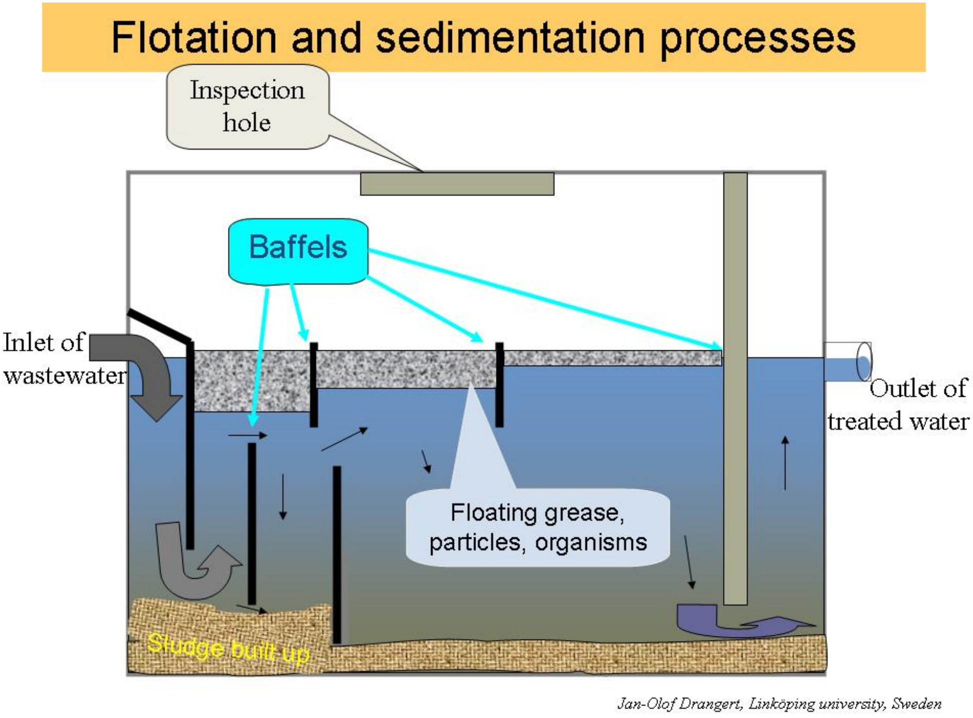
Jan-Olof Drangert, Linköping university, Sweden

Debris and large particles are removed from the wastewater through screening. The finer the screen is, the smaller the items are that can be trapped. The main purpose is to avoid clogging in subsequent treatment stages, e.g. sand filters. A screen is not intended to remove pathogenic microorganisms or dissolved matter in wastewater. The size of the screen unit takes into account the requirements of subsequent treatment steps, the content of influent water, the available space, and the rate of water flow. If the screen is very fine and the wastewater contains a lot of debris, only a moderate water flow can be managed. To treat a high flow with a fine screen, the unit itself needs to be bigger than if a coarser screen is used. The trapped material has to be removed regularly to prevent blockages of the screen.

The left-hand picture shows debris and other solid items trapped by a screen in a wastewater treatment plant. This waste is taken away for incineration or disposal by other means. At one wastewater treatment plant in Stockholm serving half a million residents, 35 tons of such solids are trapped in the screen each week; everything from paper, plastic bottles to carpets and dead cats. In towns where stormwater also enters the WWTP, the amount of debris is significantly larger (see Module 1.1- 4).

Typically, the kitchen sink, washbasins, and outlets from showers are fitted with a grate to catch objects and particles which are thrown in the solid waste bin. The right-hand picture shows solids in kitchen wastewater being trapped in a plastic screen before it enters a simple grease trap. At the household level a screen removes, for instance, left-over food, potato peels, and paper coming through the kitchen sink, or hair, nails and tooth picks from the shower which may otherwise clog subsequent treatment steps. Household members cannot avoid recognising the unpleasant physical feedback of poor handling since they have to remove these items from the plastic screen and grease trap.

4.6- 5



Sedimentation and flotation are cheap methods for removing particles and suspended material which has managed to pass through the screen, and they will facilitate subsequent filtration and/or biological and chemical processes. Sedimentation works on the principle of specific weight that causes higher-density material to sink to the bottom. The process can be enhanced by intentional flocculation (see 4.6-11) of solid matter into larger and heavier particles. Flotation works both on the principle of low-density material floating to the surface of the water body and suspended material interacting with highly dispersed air bubbles that can lift the material to the surface. Flotation may also be enhanced by aeration of the tank from the bottom. Baffles can be used to force the flowing wastewater to deposit heavy material at the bottom, and the upward flow helps the light material to reach the surface (picture).

Simple ***flotation*** occurs in a so-called grease trap where, for example, fat, oil and grease (FOG) cool down and form a light solid agglomerate that floats up to the water surface. Grease traps are placed under kitchen sinks, or any other drain that collects grease, fat and oil. Removal of FOG enhances the visual appearance of the wastewater and, more importantly, facilitates subsequent treatment steps and reuse. The same benefits apply to FOG from restaurants, hospitals, hotels, convention centers, sports arenas and prisons where huge amounts of FOG is generated each year. If allowed to enter wastewater pipes, this material readily adheres to the inner surface of the piping material. Such layers harden into a crust as tough as baked clay, becoming a primary cause of clogs, backups, overflows and equipment failure, ultimately requiring replacement of the affected pipes. The U.S. Environmental Protection Agency estimates that there are over 40,000 sanitary sewer overflows each year in the USA, the majority caused by grease buildup. Maintaining sewers is expensive and costs more than US$25 billion per year in the US – a situation often exacerbated by attendant cleanup fines levied by the EPA or the authority that has jurisdiction (Building Safety Journal, 2008).

The optimal size of the suspended particles that float to the surface is 10^{-5} to 10^{-3} m (or 0.01 - 1 mm). The scum layer may form a crust so hard that the process in the chamber becomes anaerobic. Thus, the scum or crust should be removed regularly. The removed material can be used in biogas production and also as compost material. The objective, however, is not the generation of energy or compost but to improve the efficiency of further treatment steps and reduce clogging.

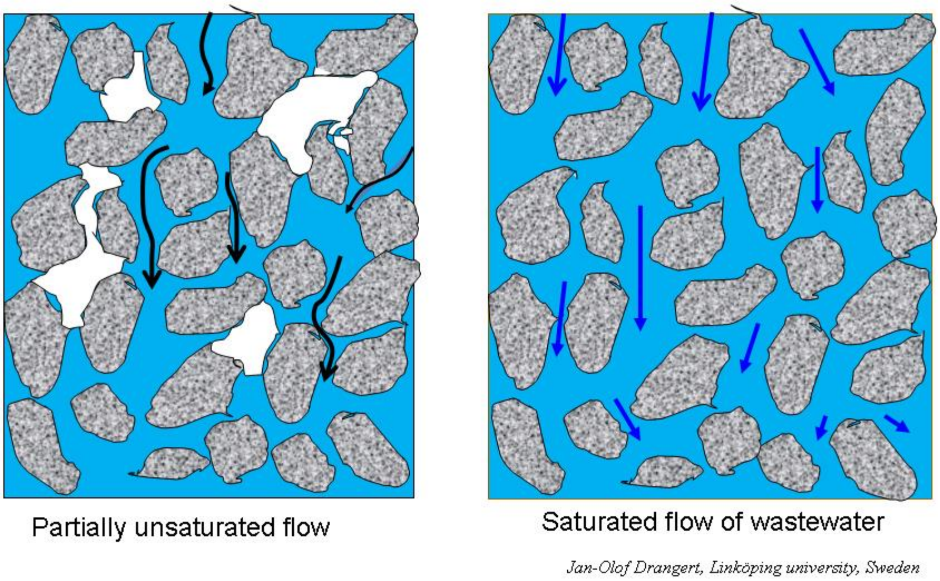
Sedimentation takes some time to occur and becomes quicker if the wastewater moves slowly. Almost all the settleable solids in the wastewater sink to the bottom within 2–6 hours. However, bacteria, viruses and metals are only removed if they are adsorbed to or trapped within a matrix of settleable solids.

If the organic content in the wastewater is low, an open pond can be used, where mainly aerobic microorganisms will decompose some of the organic matter. If the wastewater contains a lot of organic material, the aerobic bacteria will use up all available oxygen in the water, and anaerobic bacteria will continue the decomposition in the pond and sediment, causing potential smell problems. Therefore, the sedimentation unit is often covered, as in the case of the common septic tank for sedimentation of wastewater content from single households. In any system, the accumulated sludge has to be removed regularly; otherwise the treatment efficiency will go down.

After desludging a sedimentation unit, the sludge can be immediately incorporated into agricultural fields, or stabilised in different ways – e.g. anaerobic fermentation or liming – to reduce the nuisance of smell before putting it on soil. A prerequisite for reuse is that the levels of contaminants in the sludge are acceptable, and this can possibly be achieved through proper source control, as discussed in Module 4.5.

Filtration – mainly by gravity

4.6- 6



A wastewater flow through porous natural material such as sand, peat, and plant fibres, or manufactured micro filters is called filtration. This involves the deposition of suspended matter in the wastewater on the surface of granulated filling (film filtration), or the deposition of suspended matter in the pores of the filtration media, or a combination of the two. Filtration differs from screening in that it also includes physico-chemical and biological processes. Pollutants may be retained by sieving, adsorption (see 4.6–8), straining, interception and sedimentation (see 4.6–5). Pathogens can be trapped in the filter if its pore size is small enough, or if the adsorbing capacity is high enough, or by predation.

The right-hand picture shows a *saturated medium* (all pores filled with water), allowing the wastewater to flow freely through the large pores, while solid particles may be trapped in the smaller passages. If the trapped material is not entirely decomposed by bacteria the filter has to be backwashed regularly to remove such clogs and open up the pores again.

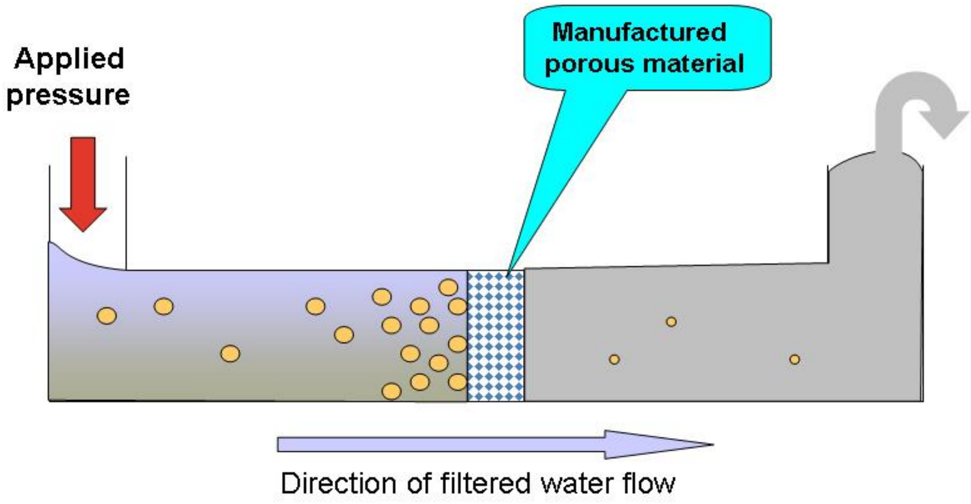
The same medium in the left-hand picture is *unsaturated* with some of the pores filled with air (white). The air obstructs the flow but air promotes the presence of aerobic microorganisms in the medium. Aerobic bacteria (breathing the air) are mostly attached to the surfaces of sand grains and an unsaturated flow allows them to feed on the passing organic matter transported with the wastewater. They are more efficient than anaerobic bacteria at decomposing organic matter – and removing disease-causing bacteria and helminths.

Wastewater tends to pass through small pores in an unsaturated medium while in saturated media the main water mass flows through the large pores as the latter have less hydraulic resistance. Unsaturated flows therefore provide better filtering but the passage will be slower than for saturated flows. In saturated media only modest chemical and biological activity takes place because there is less contact between bacteria and the sand grains and the bulk of the suspended material.

An unsaturated flow can be achieved through a proper loading of wastewater using design dimensions that account for the hydraulic conductivity of the media material (soil). A constant wastewater flow should be avoided. A simple tipping device is helpful to apportion pulses of wastewater to the filter media (4.7 - 13). The top layer of the filter medium may have to be replaced from time to time due to a reduced permeability as a result of gradual clogging.

Forced micro-filtration

4.6- 7



Jan-Olof Drangert, Linköping university, Sweden

Microfiltration is a filtration process that works by pressing wastewater through a manufactured porous material with thin micron-sized pores. Micro filters are produced mostly in the form of a quite thick porous partition (e.g. cartridge filter) or thin-film membrane filters. Microfiltration is used to remove fine suspended particles from water.

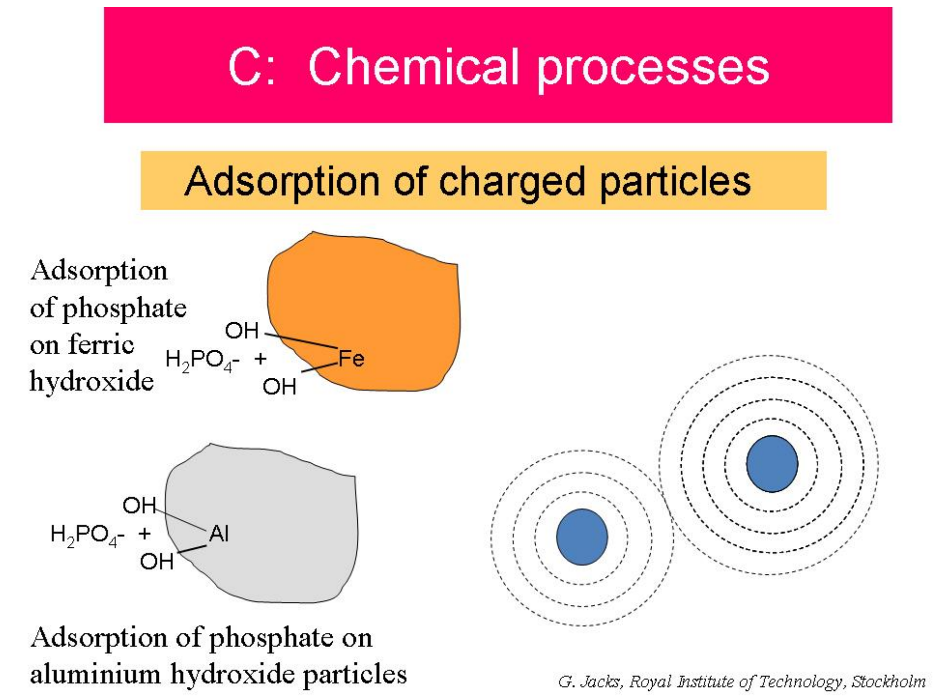
Nowadays, membrane filters can be so fine that almost any dissolved matter can be caught in them. Depending on the pore size of the semi-permeable membrane, ions (in reverse osmosis or nanofiltration processes) and organic molecules (in nanofiltration or ultrafiltration processes) can be caught. Colloid or thin suspended matter can be filtered out by ultra- or microfiltration. With a membrane pore size of 20–500 nm all pathogens, including viruses, can be filtered away. However, the filtering is complicated by the clogging problem from concentrate formation.

Membrane technology was firstly developed to treat drinking water and is now also used to turn treated wastewater to drinking water standard. In Singapore, all treated wastewater is put through a reverse osmosis filter before it is delivered as tap water for mostly industrial use.

For example, a nanofilter of 25 nm removes biotic and abiotic particles >15 nm. Clogging may cause problems, however. Even if all bacteria and viruses can be removed, metabolites of natural microbial communities in the contaminated sites may still remain and some of them could be very toxic. In addition, dissolved contaminants such as heavy metals (e.g. Cr, As) and toxic organic/inorganic compounds (e.g. pesticides) cannot be removed by size exclusion in such a device.

The cost of membrane filters has gone down, but the process (especially reverse osmosis) is quite energy intensive as it requires the application of pressure and circulation of feed water. The energy for these processes is normally generated by electricity. Also, the membrane filtration processes require constant care and maintenance. Membrane filtration is feasible only where management and economic resources are available – and where high quality water is required.

4.6- 8



The physical treatment processes discussed in the previous module depend upon particle size and specific weight. However, many substances are dissolved in wastewater or are too small to catch in this way. Instead we need to employ chemical or biological methods to catch them. Chemical processes are adsorption, precipitation, coagulation, UV-radiation, ozonation and chlorination.

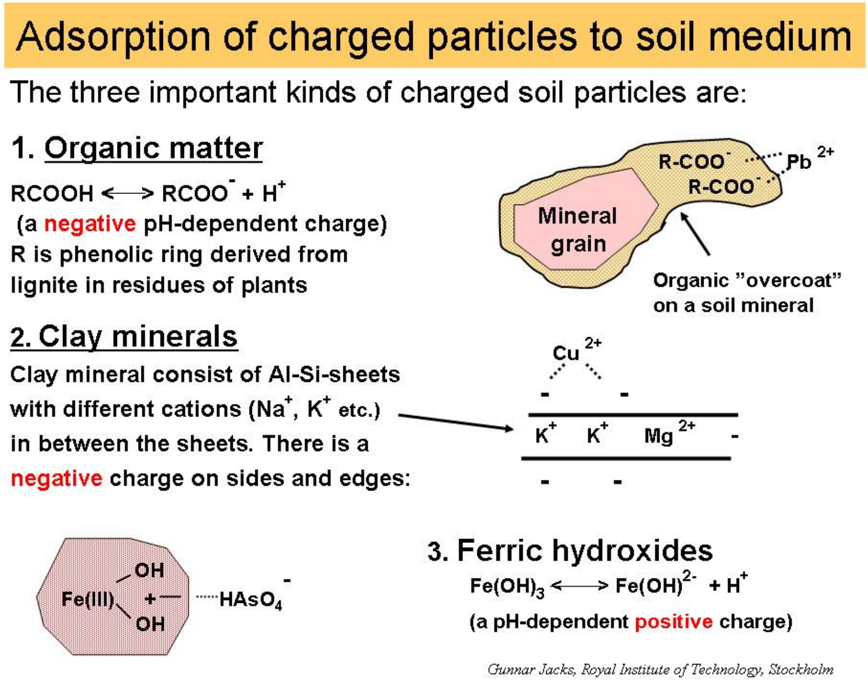
The interaction between dissolved substances in the wastewater and the medium they pass through is often governed by electrical charges of their surfaces. The medium and the dissolved substances (organic molecules, charged solutes) may bond and this is called adsorption – an electrostatic phenomenon. This phenomenon is utilised to remove unwanted particles from the wastewater. Most of the dissolved substances in wastewater can bond with solid adsorbents such as activated carbon, synthetic polymer sorbents, or natural mineral sorbents (zeolites, clausm etc.). This occurs as a result of a set of complex processes.

Adsorption is widely used in water treatment processes. Commonly, electrons on the surface of a substance determine how it behaves in relation to other substances. What happens at the level of protons/ neutrons and electrons (right-hand picture) is determined by whether the shell of electrons is "filled" or not. If the outer shell of the substance has negatively charged ions (***anions***), the substance will be attracted to a positively charged ion (***cation***). Two types of adsorption can be distinguished: inner and outer sphere adsorption. When ions bind directly to the surface with no intervening water molecules, an inner sphere complex is formed. These types of surface complexes are restricted to ions that have a high affinity for surface sites and include specifically adsorbed ions that can bind to the surface through covalent bonding. Outer sphere adsorption is less strong since water molecules which are dipoles may hinder the adsorbed specie to be closely attached to the adsorbent (Keiluweit & Kleber, 2009).

If a filter medium is positively charged it will attract particles with negative charges and vice versa. Filter media may have a permanent charge. For example, many silicates and clay minerals are negatively charged. These may therefore adsorb positively charged particles or cations like heavy metals e.g. Cu^{2+} and Pb^{2+} (slide 4.6-9). Other filter media may have a pH-dependent charge (pH is a negative logarithmic measure of the concentration of hydrogen ions H^+).

Filter media attract microorganisms such as bacteria and fungi, and some of these are charged and can attract cations. Filter media can also be modified. For example, *zeolites* are silicates with a large surface area which is normally negatively charged but by covering it with ferric iron (F^{3+}) it can be made to adsorb negative particles.

4.6- 9



Charged soil particles serve as filters or catchers of dissolved substances when wastewater percolates through the soil profile. Three types of charged particles, all of which are common in most soils, are especially important: 1) organic matter; 2) clay minerals and;
3) ferric hydroxides.

Organic matter in soils consists to a large extent of humic matter from degraded plants and animals and their phenolic rings. The phenolic rings are inherited from lignin which covers plant cells, particularly the woody parts. They are only slowly degraded (the time varies from years to centuries depending on the complexity of molecules). The rings are bonded to abundant carboxylic groups ($R\text{-}COO^-$ in picture). This means that organic matter is a weak acid which reacts, for example, like oxalic acid. Also, the higher the pH the more the carboxylic groups are dissociated (i.e. R-COOH releases H^+ ions to water resulting in the negatively charged $R\text{-}COO^-$) and the negative charge increases as does the cation adsorption capacity.

Clay minerals consist of sheets of Al-Si tetrahedral (aluminium and silicate). Sandwiched between these sheets are cations of hydrogen, sodium, potassium, magnesium or calcium. There is usually a deficit of positively charged cations which means that there is a net negative charge on the sheet surfaces and at the edges of the clay particles. The charge is more or less constant throughout the pH scale. Therefore cations such as Cu^{2+}, Pb^{2+}, and Zn^{2+} adsorb to the clay and are immobilized.

Ferric hydroxides $Fe(OH)_3$ often cover silicate mineral grains and at low pH there is a deficit of hydroxyl-ions and so the hydroxides have a positive charge which decreases with increasing pH. Many hydroxides (with an OH group) have a positive charge at lower pH, meaning a higher concentration of H^+. For instance, sand coated with $Fe(OH)_3$ may adsorb negatively charged ions as part of the OH-groups' reaction with abundant H^+ at low pH:

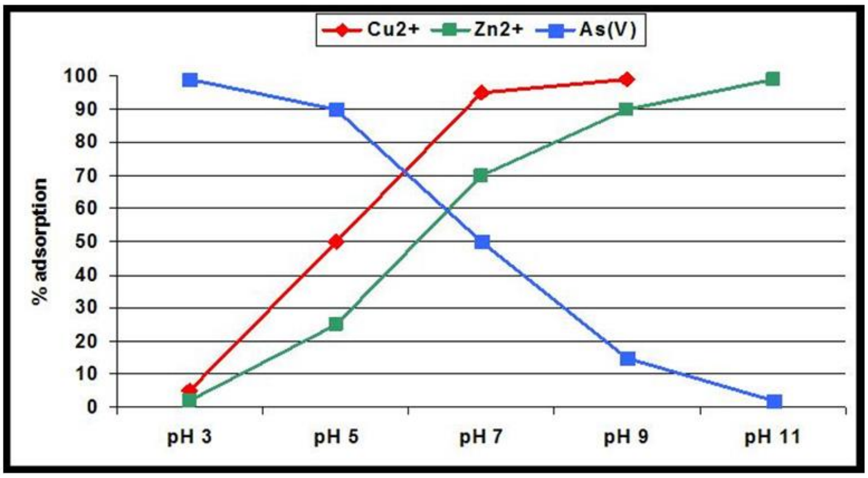
$$Fe(OH)_3 + H^+ \rightarrow Fe(OH)_2^- + H_2O$$

Any anion can adsorb to ferric hydroxides. Arsenic is an example of this but its adsorption depends partly on the charge of the ferric hydroxides and also on the dissociation of the arsenic acid: $H_2AsO_4^- \leftrightarrow HAsO_4^{2-} + H^+$

The equilibrium constant for the dissociation is 7, which means that at pH 7 the two forms are present in equal concentrations. If the pH is below 7, the $HAsO_4^{2-}$ dominates and due to the higher negative charge it is more efficiently adsorbed.

Adsorption of chemical compounds differ

4.6- 10



Copper (Cu) and Zink (Zn) are positively charged, and adsorb easily on organic matter and clays when the pH > 7

Arsenic (As) is negatively charged and adsorbs easily on ferric hydroxides when pH < 7

Gunnar Jacks, Royal Institute of Technology, Stockholm

Cations like Pb^{2+}, Cu^{2+} and Zn^{2+} are adsorbed onto the negatively charged organic matter and clay minerals. More cations can be adsorbed as the abundant carboxyl groups on the organic matter are dissociated (R-COOH becomes $R\text{-}COO^-$ + H^+. see 4.6-9). Anions like As^- are adsorbed onto the positively charged ferric hydroxides.

The graph shows that the propensity to adsorb is highly dependent on the pH of the environment (although Pb^{2+} and Cu^{2+} are strongly adsorbed even below pH 7). Half of Cu^{2+} is adsorbed at pH 5, and almost all at pH 7. Zn^{2+} and Cd^{2+} are less strongly adsorbed. Arsenate ($H_2AsO_4^-$ and $HAsO_4^{2-}$) has an opposite dependence, and adsorption decreases with rising pH as the OH^- ions fill up the positions around the ferric iron. At pH 6 some 70 per cent of the arsenate is adsorbed while adsorption is nil when pH is 11.

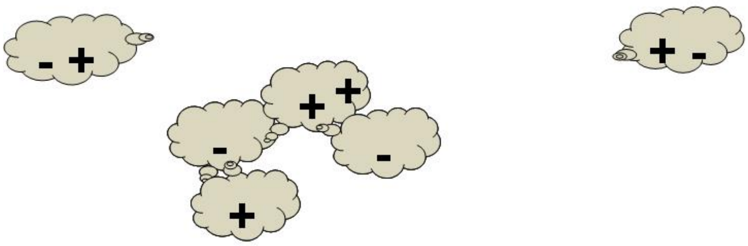
It is desirable to remove metals from the wastewater before the effluent is discharged to water bodies or is recirculated for human use. The dependence on pH complicates treatment, not least because soils can have naturally different pH levels. Human activities produce acid rain which makes soils acid (low pH), and so previously adsorbed Cu and Zn are being mobilised. Soils in Bangladesh have pH levels of about 7, while soils in Argentine have pH levels of 8.5. Therefore, copper and zinc are essentially immobilised in Bangladesh and are not found in its water bodies, while arsenic is mobile in Argentine and water bodies can contain high levels of arsenate.

In a treatment unit the pH level can be raised by adding calcium. Lowering the pH of a soil profile or in a filter is not a common practice. However it might be done if there is a question of removing arsenic for instance. Ferrous chloride is then added, which oxidizes to ferric hydroxide, releasing hydrogen ions and precipitating as ferric hydroxide. The ferric hydroxide is a good adsorbent for arsenic and can be filtered away.

Precipitation and flocculation

4.6- 11

- Precipitation – a chemical reaction between dissolved compounds to form solids
- Flocculation - an aggregation process (or processes) leading to the formation of larger particles from smaller particles



G. Jacks, Royal Institute of Technology, Stockholm

The word **precipitation** originates from hydrology and describes the process when moisture in cooled air condenses from vapour to form drops which precipitate or deposit e.g. rain and dew. In the context of wastewater treatment, precipitation is a chemical reaction where ions or molecules in dissolved form react with other chemicals (added to water) and form an insoluble compound that can sediment.

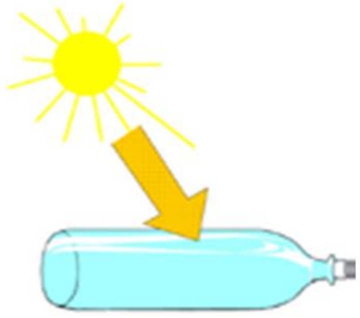
Flocculation is an aggregation of smaller particles to a bigger one, usually with the help of polymers as flocculants. In wastewater treatment this process is often preceded by coagulation. This is an aggregation of highly dispersed particles (colloids) in wastewater by addition of coagulants (hydrolysed salts) such as ferric chloride ($FeCl_3$), aluminium sulphate ($Al_2(SO_4)_3$) and chloride ($AlCl_3$) and others. The positively charged (cations) coagulants reduce the negative charges of the colloids, and thus neutralize the forces that keep them apart. As a result, the dispersed particles collide to form larger particles (flocks). The size of the flocks ranges from a few micrometres to a few millimetres. Further flocculation by polymers is an electrostatic process in which the polymer has numerous “arms” which collect small particles and form larger ones that are of high density and can be separated from the water by sedimentation. The aggregating particles in greywater are heterogeneous and are composed of dissolved, colloidal (gluey), and particulate materials of varying size and composition.

The processes of flocculation and precipitation can be speeded up by forcing the wastewater to flow through lamellar baffles in a settling tank. The retention time may be reduced from four to six hours in an ordinary settler down to less than one hour in the lamellar settler. The design has to strike a balance between building a more complicated lamellar settler and the cheaper settler that requires more space. In both cases helminth eggs will settle, while part of the organic matter and nutrient content remain in the effluent which makes effluents more valuable to agricultural use. However, bacteria and viruses remain in the effluent and have to be inactivated for some uses. As discussed before, metals and organic substances that tend to adsorb to inorganic and organic particles will settle with the particles that are removed.

By adding different types of chemicals, precipitation can be combined with flocculation to increase the removal of certain compounds. This is commonly done in conventional wastewater treatment plants, where iron- or aluminium-containing chemicals are added to precipitate phosphorus. In the process, a substantial amount of organic matter is also flocculated and removed by sedimentation. However, flocks are fragile and can easily break, and therefore the water velocity to the settling tank should be gentle to maximise sedimentation.

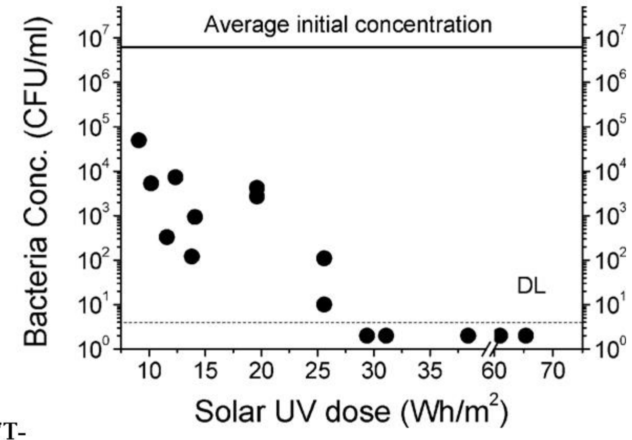
UV-radiation by sunlight

4.6- 12



Inactivation of micro-organisms by UVA-radiation and increased temperature

http://www.sodis.ch/Text2002/T-TheMethod.htm



Source: Ubomba-Jaswa et al. 2009

Exposure to UV light is an effective disinfection method which kills microorganisms. However, it is costly to use if the UV light has to be generated by lamps. Solar UV light disinfection, on the other hand, can be both practical and inexpensive.

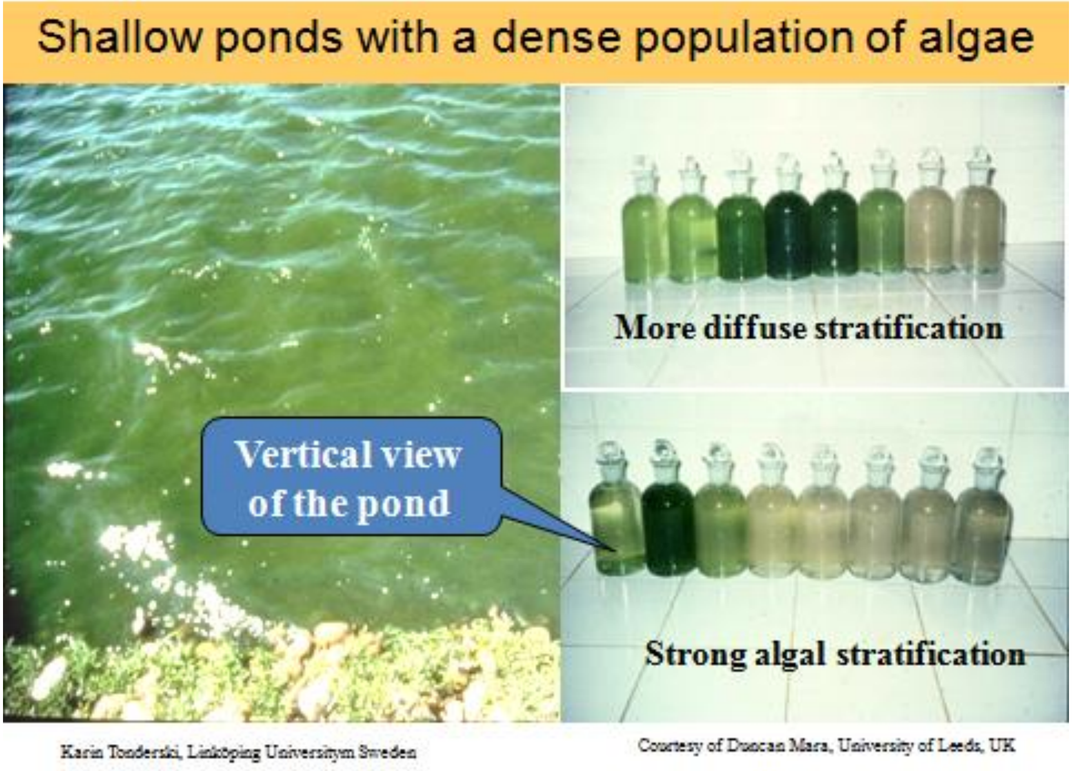
The main ultraviolet component of sunlight is UV-A, and this can inactivate pathogenic organisms through photo oxidation, where the energy-rich light causes the loss of one or more electrons from a chemical compound as a result of photoexcitation. The energy contained in the UV-light may also cause the formation of reactive forms of oxygen in the water that are damaging proteins, bacterial membranes and DNA.

Our understanding of the disinfection process is incomplete, but it seems that its efficiency depends on the uninterrupted total dose of UV light received by the bacteria (see graph above).

There are examples of microbial pathogens in drinking water being inactivated after 6 hours exposure to intense sunlight. A common method is to keep the water in a half-full transparent PET bottle exposed to the sun (Sodis method). A number of factors affect the time required for an efficient disinfection process. A high turbidity of the water will annul the process, since viruses and bacteria can hide behind particles. The intensity of the sunlight and the way the sunlight reaches the water also impact the time required. A general recommendation is to keep the bottle in the sun for two days provided that the water is clear and not turbid.

Treated greywater is usually more turbid and contains more particles than drinking water and therefore the required dose of UV to obtain a safe level of bacteria inactivation is higher. There is still not enough scientific evidence of the die-off of viruses in the process. However, UV radiation reduces many pathogens and is a cheap method to reduce health risks.

4.6- 13



We often view eutrophication as a serious problem when it occurs in lakes. The argument is that the decomposition of large numbers of dead organisms depletes oxygen and results in bottoms devoid of higher life forms. The oxygen-free environment gives rise to anaerobic bacteria which survive and produce methane gas and other residues.

However, in a controlled situation with a shallow pond, eutrophication can be used productively. The difference between shallow ponds and lakes is that the photosynthesis is active in the whole water body down to the bottom (see left picture). The released oxygen from the photosynthesis is used by aerobic bacteria to break down decaying organic material (dead algae, plants, etc.) without producing methane.

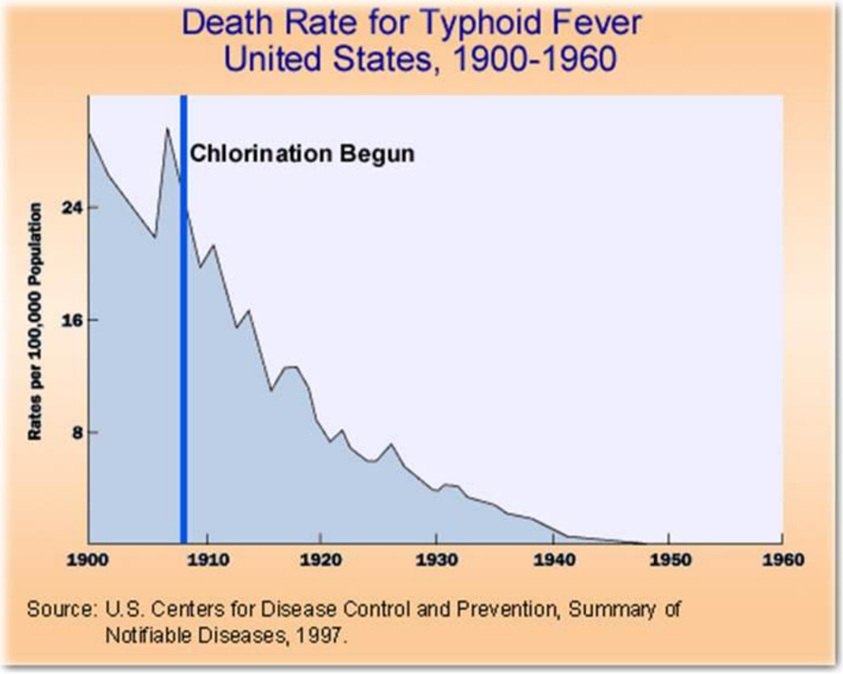
The water in a pond may contain a strong algal stratification or it may be more diffuse as indicated in the pictures to the right.

Experiences from sewage stabilization ponds show that in shallow ponds with high populations of algae the concentrations of bacteria known to be potentially pathogenic drop rapidly. This is thought to be due to a combination of UV from sunlight, a high pH caused by intensive photosynthesis by the algae, and possibly the high oxygen concentration resulting from photosynthesis.

Hence, adding a shallow pond for greywater polishing after the main treatment can be a low-cost method to reduce its pathogen content. The effluent leaving the pond also has low levels of algae and has a near-neutral pH if the discharge point is placed a bit below the pond surface, where the algae population and photosynthetic activity is highest.

4.6- 14

Ozonation and chlorination



Chlorine such as Cl_2, chlorine gas or sodium hypochlorite are very strong oxidants (= covers with a layer of oxygen) that can degrade organic matter and damage cell membranes, thereby killing bacteria and viruses. Chlorine can also combine with organic matter in the water to form chlorinated compounds. A common name used for such compounds formed as by-products of the chlorination of water is Trihalomethanes (THMs). Chloroform is one example. Such chlorinated compounds are potentially carcinogenic, and hence this is a non-desirable side-effect of chlorination. However, the risk to humans from those byproducts is small in comparison to the risks associated with inadequate disinfection (WHO Guidelines, 2006).

Ozone is an alternative to chlorine for killing bacteria and viruses as it is very reactive and a strong oxidant. It is effective over a larger pH range and needs a shorter reaction time. No other chemicals are added. In addition, the ozone also oxidizes hydrogen sulphide, manganese and iron into sulphur or sulphate, and insoluble iron and manganese oxides that can be filtered away. The disadvantage with ozone is that it is more expensive and the regrowth of bacteria cannot be controlled. The risk posed by possible toxic byproducts is not well known. Another disadvantage with ozone is that – unlike chlorine products – it does not have any residual disinfectant effect after its immediate action. This means that regrowth of microorganisms may occur in the network of distribution pipes. Possible formation of toxic by-products is less evident than for chlorination, but cannot be excluded as a possibility.

The graph above gives a tentative relationship between the water-borne disease typhoid and chlorination of drinking water in the USA. There are also other factors that have promoted the decline of typhoid in USA, and discussions about how to interpret epidemiological data are relevant in this case (Chapter 3).

4.6- 15

D: Biological processes

Karin Tonderski, Linköping university, Sweden

A number of wastewater treatment systems are based primarily on biological processes, where microorganisms decompose energy-rich organic substances, such as proteins, fats, starches and cellulose to support their growth. Biological treatment relies mainly on microbiological processes that take place in the water, sediment and on plant tissue (stems, leaves and roots) in ponds and wetlands, or on the surfaces of sand and soil grains in sand filters with or without plants (see photographs above). In both ponds and wetlands, plant and algal uptake of nutrients may periodically be important for nutrient removal, particularly if the plant biomass is harvested, while the interactions between wetland plants and microorganisms are significant for all water treatment processes. The oxygen supply to biological treatment systems is of crucial importance for their functioning and for determining what the end products of the decomposition processes will be. If the biological treatment systems are supplied with sufficient oxygen, the major end products from organic molecules will be carbon dioxide (CO_2), water and new microbial cells.

Both plants and microorganisms also contribute to partially remove organics, heavy metals and toxins in wetlands and filters.

The effluent from biological systems can be used for irrigation under certain restrictions (WHO, 2006). If the treated effluent is just discharged it may pollute the groundwater. Therefore, planning of biological systems should consider potential impacts on shallow groundwater and leakage of the effluent into receiving surface waters.

Soil organisms vary tremendously in size and numbers

4.6- 16

A teaspoon soil ~ one gram

Microbial group	Example	Size (µm)	Numbers (per gram soil)	Biomass (g wet mass per m^3 soil)
Bacteria	Pseudomonas	0.5 – 1.5	10^8 - 10^9	30 – 300
Fungi	Mucor	8 (hyphae diameter)	10^5 – 10^6	50 - 500
Protozoa	Euglena	15 * 50	10^3 - 10^5	0.5 – 20
Nematodes	Pratylenchus	1000	10 – 10^2	0.1 – 10
Earthworms	Lumbricus	100 000		1 - 100

Modified from Sylvia, D. *et al*. 2004. Principles and applications of soil microbiology

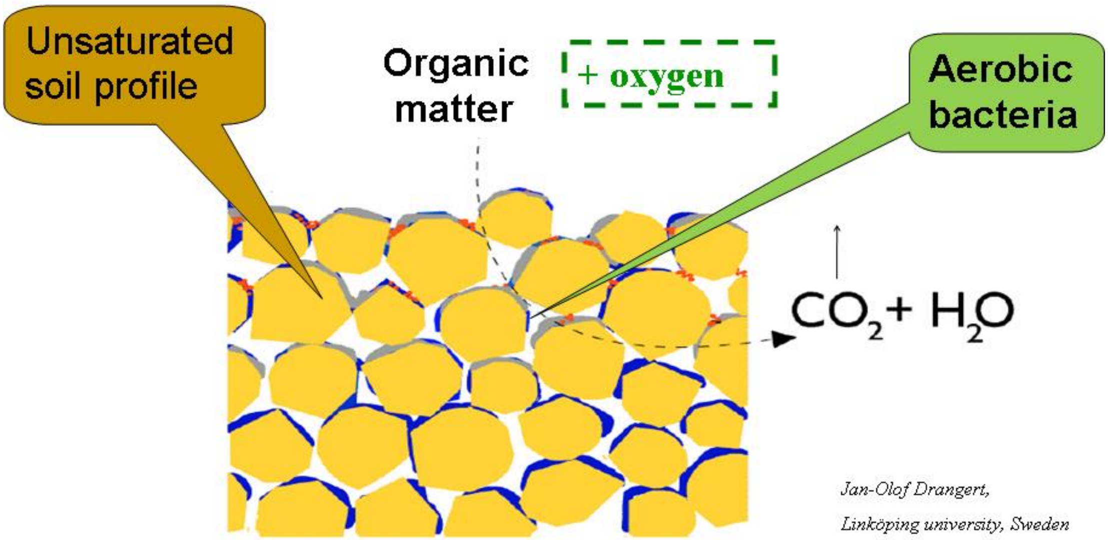
Despite their minuscule size (one µm is 10^{-6} meter or one thousands of a mm), bacteria and fungi make up the major part of the total biomass in an aerated soil profile. It is worth remembering that a teaspoon of soil is the home for a billion invisible organisms, most of which contribute to the treatment of wastewater if we use the soil/sand for that purpose.

The table above shows that other, larger, microorganisms are fewer but they are nevertheless important in soil ecosystems. It has been shown that predation by soil animals promotes decomposition, which releases the available nutrients and thus enables the growth of plants. One mechanism is that the animals constantly feed on the bacteria and fungi populations and thus maintain them at a high growth rate. In addition, when earthworms feed on nutrient-rich bacteria or fungi, they excrete nutrients that become available to plant roots and stimulate plant growth. Hence, we should view a soil or sand filter as a complex ecological community in which the interactions between organisms are vital for the efficient decomposition of organic matter contained in the wastewater we want to treat. As most animals are dependent on oxygen for their survival, when using filters to treat wastewater it is important to keep the soil unsaturated for this ecological community to function the way we want it to.

Biological processes - with air

4.6- 17

Oxygen is vital for most living organisms, including bacteria and viruses. When oxygen is present, organic matter (measured as BOD) is efficiently decomposed by organisms into CO_2 + water:

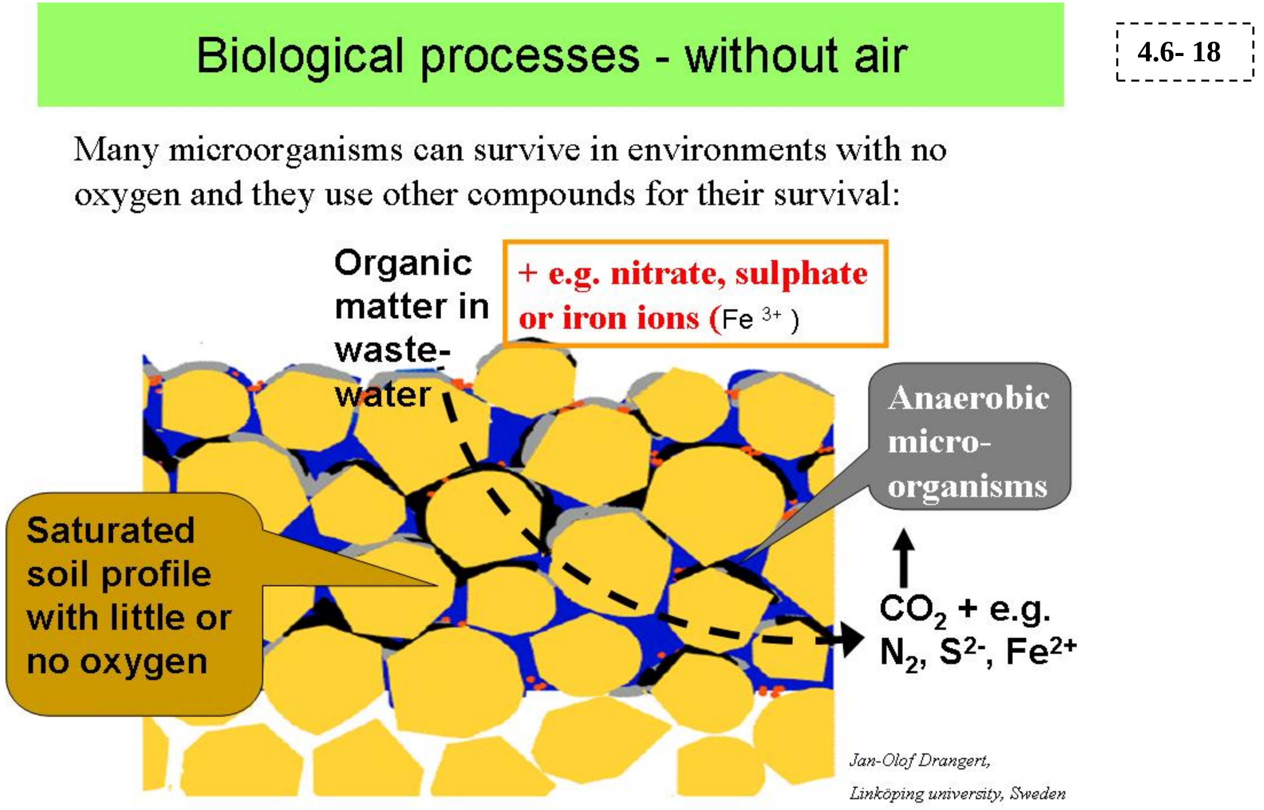


Microorganisms are adapted to live in aerobic (with oxygen) environments or in anaerobic (without oxygen) environments. Some can live in both. Aerobic microorganisms decompose organic matter into new cell material, carbon dioxide and water ($CH_2O + O_2 \rightarrow CO_2 + H_2O$ which is the reverse of photosynthesis). The most complete and rapid decomposition of organic matter takes place when oxygen is available.

The picture above shows the profile of an unsaturated soil or sand filter with voids or pores of air/oxygen (white colour). In practice, the best way to maintain aerobic conditions in a treatment system based on filtration through sand is to apply the wastewater at intervals. By using a device such as a pump or siphon (see 4.7-13), the flushing wastewater is distributed over the whole surface. Also, the sand profile can dry up and passive aeration of the pores occurs in between the wastewater applications. Such passive diffusion of O_2 through a porous medium such as drained soils is about 10 000 times faster than diffusion of O_2 in an aqueous solution.

Aerobic microorganisms can live and grow on the filter particles and form a thin layer or biofilm around the soil particles (blue on the picture). They come into close contact with the organic matter in the wastewater which (intermittently) flows past the particles. They decompose the organic matter and the by-products are water, carbon dioxide which dissipates into the air, and the newly formed cells are small and do not clog the pores when they move along with the wastewater flow. If the application rate of wastewater is reasonably low, the filter will remain unsaturated and aerobic.

Sand filters do more than just reduce organic matter – as mentioned in the previous module about chemical treatment. Ions of metals may adsorb to the microorganisms and sand particles. Some potentially pathogenic organisms will also be removed by adsorption, decomposition and predation by the micro-fauna (small animals).

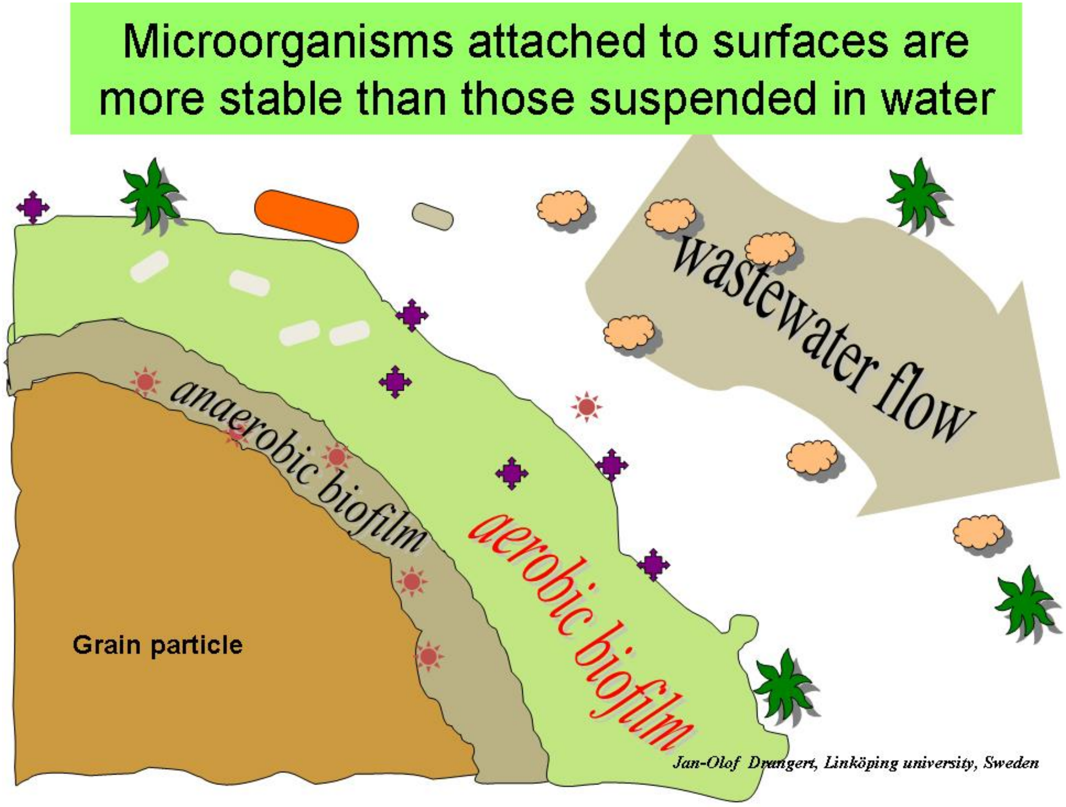


If the loads of wastewater entering a soil or sand filter are too high, if they contain too much organic matter, or if the filter is operated with a continuous load of effluent, the soil profile will become saturated – that is, all pores will become filled with wastewater (blue section). Typically, a thick biofilm develops consisting of live and dead cells and a "gel" of exudated organic molecules between the cells (black layers). The hydraulic conductivity of the soil decreases as a result of the accumulated organic matter in the soil pores. We say that the filter has clogged and anaerobic conditions develop in the soil filter.

Anaerobic microorganisms can survive in this harsh oxygen-free environment. Instead of oxygen they can use other chemical components to extract energy from the organic matter for their growth (details in 4.6-17). For example, the sulphate-reducing bacteria transform sulphate (SO_4^{2-}) in the wastewater into sulphide (S^{2-}) in order to make use of the energy contained in the organic matter. In turn, this sulphide ion will efficiently attract positively charged metal ions in the wastewater and the resulting solid substance precipitates and settles at the bottom of a pond or in a soil filter. The smell of sulphide is an indicator of anaerobic conditions.

Anaerobic microorganisms are less efficient than aerobic ones in decomposing organic matter, and if saturated conditions prevail for a prolonged period the treatment efficiency drops due to the lack of oxygen. Even in an unsaturated profile (previous slide), the microorganisms may consume all oxygen locally if the treatment system lacks artificial aeration, and anaerobic zones are interspersed with aerobic ones. A more detailed discussion of the change that occurs in the microbial community and metabolism when systems turn from aerobic to anaerobic is given on page 21.

Enteric bacteria are essentially anaerobic bacteria (excreted from our anaerobic intestines) and will therefore survive better in an anaerobic sand or soil filter. Survival of pathogens is dealt with in Chapter 3



4-6- 19

In a wastewater treatment system with a solid medium such as a sand filter, microorganisms become attached to the surfaces of the medium. This contrasts to activated sludge systems or open ponds where microorganisms remain suspended in the water. The active bacteria form a biofilm on the grain particles and they decompose substances in the flowing wastewater. Bacteria multiply by building new cells out of the decomposed material. Organic matter, nutrients and oxygen diffuse into the film and are absorbed by the (growing) microorganisms, resulting in a gradually thickening microbial film (green layer in picture). Eventually, the film is so thick that oxygen-free conditions develop in the inner (grey) layer, where organic matter from the wastewater and dead microorganisms are decomposed anaerobically. In high-loaded systems the thickest part of the outer layer is gradually sloughed off, and must be removed in a settling unit beneath or beside the filter (slide 4.6-17).

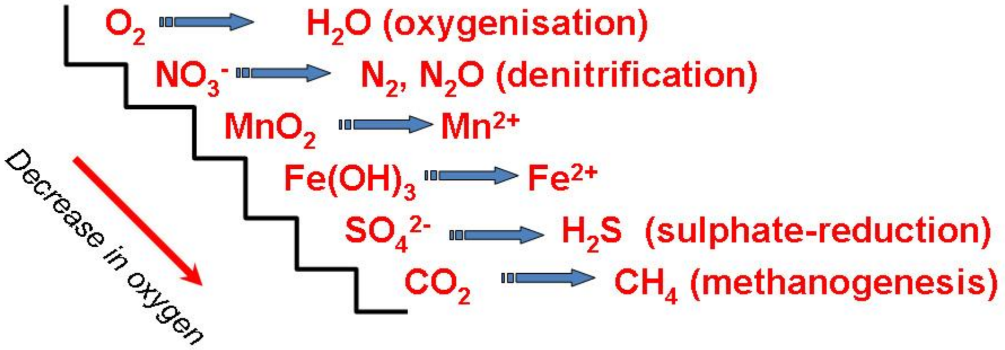
Such attached growth allows a much higher cell density than is possible in a system with suspended growth (e.g. activated sludge). This permits the use of smaller reactor volumes with a lower specific growth rate of microorganisms. As a result, the amount of biological sludge (i.e. dead microorganisms) that is formed and needs to be removed in a settler is less than in a suspended growth treatment system (Pandey, 2004).

Microbial studies have also shown that microorganisms growing attached to surfaces are less susceptible to different kinds of potentially harmful chemicals, e.g. antibiotics. A microbial community growing attached to surfaces, for example sand or soil grains, is also more tolerant to large flow variations that might wash away microorganisms growing in a suspension.

4.6- 20

"Redox-ladder"

When microorganisms descend the redox-ladder they first use O_2 as an electron acceptor, then nitrate NO_3, and further down other compounds as electron acceptors. The blue arrow indicates a reaction with energy-rich organic substances (electron donors) in the wastewater



Gunnar Jacks, Royal Institute of Technology, Stockholm

In the photosynthesis *autotrophic* organisms use energy from the sun to form new cells from carbohydrates, carbon and water. The new cells consist of carbohydrates, proteins and or fats, in which energy from the sun has been converted into chemical energy. Most living organisms (both humans and bacteria) want to use this chemically bound energy for their own growth and survival. To do that, they decompose such carbon-containing molecules back into carbon dioxide, water and nutrients, to free the energy for their own metabolism. Humans and other mammals, earthworms, many fungi and bacteria use oxygen for this decomposition in a so-called *oxidation* reaction.

The microorganisms can initiate two types of *chemical* reactions that are instrumental in wastewater treatment; acid-base reactions and redox-reactions. Acid-base reactions involve transferring *hydrogen ions* (H^+) from one molecule to another. The redox-reactions (REDuction and OXidation reactions) involve transferring electrons (e^-) where one molecule is an *electron donor* and another is an *electron acceptor*. These reactions occur in most treatment processes. In this module we discuss the reactions in environments with a lot of oxygen, small amounts of oxygen or no available oxygen.

The organic matter contained in the morning sandwich for a human being, or the carbohydrates and grease in greywater for the microorganisms in a treatment system, are examples of *electron donors*. The amount of energy that an organism can retrieve from an electron donor molecule depends on which molecules are available as *electron acceptors.* Oxygen is the best and enables the organism to make use of much of the energy contained in the carbohydrates. The less favorable ones follow as we go down the so called *redox ladder*.

Aerobic bacteria, as well as humans, have enzymes in their cells that can use oxygen (O_2) molecules as electron acceptors to form water molecules (H_2O). In the process, each oxygen atom receives two electrons from the organic matter that is being decomposed and the now negatively charged oxygen attaches to available hydrogen ions (H^+) and forms a non-charged water molecule. In this process, energy from the electron donor molecule is released. This describes the process of the highest rung of the redox-ladder where oxygen meets with any molecule which is an electron acceptor.

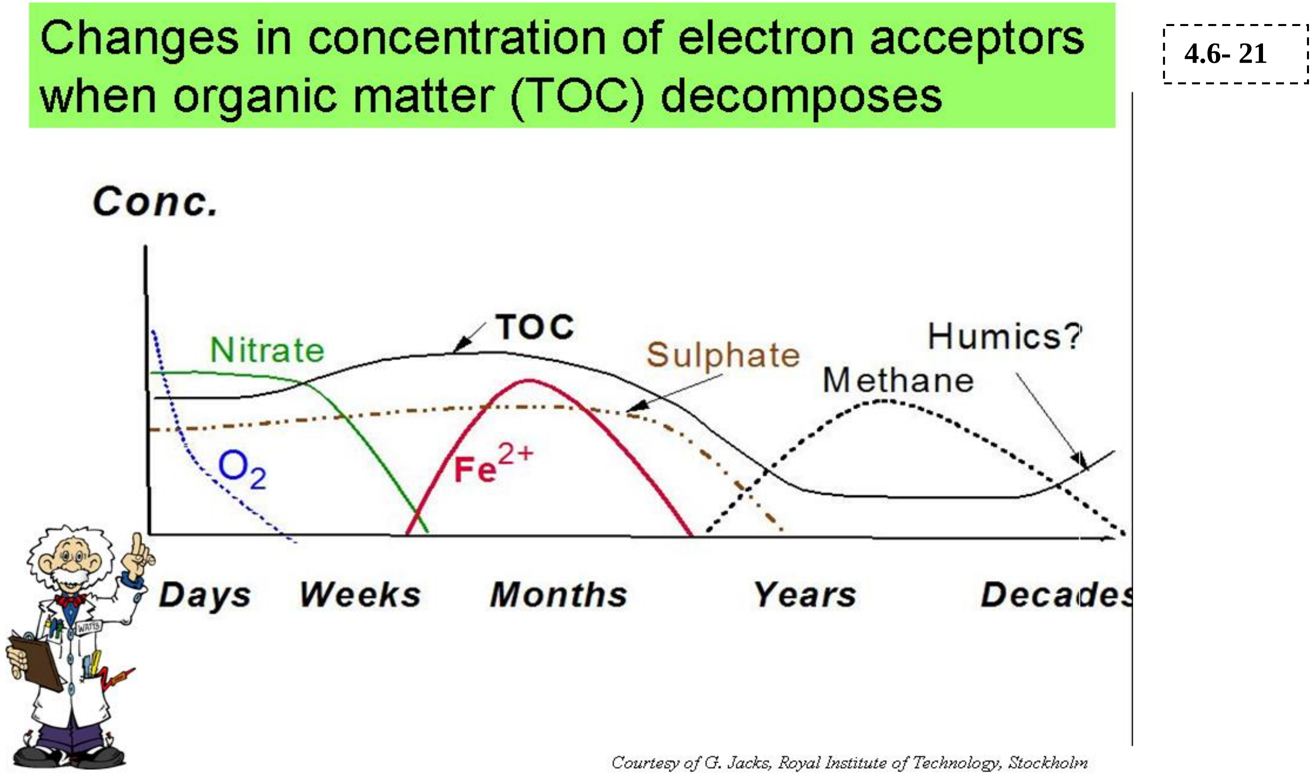
Environments with no oxygen are found in certain wet soils, and in wetland and lake sediments. When oxygen is being depleted another group of bacteria can recover energy by using the second best electron acceptor molecule one step down in the ladder, nitrate NO_3^-. Also denitrifying bacteria use energy from an organic substrate to transfer electrons to the nitrate ion, which changes into nitrogen gas or dinitrogen oxide. As nitrate is depleted and less and less favorable electron acceptor molecules are the only ones available down the ladder, other anaerobic microorganisms can use other molecules to get energy from the organic matter.

The next electron acceptor to step in, if the nitrate is not there or depleted, are manganese oxides which can be three- or four-valent. There exists a large number of different manganese oxides formed under different conditions. When manganese oxides are used as electron acceptors the manganese is transformed into Mn^{2+} which is fairly soluble and is a common problem in groundwater.

The next type of organic matter degrading bacteria use ferric iron in iron hydroxides (see slide 4.6-9) as electron acceptors forming ferrous iron (Fe^{2+}) which is quite soluble and is a common problem in groundwater.

We mentioned before that sulphate-reducing bacteria use sulphate (SO_4^{2-}) in the wastewater as electron acceptors, and transform it into ion sulphide (S^{2-}). Sulphide has a distinctive smell which is therefore an indicator of anaerobic conditions. In turn, this sulphide ion will efficiently attract positively charged metal ions in the wastewater and the resulting solid substance precipitates and settles on the bottom the pond or in the soil filter.

The methanogenesis reaction is important for biogas production. This is the last step in the “ladder” and is quite “uneconomical” for the microorganism since it forms an energy-rich compound, methane. The methane fermenters are a unique group of microorganisms, Archaea, that can operate in a very reducing environment where all other oxidants like oxygen, nitrate, manganese, ferric iron and sulphate have been consumed (see biogas Module 4.4-12).



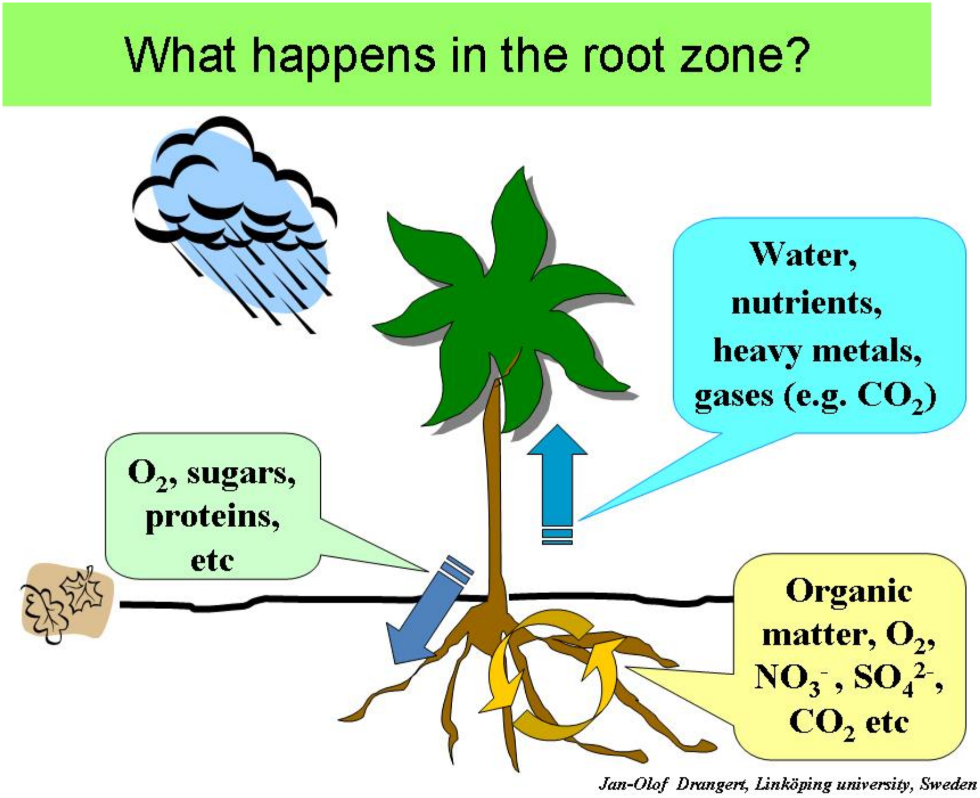
A solid waste deposit is a good example of a redox-sequence. In a landfill with organic matter, all the processes in the aerobic-anaerobic "ladder" take place simultaneously but in different parts of the landfill. The initial oxygen in the waste is consumed soon after it is dumped and more and more reducing conditions develop in the deposited organic matter. Eventually, we reach the bottom step of the ladder in an environment where methane-producing organisms are favoured. A similar sequence of redox reactions can also be observed as we move down through sediments of treatment wetlands or ponds, or even in septic tanks, with methane production occurring a bit below the sediment surface.

When the waste is fresh, oxygen in the pores is consumed by bacteria that degrade the organic matter. The organic matter is quite reactive and the oxygen is fast consumed, within days (blue curve). Then nitrate is used as an oxidant (green curve) and is depleted within weeks. Further on in the process manganese oxides and ferric oxides are used. These oxides can be present in the waste itself but also in soil used to cover the waste. The next step is sulphate reduction (brown curve) and finally methane fermentation.

The redox sequence has a practical implication as the first steps produce high concentrations of total organic carbon (TOC) in the leachate which consumes oxygen in water courses receiving the effluents from the waste deposit.

The methane step produces a leachate with lower TOC and in addition, for a period of about ten years it produces methane which can be used commercially as a fuel. Thus the deposition of waste involves compaction of the waste to squeeze out air/oxygen from the waste, usually by using a bulldozers and covering "pillows" of waste very soon with soil.

4.6- 22



The soil offers physical support for plants and acts as a store for water and nutrients. In contrast to animals, plants cannot move and they depend entirely on the soil on which they are growing for all their nutrient supplies. Given sufficient water, a soil is considered fertile when it allows plants to grow to their genetic potential.

Many wetland plants are able to transport oxygen from the leaves down to their root systems to help the root cells survive in the anaerobic sediment. Some of this oxygen leaks out to the surroundings, and usually creates a very thin film around the roots and underground stem (rhizome) in which somewhat oxygenated conditions prevail – the so-called *rhizosphere*. The oxygen sustains aerobic microorganisms and, for instance, they oxidise and precipitate ferrous ions as reddish ferric oxides and hydroxides around the roots in treatment wetlands. It is still debated whether this oxygen leakage is large enough to play a significant role for the microbial community in decomposing the fats and carbohydrates in a wastewater treatment system.

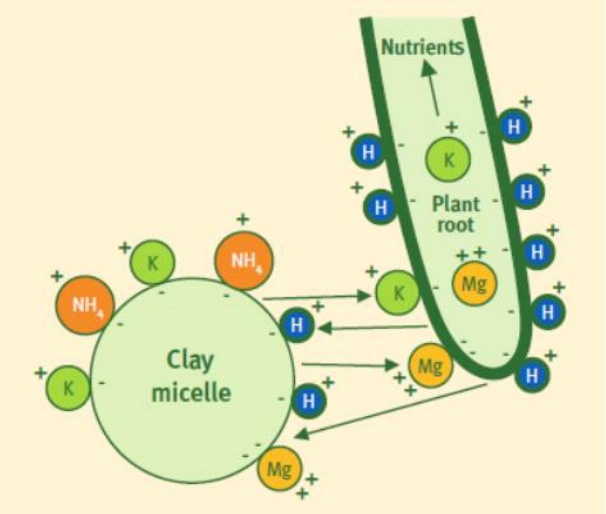
Whatever the answer to this question, both plants and microorganisms contribute to partially remove organics, pathogens, nutrients, heavy metals and toxins in wetlands and planted soil filters. The total environment in the vicinity of the roots (*rhizosphere*), represents a complex biogeochemical entity comprising both aerobic and anaerobic zones, and the corresponding processes are in operation. When the greywater enters the rhizosphere some of its components are digested by microorganisms. Enzymes produced by bacteria and fungi help break down greywater components and transform these to energy and building blocks for new microorganisms. Rest products are excreted and other microorganisms and plants can use these products, along with dead microbial and root cells.

Plants take up nutrients through their roots to use for their growth and for fruit and seed production. Ions are at lower concentrations outside the plant in the rhizosphere than inside the root cells and they move into the plant cells by a process called “active transport”. Active transport is catalysed by enzymes and consumes energy. Ions which are at higher concentrations outside the plant than inside can be transported by diffusion (Del Porto, 1998). However, too high a level of salt in the water is detrimental to the plants, which is also worth remembering when applying urine in the garden, as urine is rich in salts (Jönsson et al., 2004). For example the common sodium Na^+ and chloride Cl^-, ions may provoke specific ion toxicity if high concentrations build up in the soil, and they may interfere with plants' uptake of nutrients such as nitrate and potassium. If the proportion sodium to the sum of calcium and magnesium is too high, the soil structure is negatively affected leading to clogging of soil pores. Hence, in arid and semi-arid regions, where excess salt is not washed away with rainfall, it is important to follow guidelines when using greywater for irrigation (WHO, 2006). If the dosage of urine is based on the N demand of the crop, we avoid the detrimental effects of the salt concentrations (Jönsson et al., 2004).

The plants also need water to replenish the water lost through evapotranspiration from the leaves' open stoma during photosynthesis. In small planted greywater treatment systems, a significant amount of water is lost to the atmosphere due to evapotranspiration, particularly in hot climates. There are examples of papyrus taking up all water, and no effluent is released.

A first step in retaining heavy metals in wetlands is the adsorption on organic matter that accumulates in wetlands due to the slow degradation in the absence of oxygen. These metals may then be transformed into sulphides when the sediment grows and bury the organic matter deeper and the environment becomes sulphide reducing (slide 4.6-20). Clays deposited in estuaries with abundant growth of algae and organic production often contain black iron sulphide (FeS). When aging, the monosulphide may slowly be transformed into pyrite (FeS_2). Other sulphides are co-precipitated. When a black clay soil is drained for agricultural purposes, the sulphides may oxidize producing sulphuric acid. Thus they are often called "acid sulphate soils" and are common in many coastal areas.

In Europe, the main soil resources of nitrogen and sulphur are in the long-term organic matter which is slowly mineralised to ionic forms such as ammonium (NH_4^+), nitrate (NO_3^-) and sulphate (SO_4^{2-}). These are nutrient forms which plants take up from the soil and from applied fertilisers. However, the negatively charged anions are not well retained in soils, and if not taken up by plants they may leach from the soil during rainfall events. Phosphate anions ($H_2PO_4^-$ or HPO_4^{2-}) are exceptions, as they are readily adsorbed to different soil minerals such as iron and aluminium oxides, and thus quite immobile in soil. Cation-forming nutrients (NH_4^+, K^+, Mg^{2+}, etc.) are adsorbed onto the surface of the negatively charged clays and humus particles and are not therefore liable to significant loss by leaching, except for through ion exchange in situations of soil acidification.



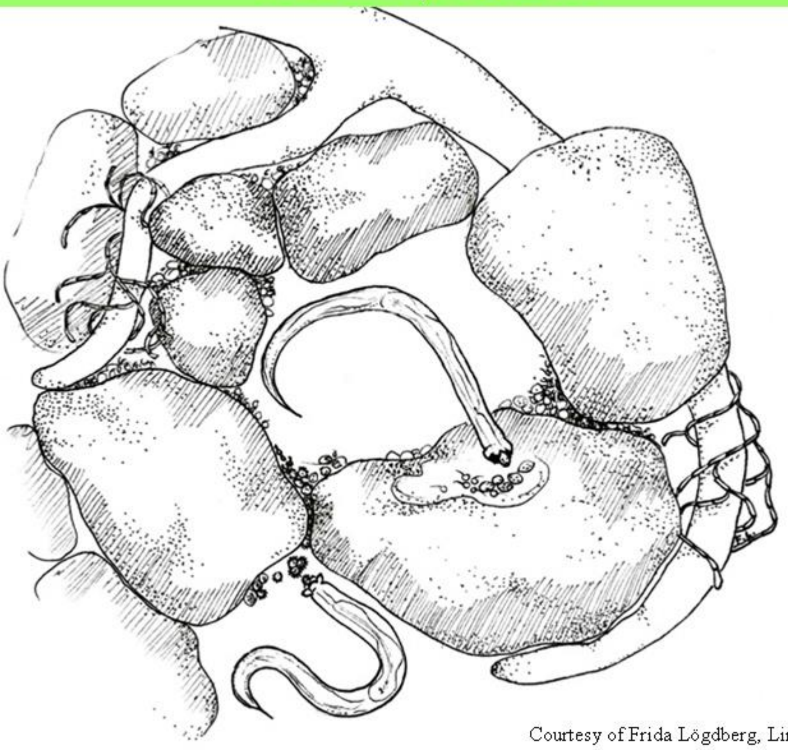
Schematic illustration of the transfer of positively charged nutrient cations from the negatively charged surface of the clay particles to a nearby plant rootlet, so-called 'cation exchange' (after Courtney and Trudgill 1975).

Source: EFMA 2006.

Another fate of heavy metals is that they get co-precipitated in the ferric hydroxides formed around the roots of wetland plants. Also, negatively charged substances like arsenic can get trapped by adsorption onto the ferric hydroxides (slide 4.6 – 17).

Predation on microorganisms stimulates decomposition

4.6- 23

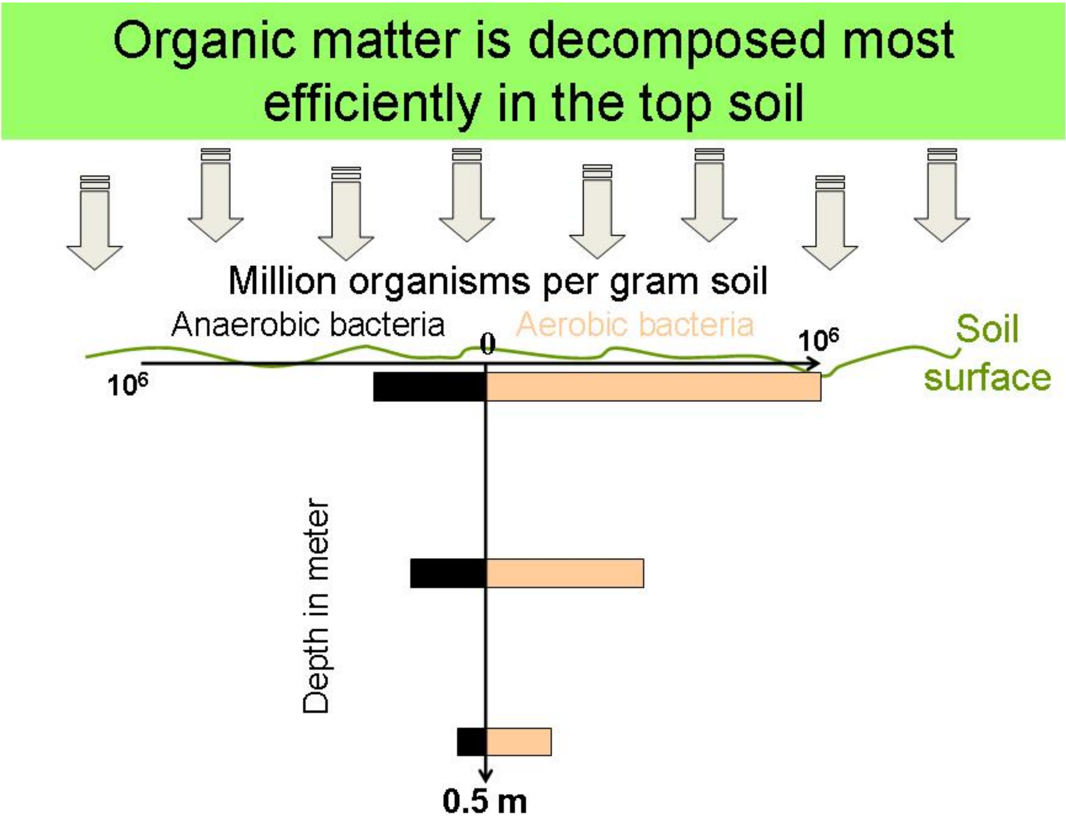


Courtesy of Frida Lögdberg, Linköping university

In a soil ecosystem, the microbial biomass formed when microorganisms decompose organic compounds in the soil, such as dead plant parts and organic matter in wastewater, becomes food for small animals. Protozoa, small worms called nematodes, and earthworms can all feed on fungi and bacteria in the biofilm around soil particles (picture). It has been shown that this predation stimulates decomposition of organic matter and other biological processes, probably because the microbial population is kept in an exponential growth phase. It is also possible that the predation helps control the thickness of the biofilm thereby preventing clogging of sand filters.

Potentially pathogenic microorganisms like *Salmonella* and *Campylobacter,* which cause human enteric diseases, can be present in wastewater. Bacteria-eating animals consume them, thereby helping in the disinfection of wastewater during treatment.

4.6- 24



Courtesy of G. Jacks, Royal Institute of Technology, Stockholm

Now we view the soil profile and the number of microorganisms living there in order to understand how to get the best treatment results for wastewater.

Under natural conditions soil structure develops and maintains itself depending on soil type, climate and vegetation through the activities of the soil flora and fauna, especially earthworms. About 35 to 60 per cent of the soil volume consists of pores. The fine cavities (capillaries) are normally filled with water, whereas air circulates in the larger pores and supplies oxygen to the soil biota, including plant roots (EFMA, 2006).

The largest source of energy for soil ecosystems is normally organic matter from dead plants, with the highest amounts, consisting of leaf litter and dead fine roots, in the top layer. In addition, oxygen availability is highest closest to the soil surface and therefore many aerobic microorganisms dwell here (10^6 per gram of soil). As explained before, there are always small spaces with no oxygen, even at the top layer of the soil profile, where completely anaerobic bacteria can survive, for example inside aggregates formed by clay and organic matter. As a consequence, the number of both aerobic and anaerobic soil organisms is highest closest to the soil surface (picture). Hence the activity of the microorganisms is also highest in the upper layer of the topsoil. This must be considered when using soils for wastewater treatment, and also when treating drinking water.

As the size of the microbial community drops rapidly with depth, a good distribution of water over the surface intended for wastewater treatment is essential for a good treatment result. It also helps to avoid overloading a particular section, thus preventing saturated water flow and the formation of zones with completely anaerobic conditions.

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