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Design for Sustainability

ecological dimension

Module 2
Appropriate Technology: Water

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English version

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Table of contents

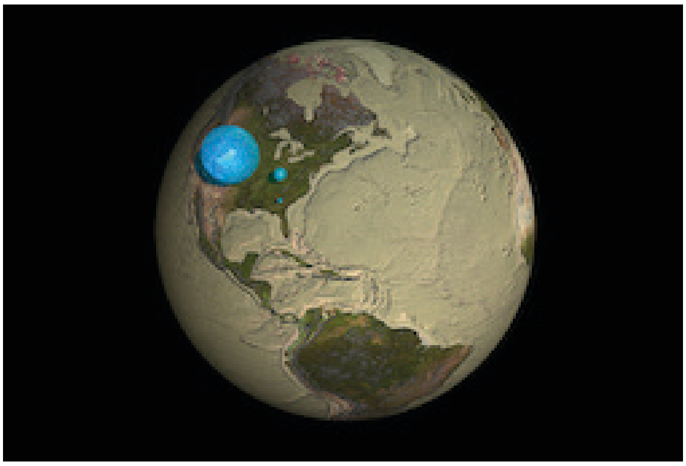
1. Introduction

"Water is a point of connection for many of our global challenges — as well as for solutions. Protecting water resources, such as maintaining moisture in soil, can help mitigate against climate change. The water cycle interacts with all basic biophysical cycles: the carbon cycle, the energy cycle and the nutrient cycle. The better we understand this, and the better we appreciate how water processes relate to alleviating poverty and hunger, reversing desertification, and rebuilding biodiversity, the more equipped we will be to take on the difficulties of our time."

Judith D. Schwartz, Water in Plain Sight: Hope for a Thirsty World, 2016

The link between fossil fuel reserves and war have been clear for decades, yet equally many violent conflicts and wars have already been fought over access to water. Freshwater is already a very scarce resource; it is just 3% of all the water on the 'blue planet'. If all the Earth's water were brought together into single drops of the oceans and freshwater, they would look like this:

And yet freshwater is wasted and contaminated on a gigantic scale. Many of the world's mega-cities, such as Chennai, Sao Paolo, Cape Town and Melbourne have already faced a significant water crisis and it is evident that the systems we have designed to provide freshwater and care for its sources are deeply inadequate.



USGS.gov Where is Earth's Water?

- **1 in 10 people** lack access to safe water, 1 in 3 do not have access to a toilet
- **women and children** spend 125 million hours each day collecting water
- **785 million people** lack even a basic drinking water service, including 144 million people who are dependent on surface water
- **at least 2 billion people** use a drinking water source contaminated with feces
- **485,000 diarrhea deaths** occur each year from contaminated drinking water
- **by 2025, half the world's population** will be living in water-stressed areas
- **by 2030, 700 million people worldwide** could be displaced by intense water scarcity
- **a third of the world's biggest groundwater** systems are already in distress
- **every 90 seconds** a child dies due to contaminated drinking water

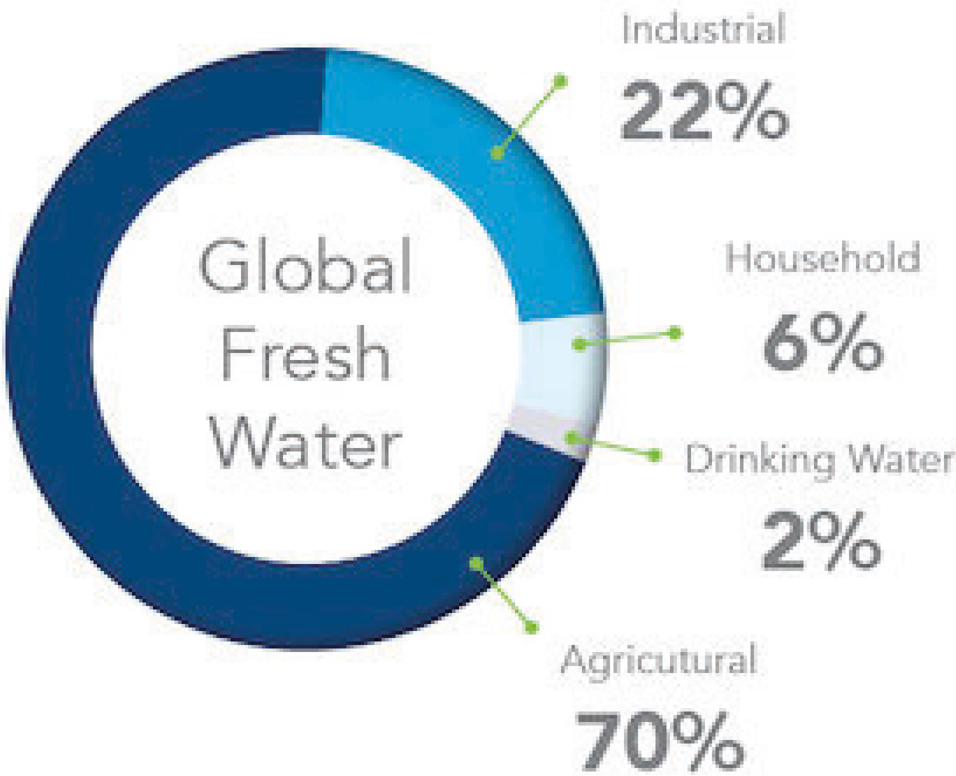
(water.org, Global Water Institute, 2013, Richey et al., 2015, Burek et al., 2016, WHO, 2015)

The Sustainable Development Goal number 6: Ensure availability and sustainable management of water and sanitation for all.

The grim statistics below affect the health and resilience of people and communities. Yet, experts estimate that for every dollar invested in clean water and sanitation, a return of US$4 is generated (water.org). In developing countries, the time children and women spend fetching water could respectively be dedicated to education and engaging in other economic activities. The knock-on effects of the lack of clean water and sanitation are major drivers of poverty, hunger, ill-health, and environmental degradation. What many people in the global north take for granted - a tap with drinking-quality water - is out of reach for 800 million people. We cannot create a sustainable world without also creating a more equitable world in which essential resources are available to all global citizens. How can we ensure that the ambitions that created SDG 6 are fully achieved?

How do we use freshwater? As we can see, agriculture takes the highest percentage and most of this is for irrigation of annual crops. Industry takes up nearly a quarter of the freshwater use. Is there any point in trying to take shorter showers and turn off the tap when brushing our teeth?

Here is a short video (4min) outlining ways we can change our attitude to the freshwater crisis.



2.

The Whole-Systems Approach

In module 1 we saw how a whole-system approach to restoring the hydrological cycle can combat desertification and global warming through ecosystem restoration. We have the ecological knowledge and appropriate technology to solve these issues, to protect watersheds and provide access to water and sanitation for everyone human and non-human. This module builds on that fundamental ecological knowledge to explore the relatively simple technologies applicable to regenerative communities, focusing primarily on water systems that can be applied to the household, community or neighbourhood scale.

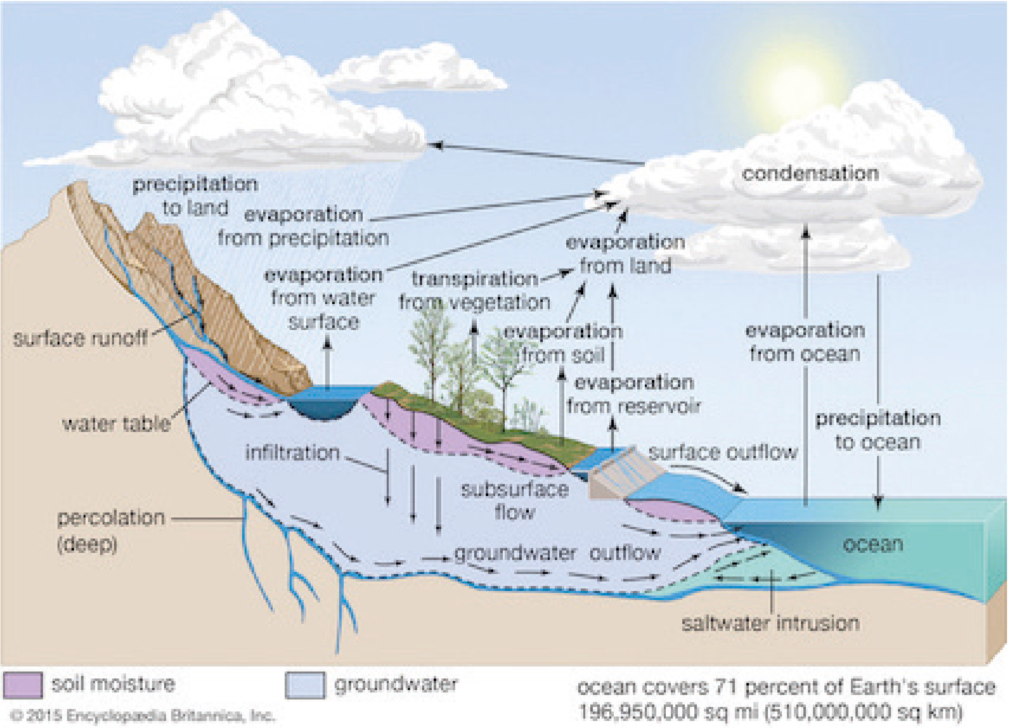
First, we will explore the basics of the hydrological cycle, the importance of watersheds for the major rivers in your region, and how water systems should be designed to link local needs to the integrated management of water at the bioregional watershed scale. Once we have established this context, we will take a closer look at how biological water treatment works and what systems might be appropriate at what scale and in which specific environmental context.

The Hydrological Cycle

Let's briefly take a look at how the hydrological cycle functions and build on the basic ecological knowledge introduced in module 1. If we hope to design regenerative systems integrated into the life-supporting processes of the biosphere, we have to become nature's apprentices first and learn to understand the ecological, climatological, and hydrological cycles on which we depend.

The hydrological cycle is a closed-loop system in which water (H2O) circulates as it changes from liquid to gases (water vapour) and to solids (ice) and back to liquid. It circulates or flows between a variety of different 'stores' and in the process, both uses and produces energy. In the stores that are reservoirs such as oceans, lakes and rivers water is a liquid. To transform into its gaseous form, through evaporation, it uses solar radiation. It is worth noting that when stored in the atmosphere as water vapour, it is a potent greenhouse gas. Overall, global heat dynamics on Earth is regulated for 75-95% by water. Restoring the hydrological cycle to store water in the 'soil sponge' and in underground aquifers, therefore, makes a major contribution to combating global warming and climate change.

Terrestrial freshwater reserves are replenished when water vapour is returned to its liquid form and falls to earth as rain. To do this, it passes through a solid form as ice crystals in clouds, a process in which microbial life figures

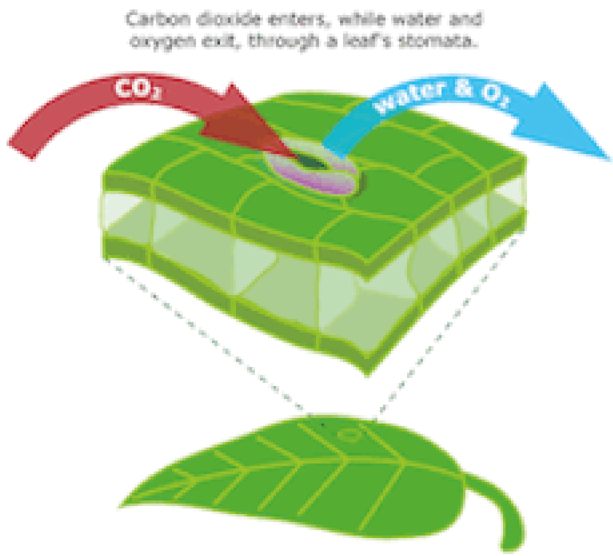


The Hydrological cycle .Source [*Britannica*]*.*

predominantly. When it falls to land where healthy, living soils and natural vegetation are waiting to receive it, rain is absorbed into the soil, used by essential soil micro-organisms and other soil life, and absorbed by plants. Any excess from heavy rainfall filters through the soil to groundwater. Land that is able to absorb and retain water is referred to as a 'water retention landscape' and we can return degraded land to this state through ecosystem restoration and regenerative agricultural practices (you will see in module 3). Urban areas can also become water retention landscapes and we will look into this in module 5.

Degraded land that has inadequate permanent vegetation cover and little soil organic matter cannot retain water and therefore rainfall returns to the oceans and lakes as runoff from the land into streams and rivers. Runoff carries with its chemical pollutants from agriculture and an excess in artificial nitrogen fertilizer. The latter feeds 'algal blooms' in lakes, rivers and oceans which remove oxygen for other freshwater and marine life. The result is 'dead zones' and toxic algae washed up onshore. Moreover, runoff from compacted land reinforces the degradation — without the infiltration of life-giving water, soil life and vegetation die, as do terrestrial species in the food webs that rely on vegetation, in an ongoing spiral of desertification. Our ecosystems are literally drying out, being drained by human activities.

In the hydrological cycle diagram below we can see that besides evaporation from the oceans, there is also evapo-transpiration from vegetation taking place. Transpiration occurs as plants breath, which they do through stomata covering the surface of their leaves. When they open the stomata to exhale, water that has been sucked up from the soil through the plant's vascular system escapes into the air as water vapour.



Source: [*evolution.berkeley.edu*]

This natural process produces cooling latent heat, which is one of the reasons why landscapes with vegetation are cooler. The temperature in a street lined with trees will always be a few degrees cooler than in a street where there are none. Evaporation also occurs where there is vegetation, so the combined processes are referred to as evapo-transpiration. The transpiration from forests such as the Amazon is a powerful driver of rainfall, weather and even climate.
The diagram below shows rainwater infiltration through a previous surface. It can be drawn up through roots and returned as water vapour to the air through transpiration. Alternatively, rainwater leaves an impervious surface through runoff.

Until quite recently, physicists regarded evaporation from large bodies of water to be the main driver of the hydrological cycle, but now we know that life itself plays a major role

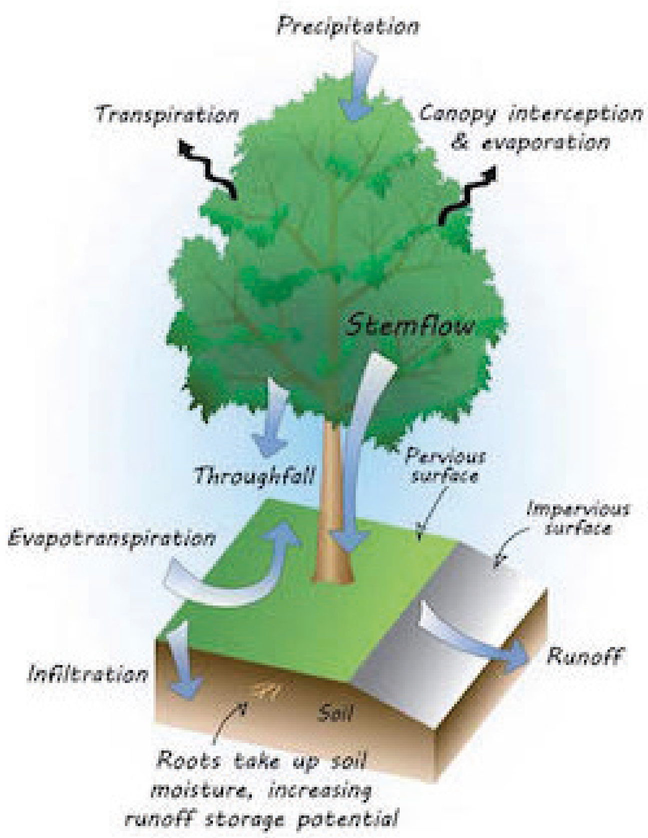
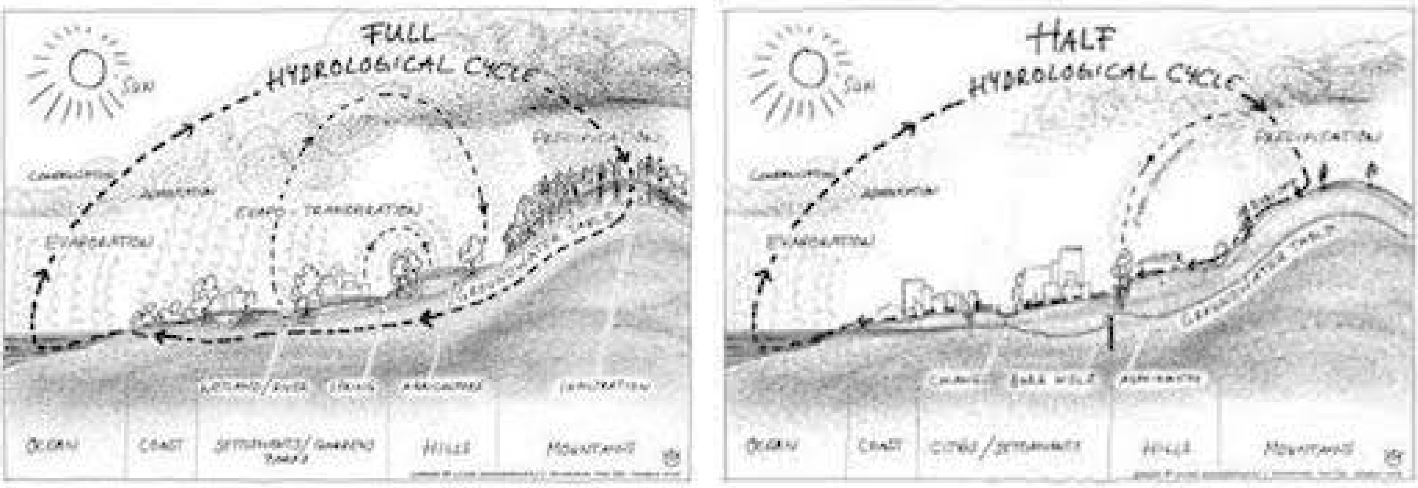


Image source:
United States Environmental Protection Agency

through transpiration and 'bioprecipitation'. New narratives, even in the sciences, often take a while to be absorbed into the mainstream, so this story starts in the early 20th century when an Austrian forest warden Viktor Schauberger, observed a decline in rainfall where deforestation had taken place. His insights lead to a theory, that there are 'half' and 'full' hydrological cycles, and that this plays a crucial role in rainfall. He also realised that creating impervious surfaces by removing permanent vegetation would impact on groundwater movements, the water table, soil salinity and cloud formation. Schauberger mapped out the effects of deforestation on rainfall and on surface temperatures in beautiful illustrations.

Schauberger identified the crucial role played by vegetation in maintaining the hydrological cycles as well as the maintenance of appropriate temperatures. We now know the science behind the 'sensible' heat rising from degraded landscapes. Schauberger also recognised the close relationship between removal of vegetation and flooding. He compared the full hydrological cycle to the passage of blood around the human body and the importance of vegetation and soil for purification and dispersal of minerals. It is an apt metaphor when we accept that the biosphere is a living, self-regulating system based on Earth Systems' sciences to which the pioneering Schauberger had no access, such as microbiology, even though he was well aware that he was observing a natural system in perfect dynamic equilibrium.

Schauberger was ahead of his time and his work took a long time to gain acceptance. It is maybe a prime example that keen and dedicated observation of nature by those living and working in close proximity to it is a valuable approach to scientific enquiry. Permaculture's first principle, 'observe and interact' is an excellent starting point for a whole-systems approach.



The Full and the Half Hydrological Cycles. Source: Heron Hill Wildlife Sanctuary

2. The Whole-Systems Approach

2.1. The 'Biotic Pump'

Two more recent developments add to our new understanding of the role played by life itself in the hydrological cycle. In 2007, a study was published by two Russian scientists, Anastassia Makarieva and Viktor Gorshkov, both nuclear physicists by training, also concerned about diminishing rainfall patterns where deforestation was taking place. Based on data from Georgia and the Caucasias where logging of old forests had been extensive, the 'biotic pump theory' showed that trees, pumping water into the atmosphere through transpiration, move rainfall around Continental landmasses from oceans to the interior and therefore play an essential role in weather and even regional climate. We have already encountered this addition to climatology in Dr Antonio Nobre's talk about the invisible rivers of water vapour above the Amazon in module 1.

Makarieva and Gorshkov show that the high leaf area index found in natural forests (rather than monoculture tree plantations and agriculture) maintain high transpirational fluxes and suck in moisture from the oceans, the basis for biotically-enhanced precipitation at any distance from the ocean. Forests along coastlines, therefore, are also essential for a continental-scale biotic pump mechanism.

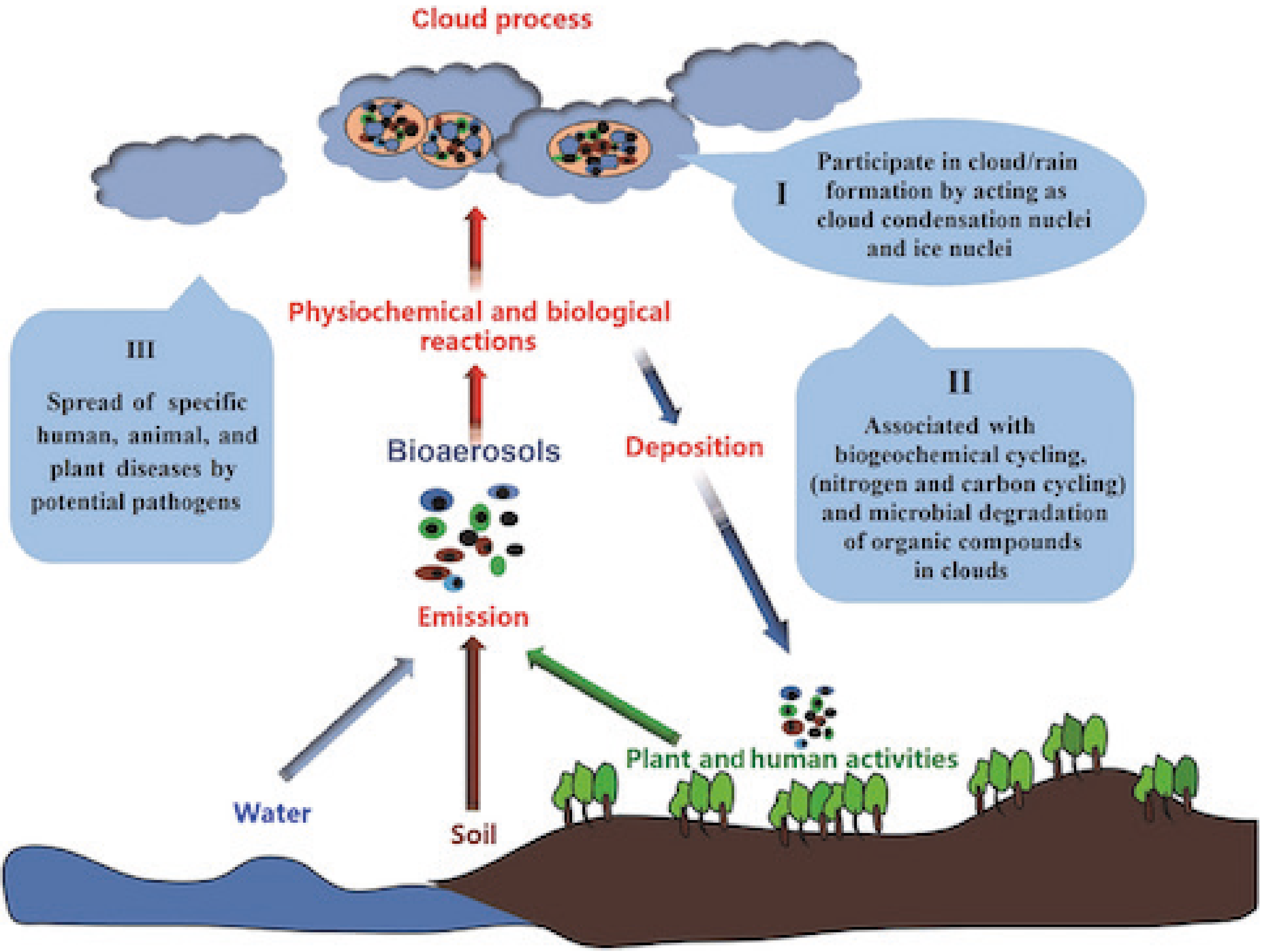
"Replacement of the natural forest cover by a low leaf index vegetation leads to an up to tenfold reduction in mean continental precipitation and runoff, in contrast to the previously available estimates made without accounting for the biotic moisture pump. The analyzed body of evidence testifies that the long-term stability of an intense terrestrial water cycle is unachievable without the recovery of natural, self-sustaining forests on continent-wide areas."

Image source: Rainforclimate.com

2.2. Bioprecipitation

Water freezes in clouds at -39 C. To freeze at a lower temperature to create the ice crystals that cause rainfall requires a catalyst in the form of aerosol particles. These travel upwards on air currents and some of them are alive.

Microbial life contributes to rainfall, travelling upwards in bio-aerosols from vegetation and soil, to nucleate clouds. Bioprecipitation occurs when bacteria in clouds freeze drops of water, they have nucleated around themselves from water vapour to form ice crystals which, being heavier than water, begin to fall and subsequently melt into rain. These micro-organisms can freeze water at temperatures of -2 degrees C, whereas aerosol dust particles trigger freezing only below -15 degrees C.



Schematic representation of bioaerosols' life cycle and potential influence on atmosphere, ecosystem, and human health, modified from Pöschl (2006). ***Source:*** *Research Gate*

Bioprecipitation is an essential aspect of the hydrological cycle and deforestation is obviously having a profound effect on patterns of rainfall and drought, warming and climate change. However, many of the organisms that cause bioprecipitation, bacteria such as Pseudomonia spp and fungi such as Fusarium spp, are also present on agricultural land and can damage vegetation and annual crops. Some scientists have suggested that the ability to freeze water is a evolutionary adaptation that enables the micro-organisms, having been swept up into the clouds far away from their natural habitats, to return to earth and their food supply. Pseudomonia spp can access sugars from plants by freezing the stomata open. Fusarium spp are commonly found on fruit trees and cereals. Pesticides that target these organisms are effectively disrupting the bioprecipitation that is an essential aspect of the hydrological cycle and, therefore, contributing to climate change in this way.

The small water cycle

"...in natural ecosystems, water is integrated into small, regional water cycles, which supply vapour to the atmosphere to condense and form rain, the sun being the driving force of the circulation of water in small water cycles. We also need to appreciate the thermoregulatory processes provided by the movement of water between the surface of the earth and the atmosphere, which maintains the proper temperatures for life on earth"

Michal Kravčik and Jan Lambert, *New Water Paradigm, 2007*

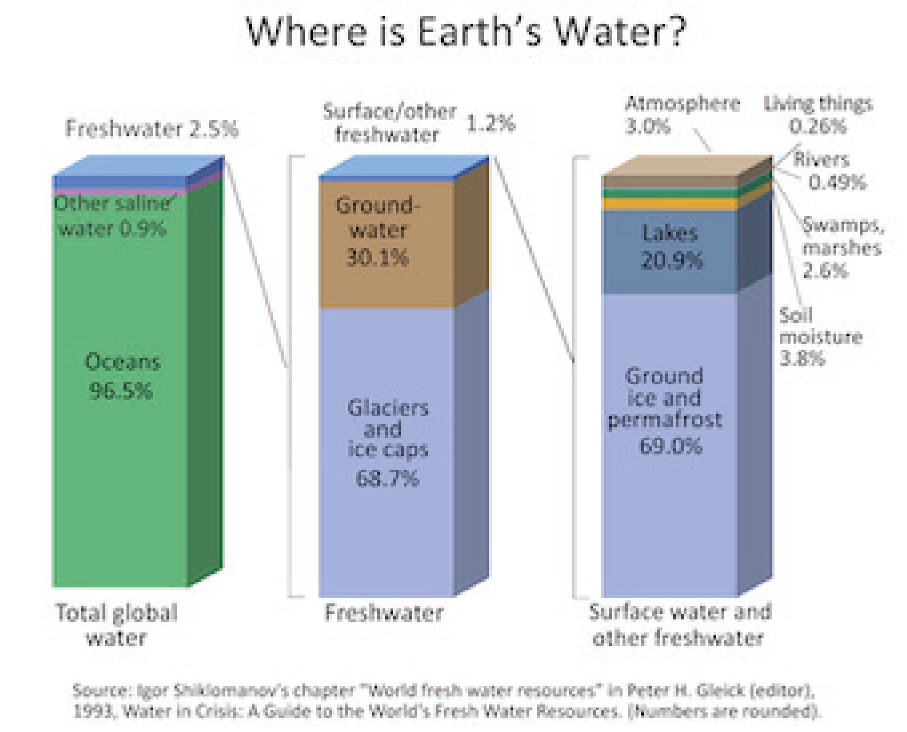
While the global hydrological cycle might seem dauntingly vast, so huge that as individuals and communities we can't influence it positively, working locally to restore the small water cycle is always within our power. We can work towards rehydrating our drained ecosystems by protecting natural forests, designing and planting new ones, resisting schemes for monoculture plantations, transitioning to regenerative agriculture, recycling water back into the landscape, especially in urban areas. These local actions also contribute to achieving SDG 6 globally. To do this we need to know more about how the hydrological cycle operates in our bioregion.

3.

Bioregional Watershed Management
and Mapping Your Water Supply

As mentioned previously, water is in constant circulation between various states and stores. However, it tends to stay in some stores longer than others. Ice caps and glaciers can hold water for millennia; stores in aquifers deep underground are called fossil water for good reason.

Water is used by agriculture, industry and municipalities as we mentioned in the first section. Unsustainable extraction from aquifers lowers the groundwater level. Within a bioregion it is good to assess the water budget – inflows and outflows. Sustainable communities can then ensure they are using water from sustainable sources and conserving it wherever possible (see picture below: Conceptual Water Budget).



Source: USGS.gov Where is Earth's Water, from Igor Shiklomanov's "World Freshwater Resources" in Peter H. Gleick (ed) Water in Crisis, 1993

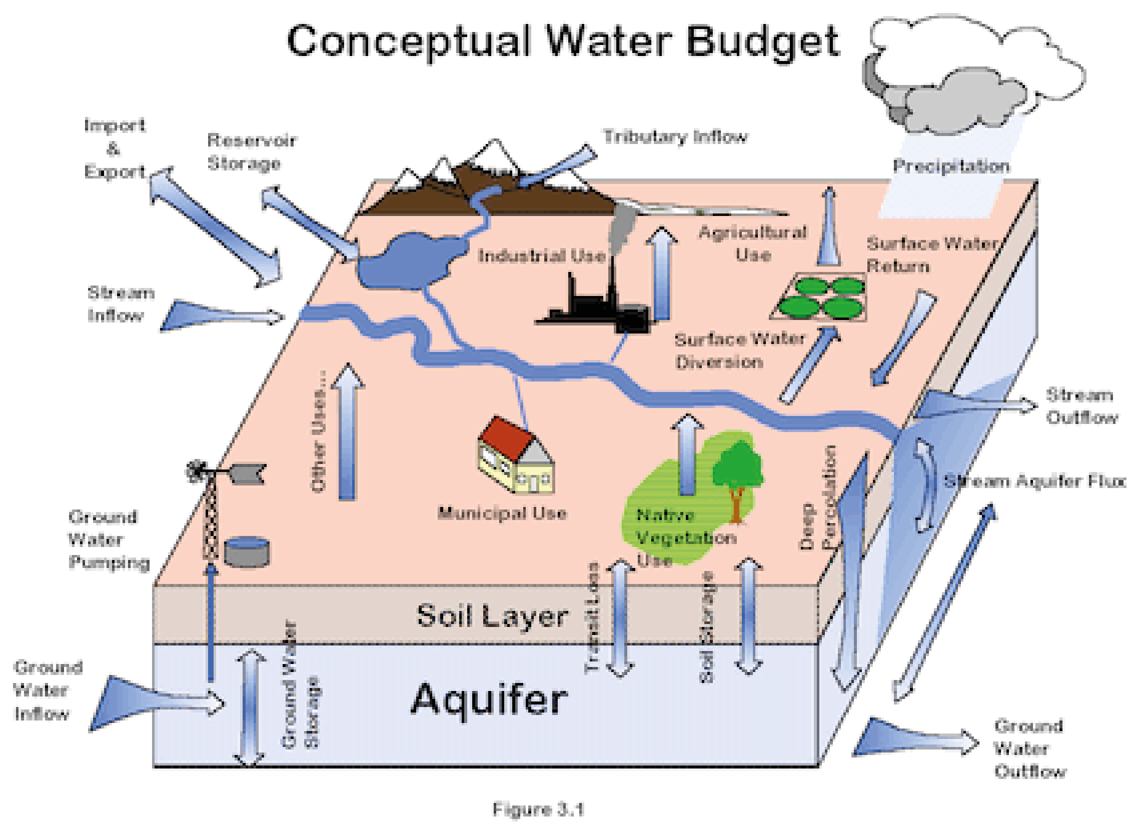
The end of the age of fossil fuels, therefore, is an opportunity for us to meet our needs through regenerative practices that restore degraded land and combat biodiversity loss.

The calls for a rapid, radical and sustained response to climate change are getting louder and louder. The scientific community has been in consensus for many years. Reports on biodiversity loss and desertification have called for a whole-systems approach support. Ecologists, hydrologists and soil.

Do you know where your water comes from and how it is treated?

When we understand how the water cycle works, the next step into designing appropriate water systems should be to take a close look at the water budget for the building, community and bioregion. Even if you are only designing a single house in your community, to integrate your design appropriately into its landscape you will have to pay attention to water flows at the community and regional scale.

[In this enjoyable and excellent talk] on rethinking and retrofitting for resilience, Brock Dolman, the director of the Water Institute at the Occidental Arts and Ecology Centre, shares how we can all become part in creating appropriate water use patterns through practising ecologically regenerative watershed management. His mantra for water management is: Slow it! Spread it! Sink it!



Source: [water-research.net]

Brock also emphasizes the whole-systems ecological approach to dealing with climate change. We have polluted and degraded the biosphere to the extent that climate-change phenomena can clearly be seen to be the symptoms of stressed planetary systems trying to deal with the excess heat, trying to rebalance and return to the dynamic equilibrium of the Holocene. We can enable the Earth to do its work of regeneration when we see ourselves and our communities as part of the bigger picture, starting with our watershed.

Compacted agricultural fields with no permanent ground cover, no hedgerows and trees stop rainfall from filtering into the ground and washing away soil with runoff. In cities, rainwater is regarded as a problem and channeled away as quickly as possible through the sewerage system. Impermeable surfaces reduce water filtration into the ground and add to pollution of water as runoff picks up the heavy metal residues left by fossil fuel exhausts. In many places rain falls in seasons, yet rainwater is not retained and stored in the landscape but is allowed to rush off to rivers and back into the sea. For sustainable watershed management at local and regional scale, we need water to be retained for use throughout the year. Instead of piping wastewater long distances for centralized treatment, we could regenerate water quality locally in smaller, more decentralized and resilient waste management systems. We should minimize pollution and recycle water locally. Hydro-electric plants, especially mega-dams, cause considerable damage to riverine ecosystems and in some countries,

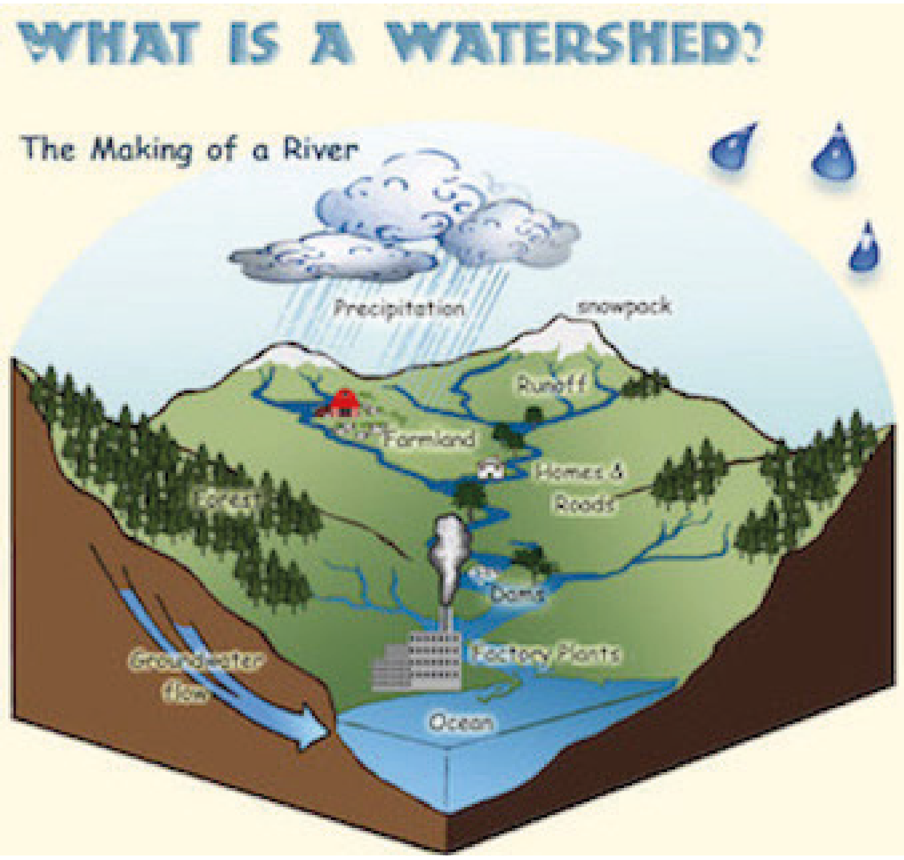
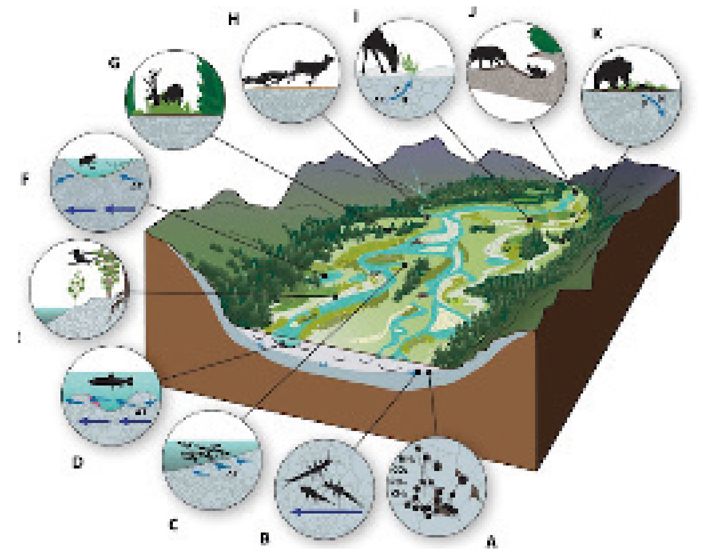


Image from [Center for Watershed Protection]

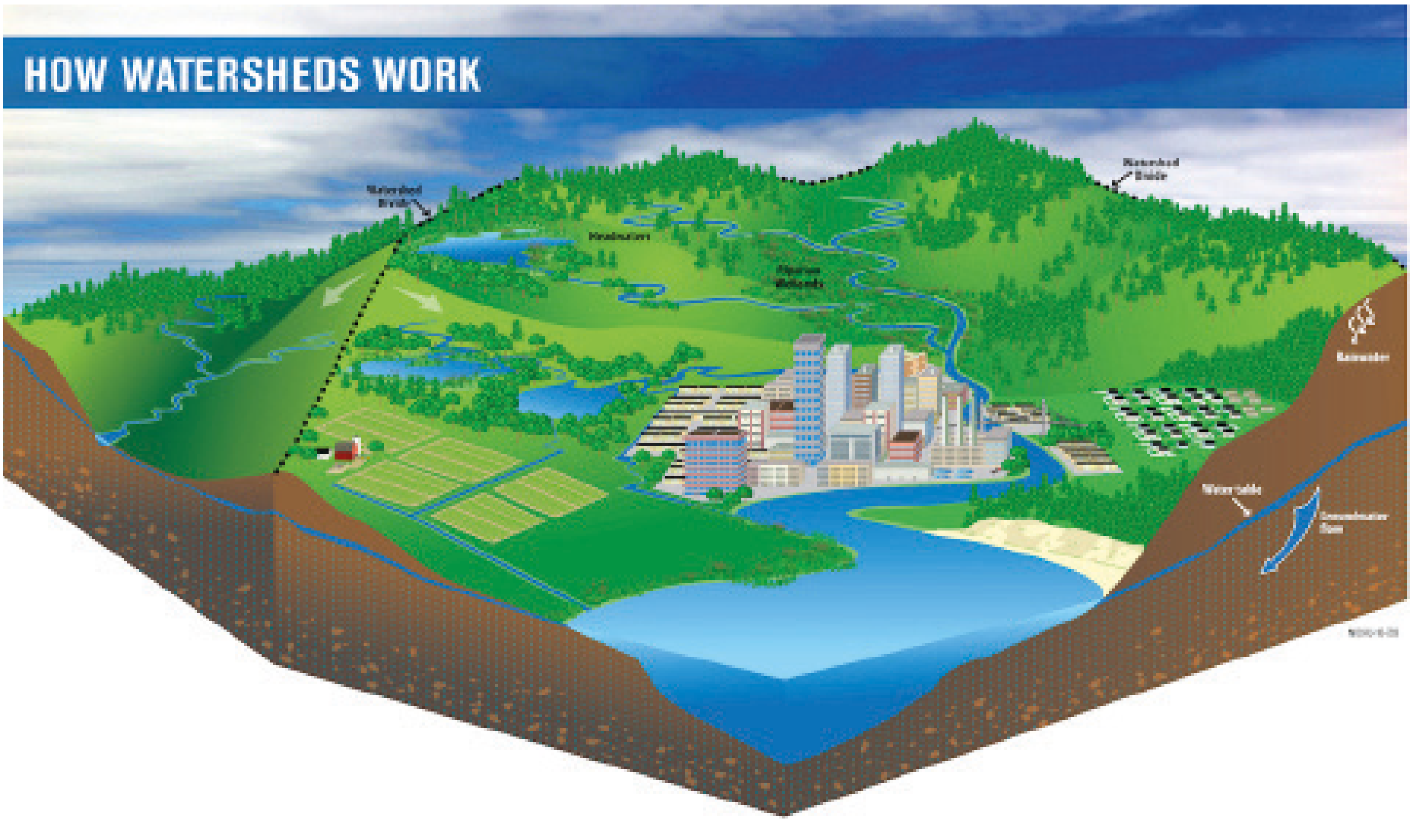
dams are already being dismantled as part of watershed restoration projects.

The diagram below shows a schematic watershed with a river and its tributaries rising in the hills around it. The contours of the hills have been added. When the hillsides are bare of vegetation, the water will run downhill as quickly as possible, following the path of least resistance, taking soil with it and causing erosion.

The regenerative approach is to store rainfall in the landscape through ecosystem restoration including major reforestation on the uplands to capture rainfall through infiltration and to facilitate evapo-transpiration and bio-aerosols. Other ecosystem restoration strategies could include the re-introduction or protection of animals that play a key role in watershed restoration, the so-called keystone species. Beavers are natural dam-builders; they slow down the flow of water allowing it to infiltrate and streams to meander. This alone has a rapid and positive feedback effect on other species that steadily increase the resilience of the freshwater and riparian ecosystems. In some places specialized ungulates (hoofed animals) are part of a restoration project, in others, the numbers of animals should be reduced through the re-introduction of top predators such as wolves. This is where watershed restoration and rewilding join forces. Techniques for watershed restoration are also reliant on local geology.



Source: Research Gate



Source: [BBKGSS]

This gravel-bed floodplain in a mountain region contains wildlife ranging from the smallest microbes to the top herbivores and carnivores.

Of course, in densely populated areas watersheds accommodate human settlements on a variety of scales from mega-cities, usually on the coast, to smaller towns and cities along the major arteries of the river and smaller communities in rural areas. Industry, agriculture and cash-crop forestry are all major exploiters of watersheds. Population growth, economic growth and the export imperative can compromise watershed integrity.

Suggested activity:

- **How would** the watershed in this diagram above stand up to scrutiny?
- **Can you think** of ways to improve it as a 'water retention landscape'?

4.

Whole Systems Approach to Domestic and Community Water

A whole systems approach to water involves closing the water cycle with re-use. Potable water in ecovillages is typically obtained through rainwater harvesting, community boreholes or both. Often wind power or photovoltaic panels are used for pumps.

After use within the community, the water is treated, preferably with a natural treatment system, as described later in this module.

The treated effluent is then disinfected where necessary and re-used, most often in a drip irrigation system. It is safe to use recycled water for the irrigation of trees, including fruit trees. If composting toilets are used in the village, the humic material can be added to the household and garden compost and used to build up the soil in the orchard.The use of composted humanure as tree fertiliser is perfectly safe.

A Whole Systems approach to Water from Gaia Education

Many communities have used participative art and community education creatively to educate the residents about the whole-systems integration of their local water supply, highlighting the need for conscious use of water, and especially the chemicals in household products that end up in our water systems.

One of the community-owned windmills at Findhorn ecovillage had a mural of a watershed painted on it by local children under the guidance of a local artist. In the past Lisa Shaw and her husband Galen Fulford (founders of Biomatrix Water, as mentioned later) have built water systems in remote villages in South America and India. They found that involving the community in a mural art project to explain the system is the most creative way to raise awareness about its appropriate use and maintenance.

4. Whole Systems Approach to Domestic and Community Water

4.1. Rainwater Harvesting

Watch this video from the International Rainwater Harvesting Alliance, a Geneva-based NGO. The IRHA promotes rainwater harvesting as an effective and sustainable solution in the face of water shortages and floods, which weaken ecosystems and communities.

The International Rainwater Harvesting Alliance, originally created during the World Summit for Sustainable Development, works directly on projects to install rainwater harvesting and storage systems in places where safe drinking water is not abundant. It also provides workshops in urban areas across the globe where rapidly changing rainfall patterns result in more frequent flooding. It is also an excellent source of up-to-date news on related events such as Transition, Alternatiba, agro-forestry conferences.

Tackling our changing climate requires multiple, inter-related approaches.

The technology required for harvesting rainwater from roofs is simple, easily installed and cheap. The Global Development Research Centre has free and basic information for individuals, communities and policymakers.

Domestic Rainwater Harvesting

Rainwater harvesting systems that supply storage and use are a critical design element in any regenerative water system. Rainwater is typically collected from roofs and stored in tanks adjacent to houses. Usually the first amount of rain after a dry period is flushed to the ground in order to clean the water collecting surfaces from dirt and any organic material from plants and animals that might have collected during a dry period. The rain is then stored and used as shown on the next page.

Often a sand filter is used between the storage tank and the house. This can be backflushed every year with water pressure. In this scenario, rainwater is used for domestic purposes (washing machines and toilets) and in the garden. However, in some countries (e.g. Australia) rainwater harvested from roofs is commonly used as drinking water. In some

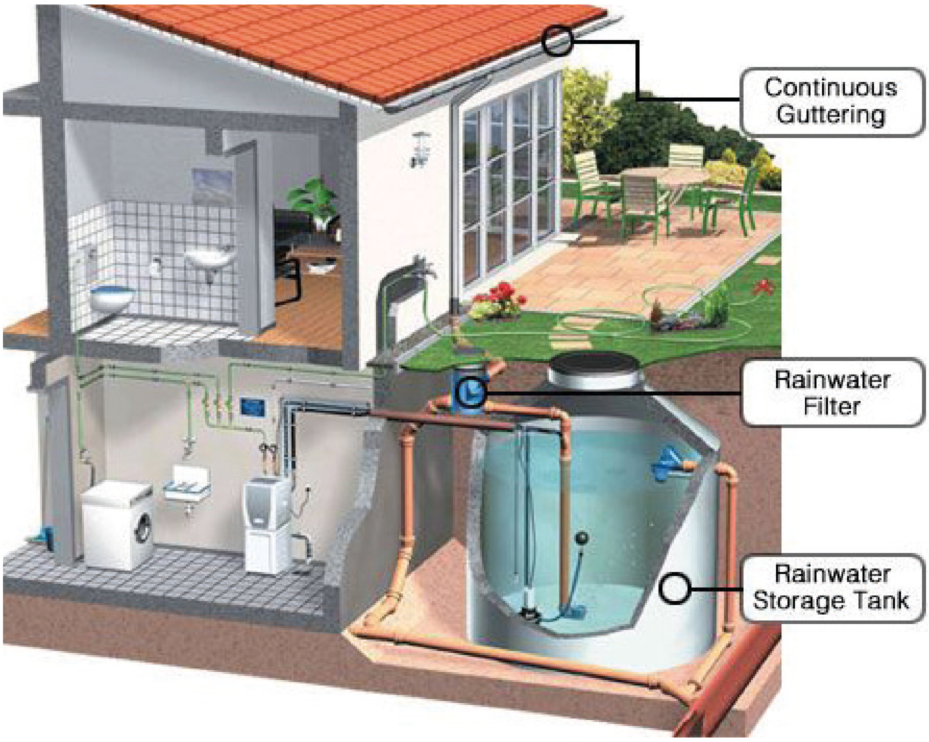


Image from [Water While Away]

countries (e.g. Thailand) using rainwater for drinking water is the norm. When necessary, water can be purified using UV light or a charcoal filter. Traditional ceramic filters are also used in some countries and some of them are very beautiful. Potters for Peace is charity uniting potters in many developing countries to provide simple ceramic filters for use a very poor neighbourhoods.

Here's how it works. Co-founder of permaculture, Bill Mollison, always preferred low-impact solutions. In these two drawings produced for the Permaculture Designers Manual, he illustrates two cheap and simple solutions to first flush systems that clean the roof prior to harvesting the rainfall.

Where water is more likely to be polluted by pathogenic micro-organisms, for example, in developing countries and where infrastructure has been badly damaged by environmental disasters such as earthquakes and cyclones, more precautions should be taken. Rebecca Todd has been researching into the use of fungi and biofilms as a means to combat disease-causing organisms. With the right combination of organisms in an ecology, nature will sort itself out.

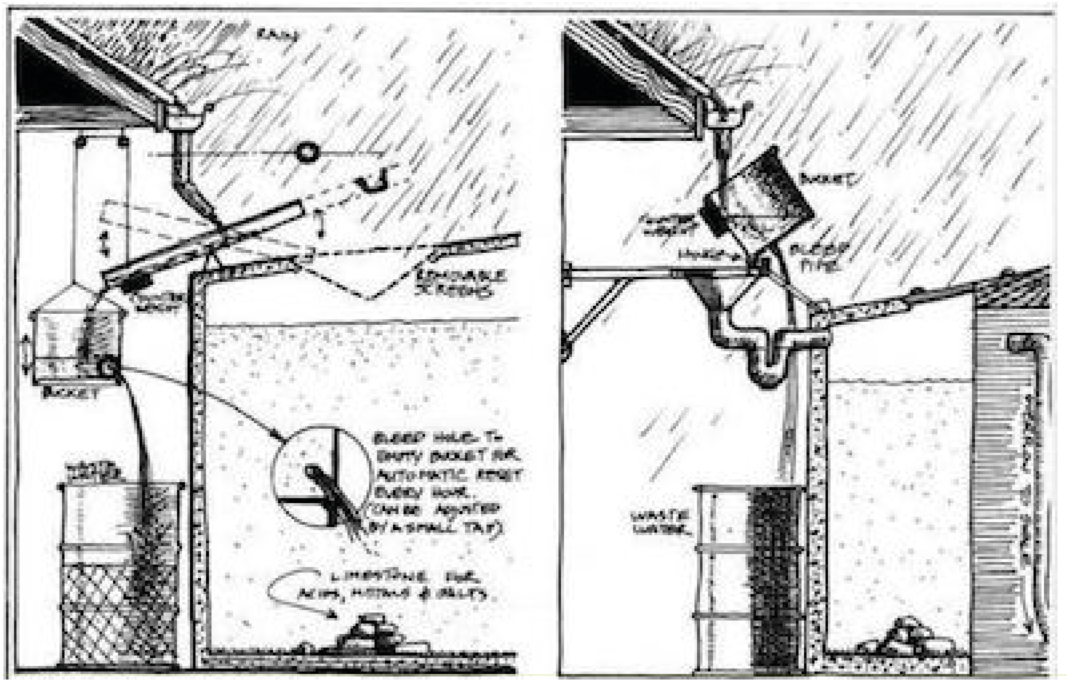


Image from [Imgur]

Source: *[John Todd, final lecture, Planetary Healing and Ecological Design]*

Pause and Bring it to Life!

How would be in your reality if you harvested rainwater?
In this link you will be able to simulate and calculate (American unit of measurement) how much water you can harvest at a given place.

Write down and discuss with friends/family what you could do with this much of water harvested, what kind of ideas spark for you?

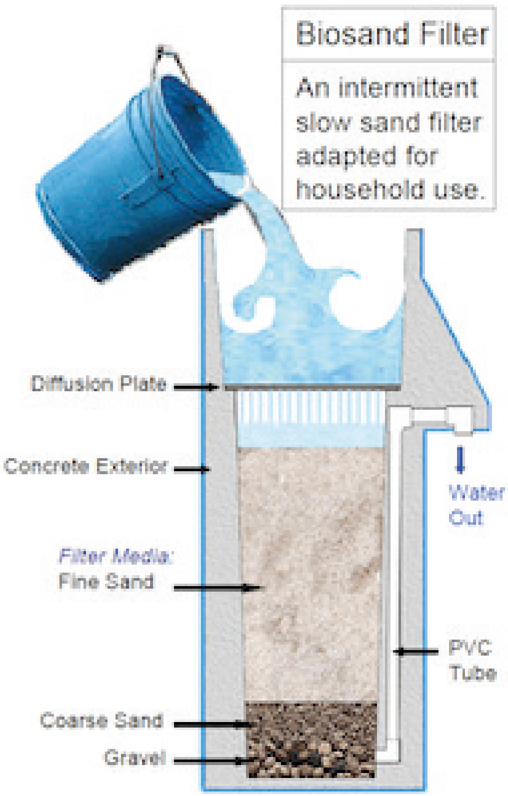
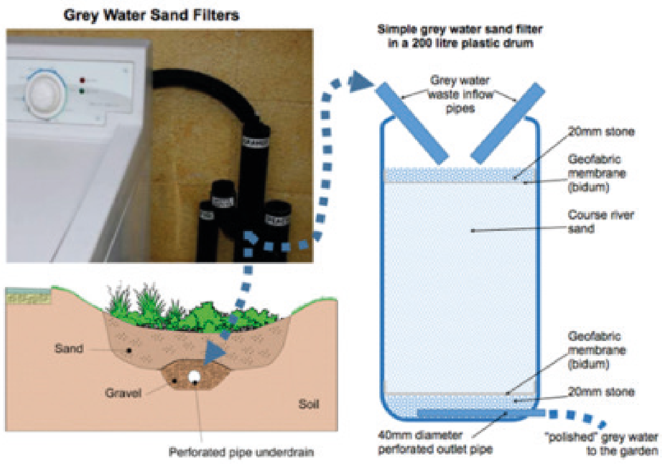


Image from The Grainger College of Engineering



Rainwater used for domestic purposes and appliances can be recycled again through a grey water sand filter.

4.2. Composting toilets

In western societies human feces are disposed of through a water-carrier system, through flush toilets that send excrement into sewers where it is mixed with other domestic wastewater and rainwater. This is a highly inefficient system, from the perspective of water use, as well as the waste of a precious resource that should be returned to the soil. Treating human waste through anaerobic digestion destroys pathogens and removes potential pollutants from the environment. Waterborne diseases transmitted through human excrement are a leading cause of death worldwide, especially in the so-called developing world. Some diseases caused by untreated human sewage are Cholera, Typhoid fever, Paratyphoid fever, Salmonella, Dysentery, Gastroenteritis, Leptospirosis, Meningitis, Hepatitis, and various parasitic diseases. Nonetheless, humanure contains nutrients and when treated in a biodigester or through (hot) composting and returned to the land as fertilizer, we can see that this is 'closing the loop'. Watch this short and amusing film about humanure from a permaculture farm in New Zealand.

Composting toilets are excellent options for individual houses and if there are only a small number of villagers in a settlement. In villages with centralised facilities, many such toilets can be built in a block. However, there can be cultural taboos against dry toilets, and the community should be consulted before adopting this technology.

Humanure can also be used in a biogas digester to produce gas for cooking.
Many small decentralized (household) biogas systems have been effectively installed all over the world.

Here is a link for a biogas digester construction which explains the step-by-step process.

The amount of biogas that can be yielded from human waste is limited in comparison to livestock manure and other feedstocks. Our stomachs are just too efficient! David House states in his excellent book that 1000 lbs of human waste produces about 0.6 cubic meters of biogas (enough cooking fuel for about 1 to 2 persons). But that amount quickly adds up. Biogas digesters have a great deal of potential to dispose safely of otherwise untreated sewage in developing countries, and can have a major role to play in the developed world as well.
Here is a link to a short documentary.
It shows the difference the installation of a biogas digester made to a village in China.

There are also hybrid systems that use normal

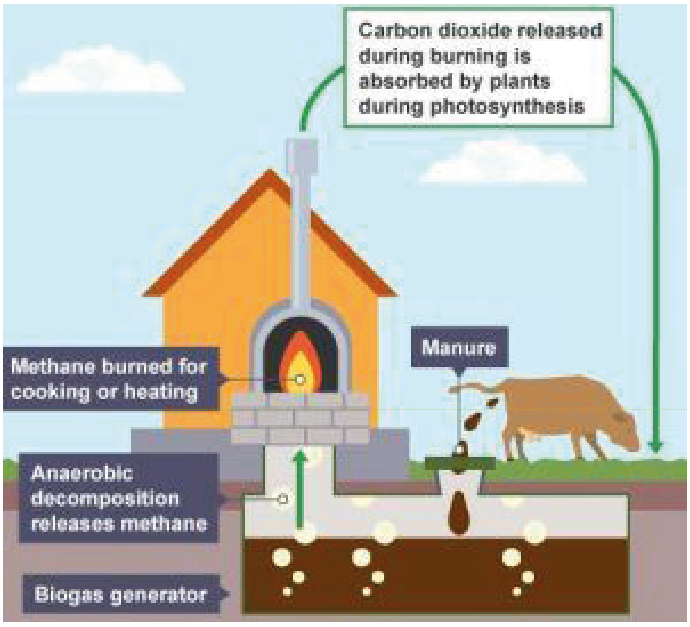


Image from Low Impact

flushing toilets followed by solids separation by centrifuge. The solids are then composted in a separate digester, while the liquids are disinfected (where necessary) and discharged with the grey water system.

Aquatron uses a normal flushing toilet which combines public acceptability and convenience with some of the benefits of composting toilets, particularly no sludge and the creation of humus.

When the toilet (1) is flushed, the contents of the bowl are transported to the Aquatron Separator (2) where approx. 98 % of the liquid fraction is separated by using the momentum of the flushing water, centrifugal force and gravity. The Aquatron Separator needs no moving parts. The solid waste (paper and feces) falls down into the Bio Chamber (3) where it is composted by bacteria and, if desired, by worms. If using worms, the volume of the solid waste will be reduced by approx. 95 %. The need for emptying and handling the waste is therefore reduced to a minimum. Optionally, after installing an Aquatron System, some 250-300 worms are placed into the Bio Chamber.

The number of worms needed to maintain the composting process will be adjusted automatically by nature. Optimal temperature for the composting is 12-25 degrees Celsius, a temperature level recommended for year-round inhabited homes. Freezing will kill the worms. The composting process is free from odour and flies because the Bio Chamber is ventilated and the small amount of liquid following the paper down into the Bio Chamber is removed by a drain at the base of the Bio Chamber. When the Aquatron 90 and 400 models are emptied, the refuse must be composted to soil in the garden together with the normal garden and kitchen waste. The liquid proceeds to the UV unit (4) where it is exposed to Ultraviolet light, which kills bacteria and viruses. The liquid may then be treated as Grey Water (bath, dish washing and laundry water), which means that the toilet wastewater may be infiltrated into the ground or into a suitable receptacle. Since the liquid fraction is separated from the solid waste, Aquatron Systems are not sensitive to peak load usage.

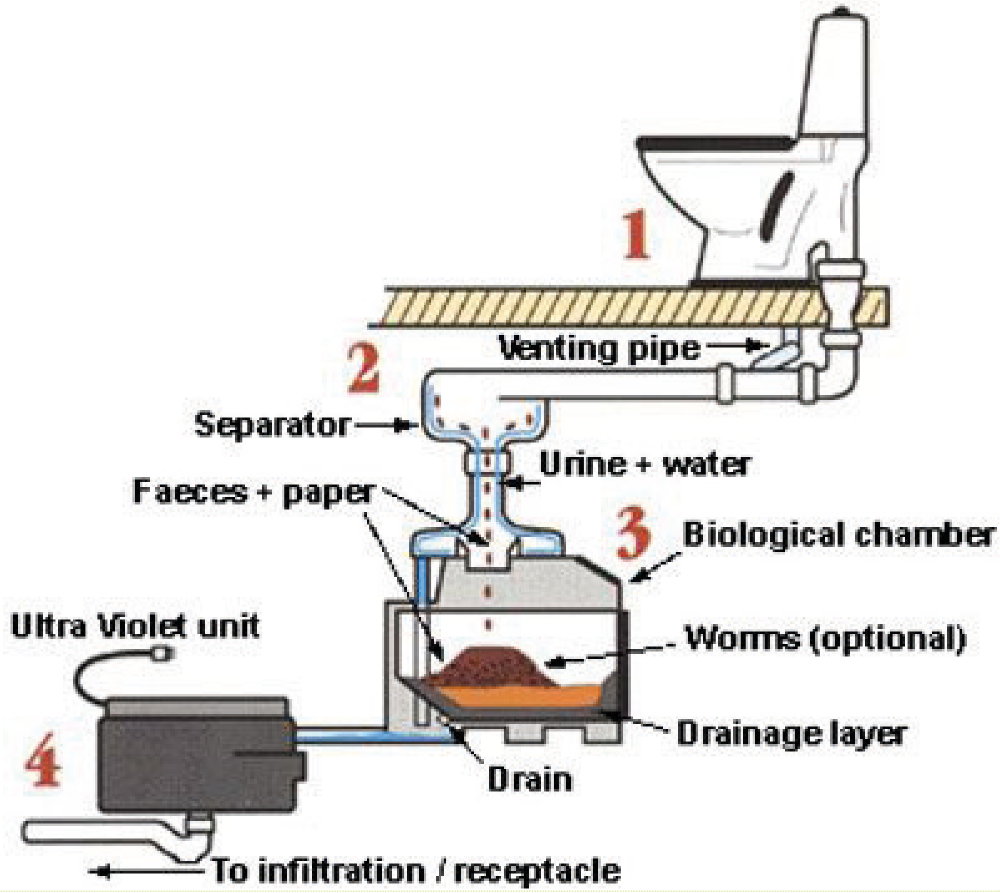


Image from Aquatron

5. Ecological Engineering for Water

"I intuited that perhaps for the first time in modern history our knowledge of the natural world has reached the stage where we can look into nature and see a coherent body of ecological information there. Life's inner workings are being decoded and its extraordinary complexity revealed. We are learning that nature has a set of operating instructions of immense significance, which I believe are critical to humanity's future."

Dr. John Todd, *Healing Earth*

Biological wastewater treatment creates a natural ecology of plants, microorganisms, small filtering animals and in some cases fungi. Bacteria living in biofilms around the roots of certain plants break down the long-chain organic molecules in the waste matter into simple non-polluting substances. A small amount of nutrients– nitrogen and phosphorus ((typically less than 5% of the treatment) – is taken up by the plants.

The Biological Processes

Nature makes no waste; the waste products from one species are food for another.

The biological processes at work in biological wastewater treatment can be divided into those in which the micro-organisms breaking down biodegradable material require oxygen and those in which the presence of oxygen is toxic to the the micro-organisms: aerobic digestion and anaerobic digestion.

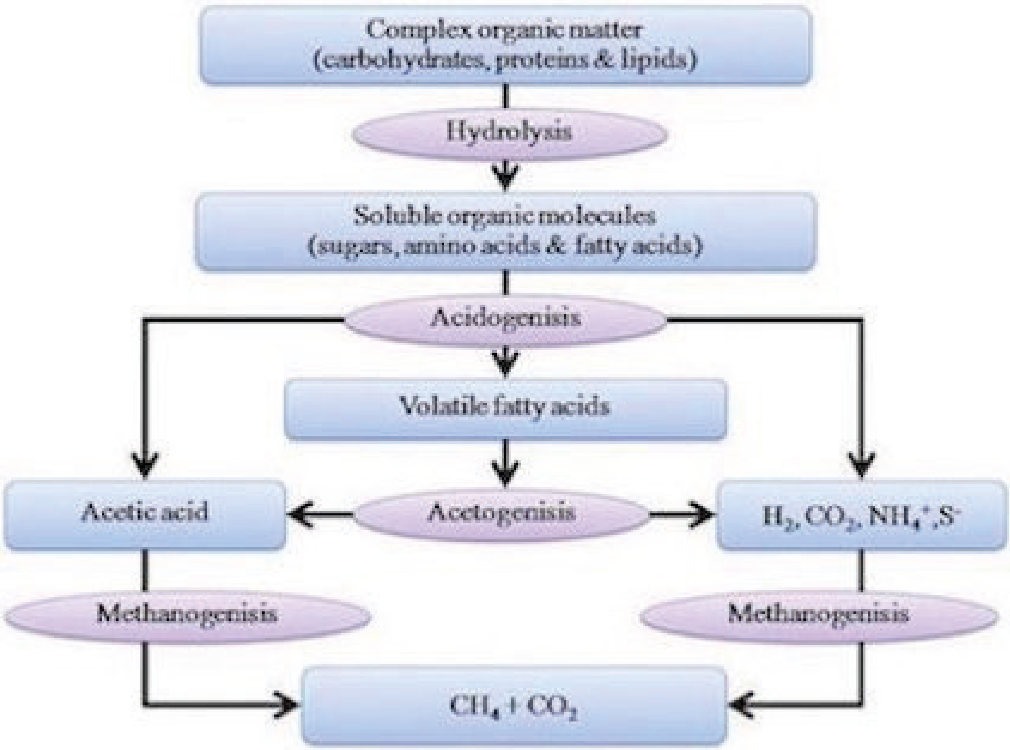
Anaerobic

Anaerobic processes take place in the absence of oxygen. Anaerobic digestion makes use of naturally occurring micro-organisms and it is essentially a process in which biomass is biochemically transformed by anaerobic bacteria and archaea leaving carbon dioxide (CO_2) and methane (CH_4). There are 4 key stages: hydrolysis, acidogenisis, acetogenisis and methanogenisis.

- **bacterial hydrolysis:** bacteria break down (digest) insoluble organic polymers, complex carbohydrates (sugars and amino acids), and make them available in soluble form for other bacteria

- **the acidogenic and acetogenic bacteria** digest them in the soluble form transforming them in a two-step process into organic acids and alcohols with release of ammonia and some other gases (see below) methanogenic archaea digest the ammonia to produce methane and CO_2.

These are naturally occurring processes using micro-organisms in the same way that fermentation of food products and alcohol occurs. Anaerobic digestion can also be be used on a small scale to create 'biogas' (methane) for cooking and energy. The bio-slurry is used as fertilizer. This is useful in poorer parts of developing countries where women and children spend hours collecting wood with the knock-on effect on land degradation, hours that could be spent in education or economic activities and growing food. We can see that in making choices about achieving SDG 6, we make headway in achieving other SDGs.



The stages of anaerobic digestion

Aerobic

Aerobic processes take place where adequate oxygen is present. For example, garden composting of food scraps and other plant material is an aerobic process using naturally occurring micro-organisms that require oxygen. The micro-organisms involved in aerobic digestion in wastewater require oxygen to remove organic carbonaceous waste material. The aerobic digestion takes place close to the surface of wetlands, in gravel or where water is aerated by plants or pumps. It is essentially, the process by which carbon is transformed up a microbial food chain through predation, feeding, and metabolism by protozoans, rotifers, and other microorganisms with CO2 as a by-product.

There are 4 stages:

- **The solubilisation** of large organic molecules in water;
- **The uptake of organic matter** (small compounds) from the wastewater by the microorganisms, effectively ingestion;
- **Once the organic material is ingested**, it is converted into the bacteria's own cellular matter through its own metabolic processes and CO2 is released as the by-product; micro-organisms proliferate in a food chain as long as there is oxygen and organic material present.

Because the micro-organisms involved require oxygen, the amount of waste in the water is measured by the demand for oxygen, known as BOD (Biochemical Oxygen Demand). The lower the BOD, the lower the levels of aerobic microbial activity, and, therefore, the lower the levels of waste. BOD is used to measure the effectiveness of the treatment and the safety of the output for health.

5.1. Nitrification and Denitrification

Nitrogen in combined molecular form is one of the principal pollutants present in wastewater; it exists in both organic and inorganic forms. The organic forms of nitrogen include amino acids, urea, uric acids, purines and pyrimidines, while free NH_3, ammonium salts and nitrogen gas (nitrogen is not a polluting compound) are the forms of inorganic nitrogen.

While the biological pathways that treat these nitrogen compounds are complex, for simplification we will regard them as just two basic natural processes that take place. Nitrification entails the biological oxidation of ammonia (NH_3) transforming it into nitrite (NO_2) with further oxidation producing nitrate (NO_3) carried out by nitrifying bacteria. These are processes which take place naturally in the soil as part of the chemical processes of the waste-nutrient cycle and the micro-organisms are therefore essential for life.

Nitrates (NO_3) can be readily absorbed by plants through their root systems to make proteins. In wetland wastewater treatments, bacteria living in nodules on plant roots oxidise the NO_2 to NO_3 which is then absorbed. This is a symbiotic, mutually beneficial relationship between the bacteria and the plants.

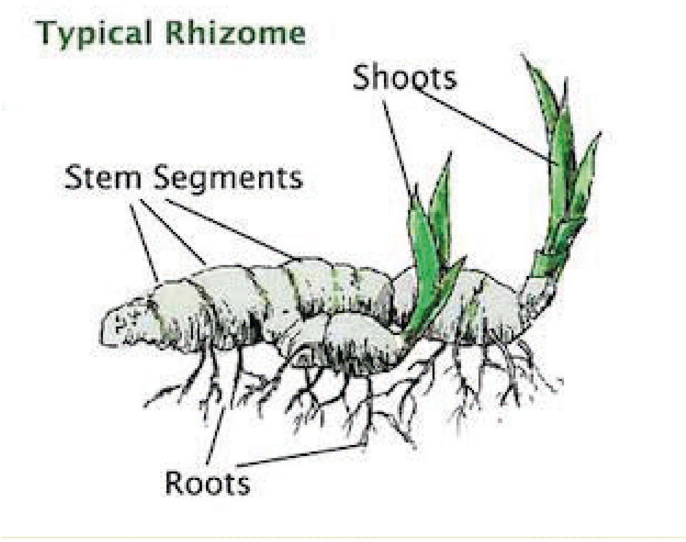
The micro-organisms involved in nitrification can be sensitive to the presence of excessive ammonia, temperature, low dissolved oxygen and acidity.
Denitrification is the chemical process by which excess nitrite (NO_2) is converted to atmospheric nitrogen (N_2) which can be released into the air.

5.2. The Rhizosphere in Wetlands Wastewater Treatment

'Rhizo' (from the Greek rhiza) means 'root'.
The rhizosphere, therefore, is the area in and around the roots of plants. A rhizome is a horizontal stem growing underground and putting up shoots and putting down roots from the stem. Ginger, ginseng, arums and many of the plants used in wetlands, such as Typha, Phragmites and Irises produce horizontal rhizomes below the surface. We too often forget that so many of the essential functions supporting life are happening in the invisible world below ground.

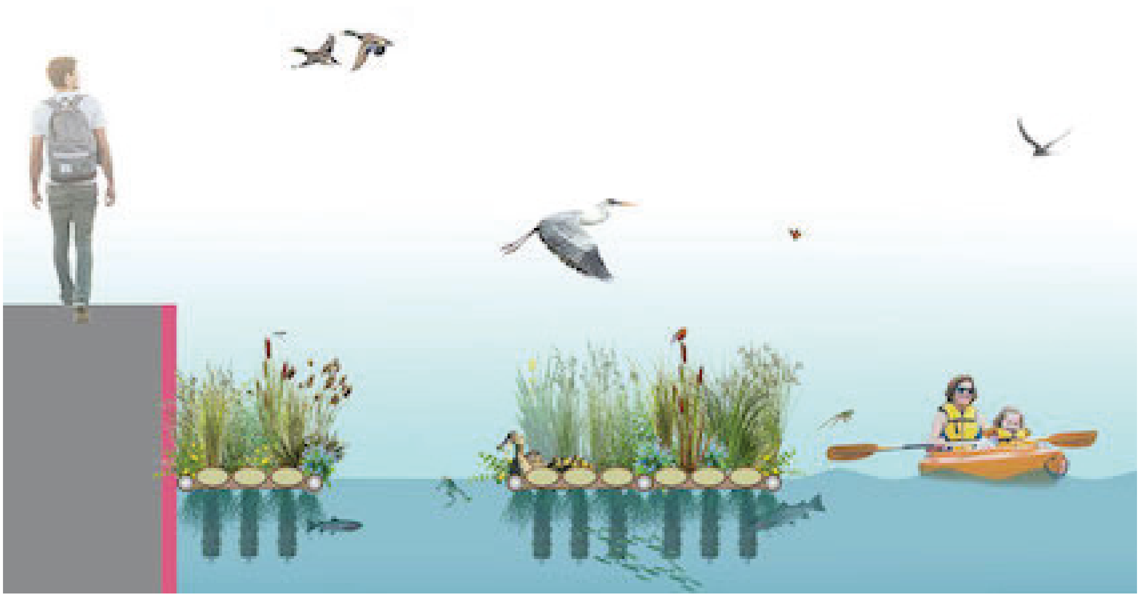
All of the processes described above are microbial. In order for the necessary microbes to thrive, appropriate habitats must be created within the treatment systems. Plants and artificial media (gravel and sand) are used in natural treatment systems to create the media necessary to support rich microbial communities.

Nitrification of ammonia to nitrites occurs in the biofilms which attach to the media. A biofilm is effectively a symbiotic relationship between microbial communities which stick together by excreting a sort of sticky slime. They can attach to living and non-living substances and are found everywhere. For example, in humans, they form in the mouth overnight (up to 600 microbial communities in a single biofilm); they are also found hiding in hospitals as biofilms of antibiotic-resistant microbial communities. Most of them, however, are not pathogenic for humans.



Source: [Gardenseeker]

In the floating ecosystem construction for purifying water shown below, the roots of plants will provide ample space for biofilms. The choice of plants with root nodules for bacteria is also crucial for nitrification and denitrification.



These root systems remove excessive nutrient, suspended solids, some heavy metals (zinc and copper) and ammonia and oxygenate the freshwater bringing it to life. Source: [Biomatrix Water]

These root systems remove excessive nutrient, suspended solids, some heavy metals (zinc and copper) and ammonia and oxygenate the freshwater bringing it to life.

The extensive root network and its rhizosphere in the planted ecologies provides the structure and nutrient support for the diverse microbial communities. Materials from the plant roots are exuded into the surrounding rhizosphere. These materials include hormones, antibiotics, metal chelators, nutrients, humic compounds and sugars (Todd et al, 1996).

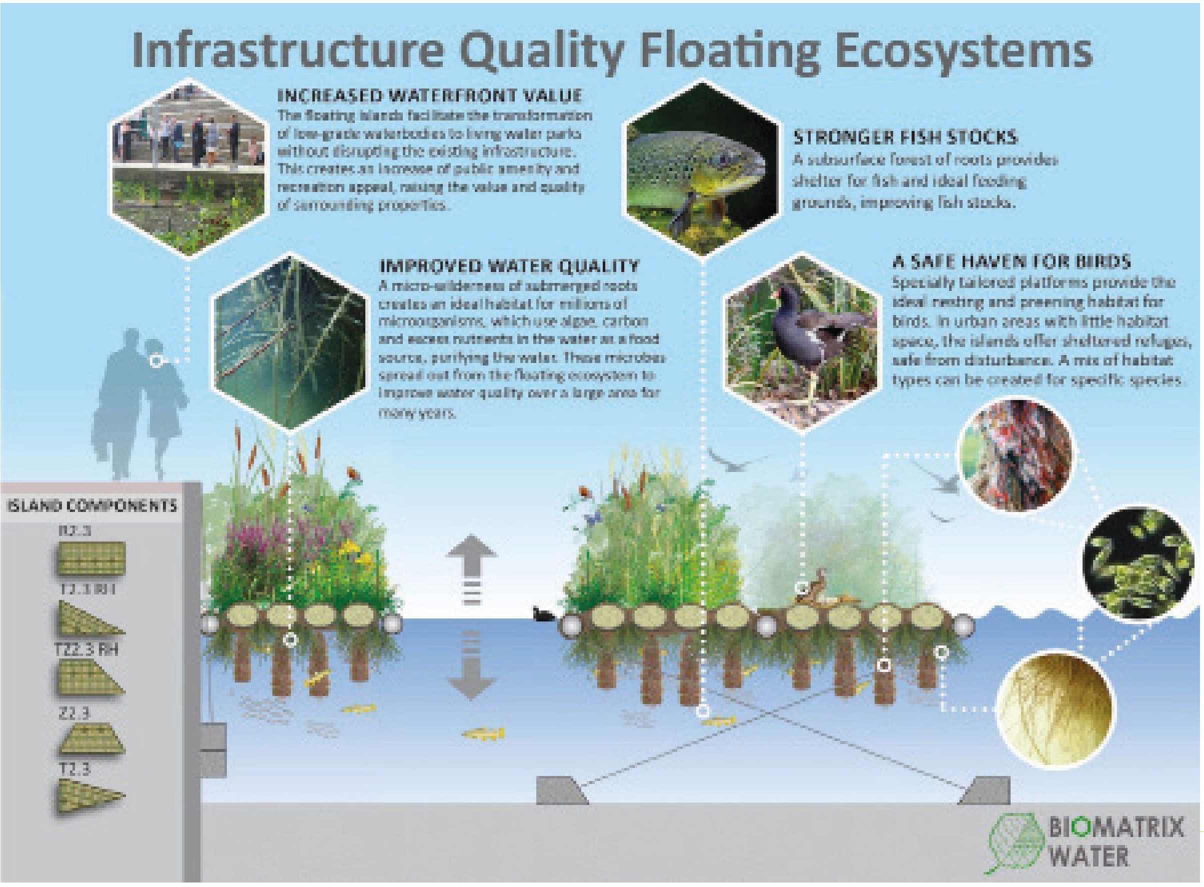
By constantly extending their root networks, plants are also forming new pathways in the sub-surface flow constructed wetland, through which water can filter. This keeps the wetlands open to the flow of water. Some plants also possess the ability to transfer oxygen from their aerial stems to their roots. This continuous exposure of organic matter to air promotes the decomposition and oxidation of the organic matter and enhances nitrification. In the aerobic treatment phase, the oxygenation of the water in contact with the biofilms is crucial for the effective functioning of treatment systems.

Attaching biofilms to surfaces significantly increases their stability and efficiency. They are also grazed by micro-animals and the number of dead bacteria that settles as sludge is minimized.

Source: [Deiceair]

Plants

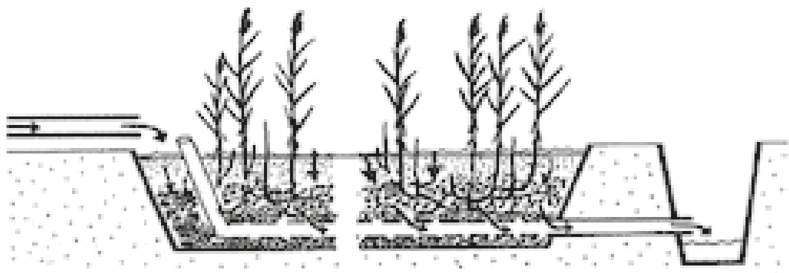
Typical plants used in Subsurface Flow Constructed Wetlands (SSFCWs) are the Cattail (Typha latifolia) and Reeds (Phragmites australis). Other plants that are locally available and robust can be added for biodiversity and colour. Typical examples are the Lily and Iris families. They are macrophytes including four types namely emergent macrophytes, floating-leaved macrophytes, submerged macrophytes and freely floating macrophytes. We can easily recognise many of these from garden ponds, or from natural wetlands but these are the most common in SSFCWs.

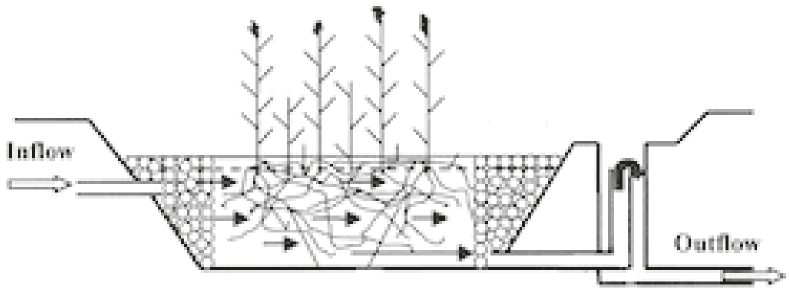


Source: [Biomatrix water]

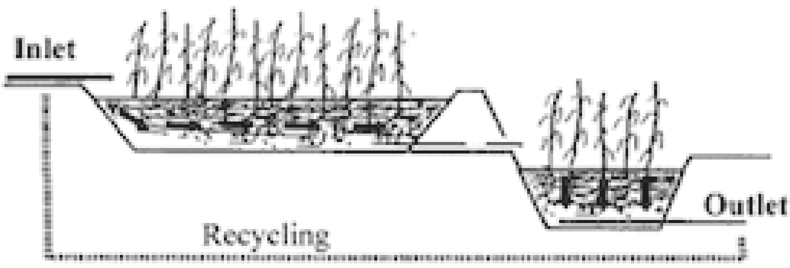
5.3. Constructed Wetlands

The constructed wetlands in which these processes take place are built either as surface flow (SFCW) or sub-surface flow (SSFCW). The former uses plants growing in soil over an impermeable liner. The SFCW runs in a flooded condition. A SSFCW has about 700 mm of gravel installed above a liner and the wastewater flows horizontally about 100 mm under the surface of the gravel – hence “sub-surface”. Plants are grown in the gravel with their roots in the water under the gravel surface.





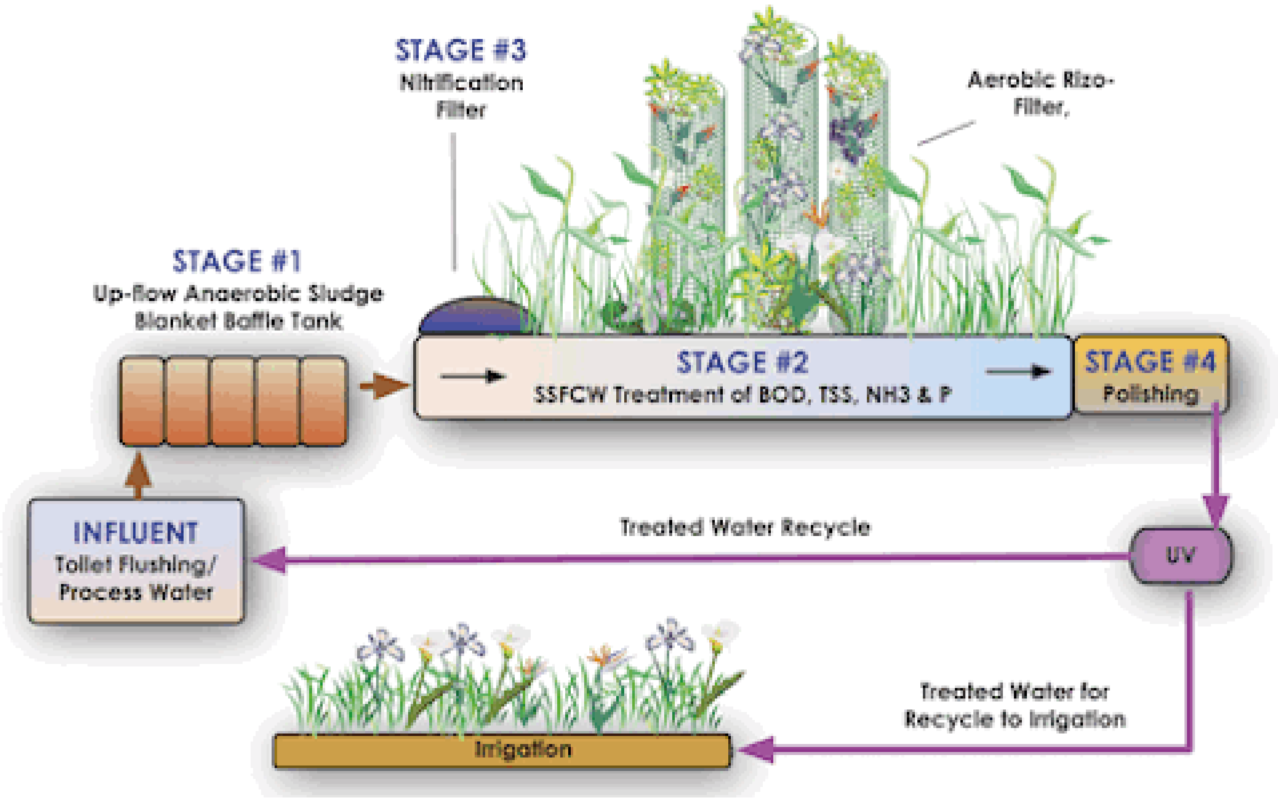
Above is a diagram of a vertical flow system and below there is a horizontal flow and a hybrid.



Source: Environmental Engineering Research

SSFCWs are further divided into vertical flow (VF), horizonal flow (HF) and hybrid systems.

In the example of a MSR (Multi-Stage Re-circulating) constructed wetland below, treatment takes place in 4 stages combining an anaerobic stage (a multiple compartment baffle tank with an option for an up flow anaerobic sludge blanket - a variant on the septic tank with biofilter - more on this later) to remove TSS (Total Suspended Solids) with a SSFCW treatment. Stage 2 the SSFCW and stage 3 is an aerobic stage where nitrification and denitrification take place. A ‘polishing’ stage runs the treated water through a rough filter and an UV treatment before it can be used for flushing toilets etc. and then recycled back as influent into the system. It is a neat and attractive closed-loop approach. When necessary, treated water can also be diverted for irrigation. Besides these constructed wetlands, other options are available to suit the size and scale of the projects they serve as well as local ecosystems: Wet Ecological Treatment systems (WET), Lagoon-Based Natural Treatment systems with floating ecologies (examples of which we have seen above), and Tank-Based Systems. We will look at examples of these systems before moving on to how they function in combination with other technologies such as a septic tank or a biodigester in a constructed wetland system.



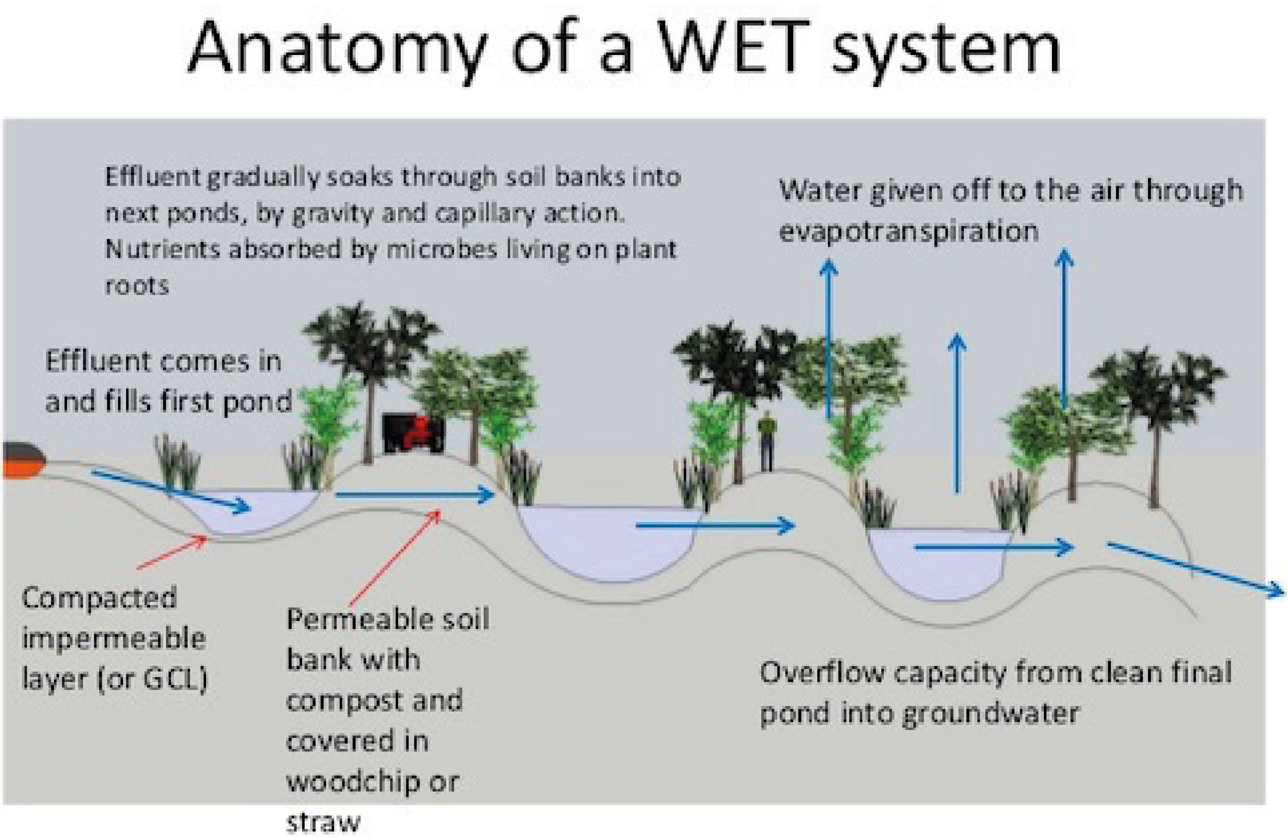
Source: *[Biomatrix water]*

Besides these constructed wetlands, other options are available to suit the size and scale of the projects they serve as well as local ecosystems: Wet Ecological Treatment systems (WET), Lagoon-Based Natural Treatment systems with floating ecologies (examples of which we have seen above), and Tank-Based Systems. We will look at examples of these systems before moving on to how they function in combination with other technologies such as a septic tank or a biodigester in a constructed wetland system. An appendix will provide extra and more detailed information about construction for those participants who feel they might be interested in this topic as a specialisation. The appendix will also contain links to further reading.

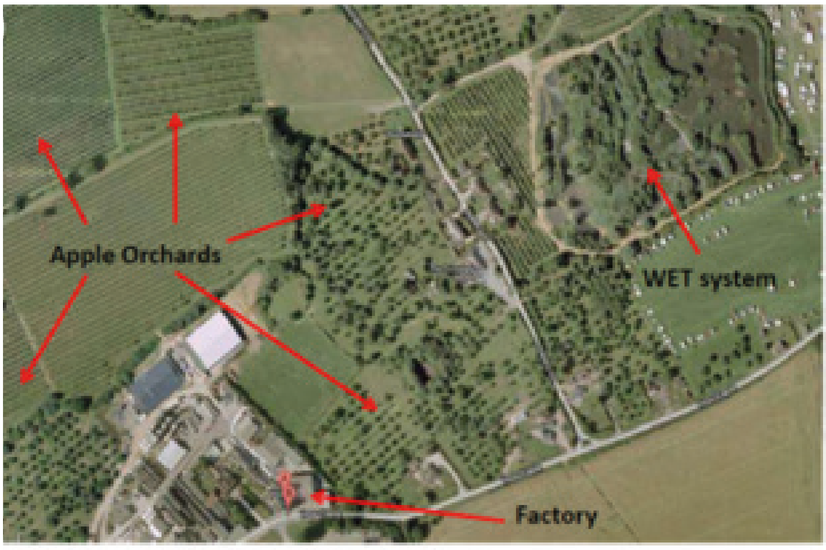
5.4. Wetlands Ecological Treatment (WET)

Wetland Ecological Treatment systems function by harnessing the innate ability of natural wetland ecosystems to absorb and transform the organic nutrients found in wastewater, converting these into plant biomass and soil. WET Systems are a regenerative form of wastewater purification, they are low-entropy systems as they use no fossil fuels or electricity to purify the wastewater. They are solar powered by the ability of plants to absorb solar energy during photosynthesis. The nutrients found in wastewater are mineralised by micro-organisms in the root-zone, which enables the plants to absorb and use them as an input for growth creating biomass - a biological resource which can then be harvested if required.

WET Systems have a low embedded energy since, unlike conventional reedbed treatment systems, no gravel or plastic aeration/distribution pipes are used in their construction; thus gravel does not need to be quarried and transported to site, and because plastics are not routinely used in the designs WET.



Source: Biologic Design



Source: [Biologic Design]

Systems have a very low embedded energy. Soil in the root-zone, not imported gravel, is the filtration medium and this is, in most cases, already on-site.

The basis of the WET System is a horizontal plug-flow, soil mycorrhizal, multi-species constructed wetland purification and production system, made up of a series of specially designed and constructed earth banks and ponds.

As the wastewater flows through these soil banks it is both purified by microbial action and transpired by growing trees and other plants. The WET System is planted with a wide range of aquatic and marginal plants and a variety of willow types and wetland tree. The Biomass Yield from a well-managed WET System, can include one-year old coppiced willow wands for basketry, two-year old willow wands for hurdle making or living willow domes and tunnels, as well as binders used for hedge-laying, and three-year old willow wands which are used for the construction of living willow structures and garden furniture.

Rapidly growing, large, biomass willow types can also be planted and when harvested and seasoned these can be used to fuel simple woodstoves and 'rocket-stoves', ceramic stoves, biomass boilers or combined heat and power (CHP) systems - and so contribute to the energy needs of the site.

WET systems can be built specifically for and in proximity to specific industrial processes. In this example, the WET system was designed for a company making cider. The wastewater is acidic and requires a large natural system to de-acidify as well as treat organic waste and it forms an integral part of the orchards and factory.

5.5. Lagoon and Tank based treatment

These two natural systems are both ideas of ecovillage communities. Both rely on the biology outlined in the section Constructed Wetlands. The first is a lagoon-based cascade system with floating ecologies. The second is a more highly engineered and compact system using tanks: the Food Chain Reactor (FBR).

Lagoon-based natural treatment system with floating ecologies

This system works on similar aquatic biological principles to constructed wetlands. However, it uses energy to supply aeration and mixing, is more highly engineered and has a smaller physical footprint. It has five components:

- **Floating Structure**, that supports the active systems
- **Aeration**, either fine bubble or submersible venturi
- **Floating planted areas**, with roots in the water
- **Geotextile media** for enhanced attached growth treatment
- **Bioaugmentation**, as necessary

This lagoon system has a smaller physical footprint than a constructed wetland with the same loading. Operating costs are higher because aeration is used. Aeration can be designed to use renewable energy (solar and small-scale wind turbines) on site.

The systems can be designed to minimize the buildup of sludge, where sufficient hydraulic retention time is available. In general, larger retention time results in the need for a larger lagoon. The sludge is digested as part of the lagoon ecology. Sludge removal every ten years is achievable. Floatation is normally provided by High Density Polyethylene pipes (HDPE).

Source: *Useful Community development*

Long lengths of pipe are welded on site. How does a lagoon system compare with "conventional" technology such as activated sludge?

- **Lower** capital cost
- **Robust** and simpler systems to operate
- **Lower** energy required for operations
- **Substantially** less sludge
- **Combination** of the above means lower operating costs, and
- **Lower** life cycle costs
- **Uses** more land
- **Beautiful** systems that are natural

For an example, see the website of the ecological engineering company Biomatrix Water, located at the Findhorn ecovillage in Scotland.

5.6. Tank based systems

Tank-based technologies take waste into a single or series of tanks, where controlled short retention time treatment takes place (in typically six-hour cycles). The Organica FCR approach described below is a good example of an ecological engineering approach to tank-based design. Constructed wetlands and lagoon-based systems are located in the open and usually have a high physical footprint and low ecological footprint. In wastewater treatment physical size can be traded for energy. Tank based systems are more highly engineered, are of a smaller size and use larger amounts of energy. The chart in the next chapter (Suitable treatment for sustainable communities) illustrates this.

In countries with cold winters, FCRs are installed in greenhouses: 8,000-pe system outside Budapest. Organica Water

Follow this link to watch a tour of the Organica Tank-Bsed System that treats water for 200,000 people in Shanghai https://www.organicawater.com/facility. FCRs can be installed in urban areas because there are no odours.

The planted ecologies on indoor tank-based systems make the greenhouses look like botanical gardens.

The Living Machine, Findhorn Ecovillage, Scotland, Biomatrix Water

5.7. The food chain reactor (FCR)

Organica has combined natural treatment biology with a highly engineered and computer-controlled mechanical technology to provide the most advanced expression of an ecologically engineered wastewater treatment system. This is the most suitable for systems larger than 3,000 pe to be installed in an urban location. The physical footprint is a fifteenth the size of a constructed wetland. It is a trade-off between land used and investment plus operating energy.

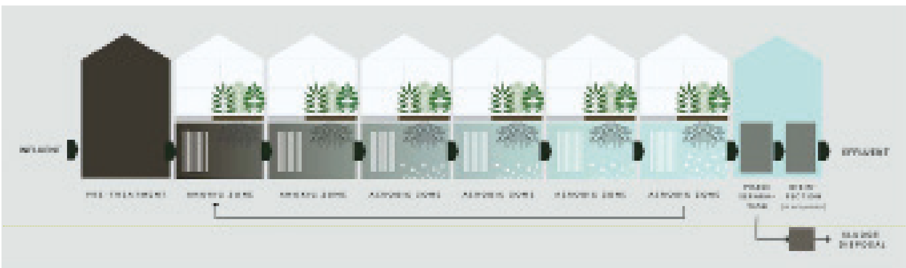
The original eco-machine design, John Todd, Burlington

The system's characteristics are as follows:

- **Attached growth** treatment with planted ecologies and manufactured media;
- **Suspended growth** treatment;
- **Anaerobic,** anoxic & aerobic batch cycles;
- Nitrification in aerobic and denitrification in anoxic cycles;
- **Improved uptake** of phosphorous;
- **Blowers controlled** by dissolved oxygen sensor activation of variable frequency drives.

The system runs four treatment cycles a day. The short retention time results in a low physical footprint. Finely tuned treatment cycles are controlled by a computer that can be accessed remotely. High efficiency aeration blowers have variable frequency drives and dissolved oxygen sensors enable the process computer to optimise energy performance.

While Organica Water and a number of other companies have further developed these technologies, many of the initial designs for so called 'living' or 'eco-machines' were created by Prof. John Todd in the 1970s. Visit his website to look at a wide range of designs for his projects.



Source: Organica Water

6. Living Water Cities

We've looked at systems from the smallest scale of simple constructed wetlands through to eco-machines and Food Chain Reactors that serve large populations in cities. Let's have a look at some of the ways that cities can be revitalized with 'living water' in this short but inspiring video from Biomatrix Water.

The video is followed by an animated design for an entire city neighbourhood. You can click on the numbers to see the scope for ecological, plant-based technologies that cleanse while reconnecting citizens with nature.

Modelling for Decision-Making: what system is most suitable for your community or project?

In this module we have been looking at various problems arising from our present water crisis and the ways we can change our attitudes and our practices. A whole-systems approach to designing regenerative communities' entails taking everything into account, the climate, the hydrological cycle, the local watershed and making choices based on ecological knowledge. Working with nature, through various forms of ecological design, we can have both local and global impacts that enable the biosphere to regenerate its ecosystems and functional cycles.

As intentional communities, we can integrate our choices for water management into a broader vision for our watershed. We make choices that are determined by an understanding of the local ecology and aim for systems that provide for our needs while adding to ecosystem restoration. We can do this by applying the 12 permaculture principles starting with observation, and we can also make choices that maximize the potential 'yields', based on the ethics: Earth Care, People Care and Fair Shares.

We can empower ourselves to be enablers of biosphere regeneration by mapping out the connections between the elements in our systems. Above we looked at the mind-map of a whole-systems approach to water as the means to envisage the bigger picture and find our place within the system. We can draw up conceptual water budgets integrated with the watershed after some research into where our water comes from, how it is used, how and where it is treated and released back into the environment. For help drawing up a conceptual water budget, follow the link provided in the appendix.

We can use this model to make our own maps, adjusted for our own community/watershed and even make improvements. For example, rain doesn't just fall into rivers (as shown in the map above), it falls mostly on land, and we have seen from the section on watersheds that healthy rivers cannot be regarded as separate from healthy, hydrated landscapes. So we can include restoration of the small water cycles, bioprecipitation, through ecosystem restoration as an essential aspect of a regenerative design.

Choices between systems can also be mapped out to compare the pros and the cons as this mind-map illustrates in comparing a tank-based system with a lagoon-based system.

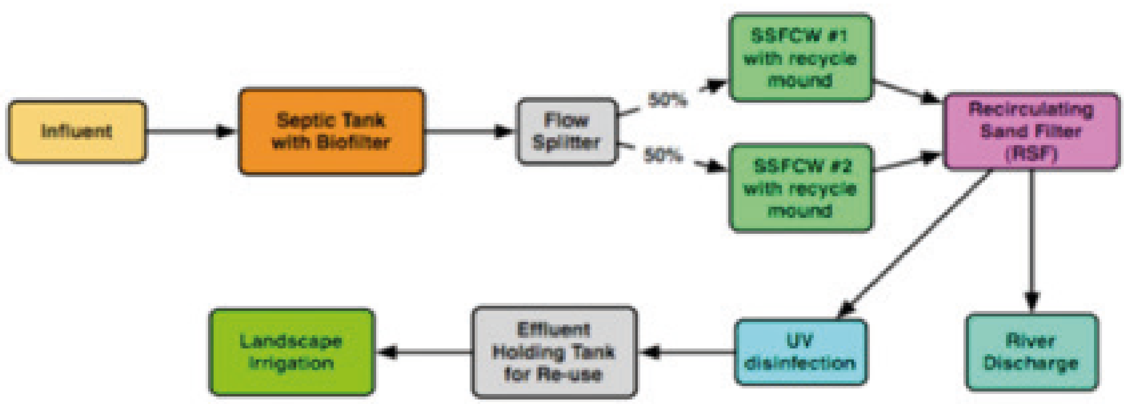
Source: *[Gaia Education]*

We can add to this mind-map too, comparing use of space, (embodied) energy, materials and costs along with environmental advantages. If we have already decided for a constructed wetland, we can map out the flow of the system. Horizontal flow constructed wetlands for treating wastewater need a pre-treatment stage to lower influent BOD (Biochemical Oxygen Demand) and TSS (Total Suspended Solids), otherwise the wetland can get overloaded at the front end, which can cause clogging.

We can see that in this flow diagram below, the choice for a septic tank has already been made. But there are alternatives. Would a biodigester be more appropriate? Let's gather some information on both. What type of information do we need?

TYPICAL PROCESS FLOW DIAGRAM FOR SEWAGE TREATMENT SSFCW

Treatment is by duplex, sub-surface flow, constructed wetlands (SSFCW), with recycle mounds followed by a recirculating sand filter (RSF) and UV disinfection for re-use.

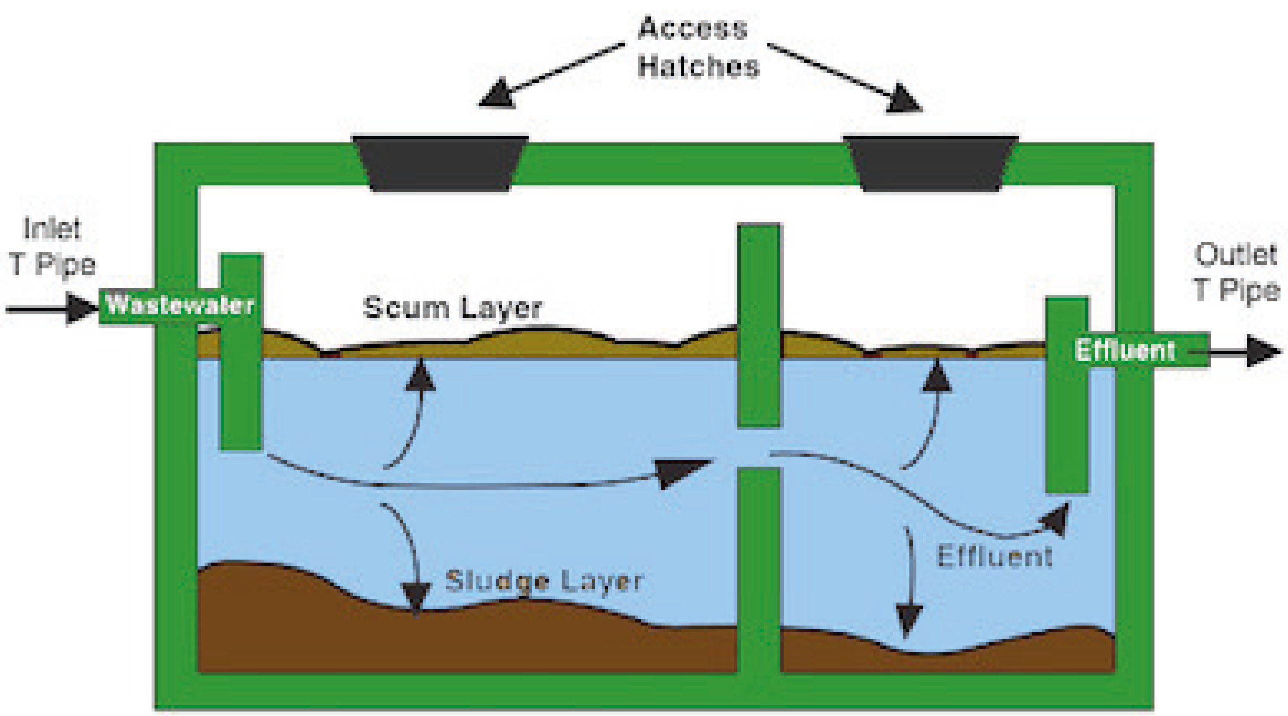


6.1. Septic tanks

This allows wastewater to separate into layers and begin the process of decomposition while being contained within the septic tank. Bacteria, which are naturally present in all septic systems, begin to digest the solids that have settled to the bottom of the tank, transforming up to 50 percent of these solids into liquids and gases. Septic tanks provide initial reduction of organic matter (BOD and TSS) through anaerobic digestion. Septic tanks remove little nitrogen, unless nitrified effluent is recycled for denitrification.

When liquids (black water) within the tank rise to the level of the outflow pipe, they enter the discharge system (see diagram below). They can be allowed to disperse into land (through a French drain) or can be moved on to the next phase in the flow diagram for treatment in a wetlands system for discharge into rivers or re-use as grey water for irrigation.

While septic systems can handle plastic and other non-biological materials that get into the collection system, they cannot dispose of all the material. Solids that are not broken down by bacteria (grit and sand, plastic, undigested fats, etc.) and non-organic solids begin to accumulate in the septic tank as sewage sludge and eventually need to be removed when they are two-thirds full of sludge, some of which might need further treatment.



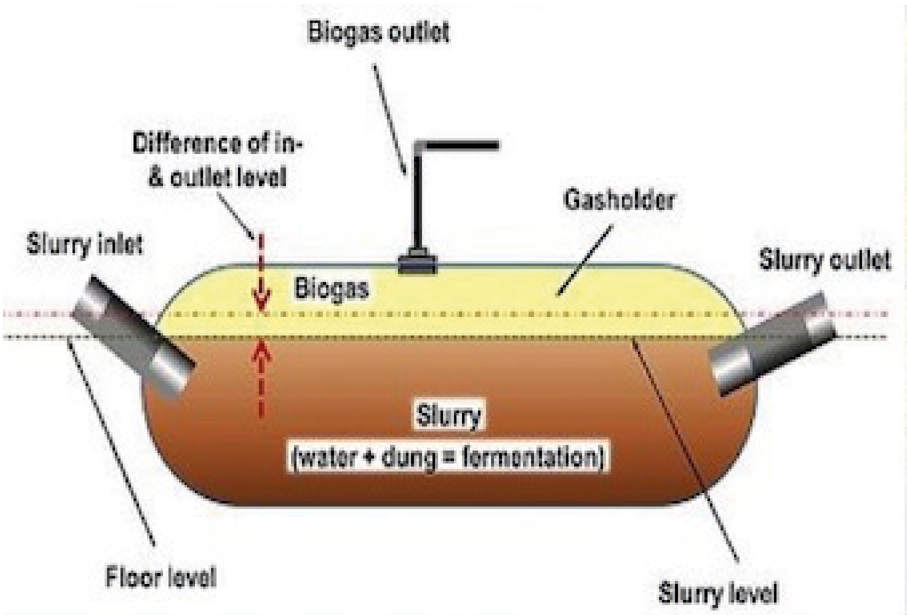
EPA Septic Systems

6.2. Biogas Digesters

A biogas digester is similar to a septic tank, except that the main chamber is domed to capture and siphon off the methane gas. Furthermore, all green waste can be loaded into a biogas digester, namely, kitchen scraps, garden cuttings, (Hu)manure, etc., thereby minimizing solid waste disposal off site. As the solid waste settles and is treated through natural anaerobic digestion, the more viscous slurry, or "black water", flows out of the biogas digester and needs to be treated through a natural aerobic process via a constructed wetland (SSFCW or SFCW) or Wetland Ecological Treatment (WET) system. Through the second treatment, "black water" is thus cleansed into "grey water" fit for use in recycling water for flushing toilets or irrigation of trees and landscape but should not be directly applied onto crops. The more solid slurry that is emptied from the biogas digester is effectively a bio-fertilizer.
The biogas digester has some advantages over a septic tank when we apply a holistic approach to wastewater treatment. In combination with a wetland treatment, the system is highly productive, turning waste into useful biogas (for cooking or heating), slurry for biofertilizer, grey water for irrigation and the wetland plants that can also be harvested for use as mulch and composting system. Some wetland plants also provide food and attractive flowers.

In permaculture, there are some excellent, small-scale examples of the combination of biogas digesters running on animal and human excrement combined with constructed wetlands that provide gas for cooking, biofertiliser for trees and grey water irrigation, the constructed wetland can also provide biomass for mulch. This system closes the loop: cows feed on grass, which is cannot be digested by humans, and add their own internal anaerobic biogester to the process, humans feed on home-grown vegetables, the manure from both passes through the wastewater treatment system, the nutrients and organic matter are returned to the soil, the water and energy is retained in the loop and there is milk and more fresh food: a perfect whole-systems' approach.

These are all good examples of ways we can combine mapping with ecological knowledge to make the most productive and regenerative choices for our communities and projects.



Source: Biogas production from waste

7. Conclusion

A whole systems design approach to water systems requires us to adapt our water use and treatment to the specific bio-cultural conditions of the places and ecosystems we inhabit. We need to contextualize what technologies we use, at which scale, and how exactly we use these technologies within the unique challenges and opportunities presented by our local and regional watersheds.

A wide range of effective ecological and biological wastewater treatment technologies and bioremediation technologies have been explored in this module. None of them are plug and play, all of them need to be adapted to specific uses and locations. By learning how and when to use these technologies and by using scale-linking design to integrate these different solutions in ways that create synergies to solve local, regional and global problems, we can all become active participants in the redesign of the human presence on Earth. Healthy watersheds, clean drinking water, frugal and restorative use of water in agriculture and industry are all important contributions of the transition to regenerative communities collaboratively nested within sustainable bioregions.

Bring it to life!

"Water is life"

Consider the above quote and what it means for you community and your life. From the different methods and whole systems approaches presented in this module, which ones would make sense in your community or in your life as it is right now? How is that method an "appropriate technology", why or why not?

Which methods and approaches would not be appropriate? Why?

Share your reflections with the group through the forum.

Further Reading:

The Permaculture Guide to Reed Beds: Designing, building and planting your treatment wetland system. Féidhlim Harty, Permanent Publications, 2017.

The Humanure Handbook: A Guide to Composting Human Manure, Joseph Jenkins, Chelsea Green Publishing, 2005.

Healing the Earth: An Ecologist's Journey of Innovation and Environmental Stewardship. John Todd, New Atlantic Books, 2019.

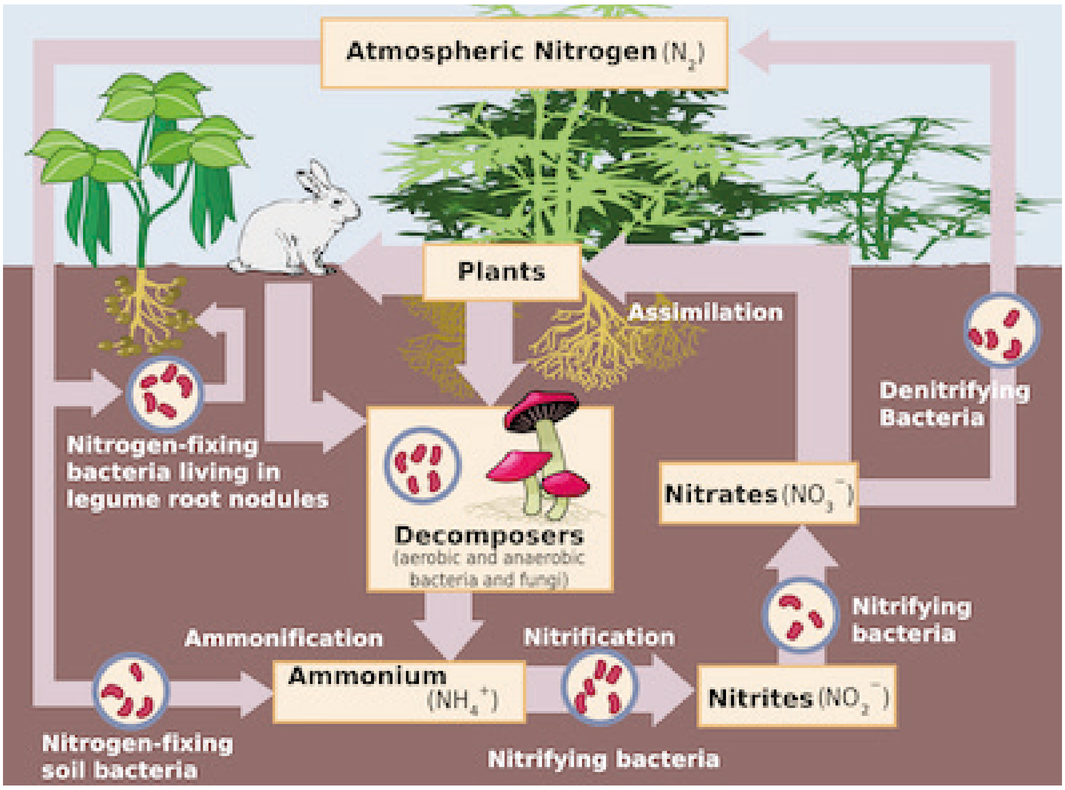
The Final Lecture John H. Todd on Planetary Healing and Ecological Design.

8. Appendix

Extra details for enthusiasts on the technical aspects of sizing and constructing wetlands and on the biochemical processes involved. This material is not obligatory as part of the module and does not feature in the assessments.

Nitrification

Nitrification is the process by which nitrifying bacteria convert ammonia to nitrate. The process happens in two distinct steps. Nitrosomonas sp. oxidizes the ammonia to the intermediate product, nitrite. Nitrobacter sp. converts the nitrite to nitrate. Nitrifying bacteria are considered autotrophic bacteria, or bacteria that utilize CO2 as their carbon source for growth.



Nitrification

The nitrifying bacteria are environmentally sensitive organisms. A variety of environmental factors can inhibit their growth. These inhibiting factors include high ammonia concentrations, low temperatures, pH outside of the 6.5 to 8.6 range and low dissolved oxygen (<1 mg/l). The pH of the system can change dramatically due to the nitrification process. The alkalinity in the wastewater is consumed at a rate of 7.14 mg of alkalinity, as CaCO3, for every milligram of ammonia oxidized. If there is not a sufficient alkalinity concentration in the wastewater, the pH will be depressed as the ammonia is oxidized. Alkalinity addition is not typically necessary for domestic sewage treatment and is not expected to pose a problem for a typical ecovillage treatment system.

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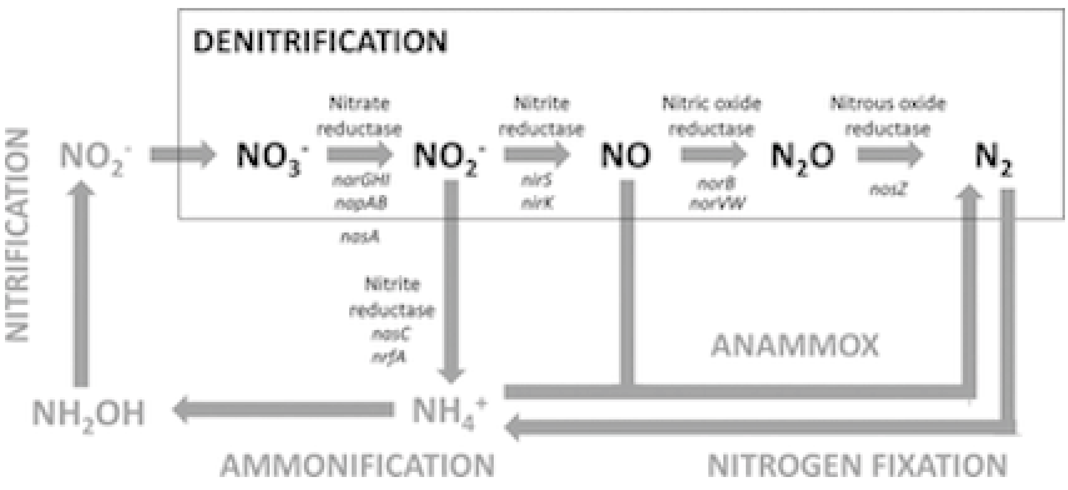
Nitrogen cycle in wetlands

The rate of nitrification is also significantly affected by the fraction of nitrifiers present in the wastewater. When the concentration of biodegradable organics, measured as BOD5, is high, the heterotrophic bacteria, or bacteria that use organic carbon as a carbon source, dominate the bacterial population. Typically, when the BOD5 is reduced below 80 mg/l the population of nitrifying bacteria is large enough to begin the nitrification process. For this reason, nitrification happens in the last stages of treatment. For systems requiring enhanced ammonia treatment, consideration of recycling internally to a gravel mound is excellent for nitrification, being primarily a simple aerobic trickling filter reactor towards the end of the treatment train. Some nitrification will also take place in the constructed wetland.

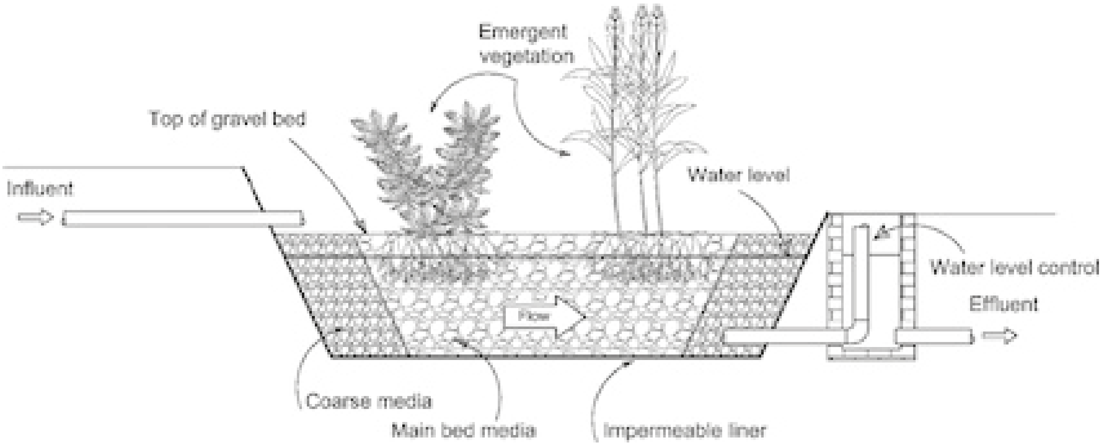


[Denitrification]

Denitrification

Denitrification is the biological conversion of nitrate to nitrogen gas, nitric oxide or nitrous oxide. These compounds are gaseous compounds and are not readily available for microbial growth;

therefore, they are typically released to the atmosphere. Nitrogen gas makes up over 70% of atmospheric gases, thus the release of N_2 to the atmosphere is benign.



Source: [Springer Link]

Biological denitrification is an anaerobic respiration reaction in which nitrate (NO_3) is reduced. Denitrifying bacteria are aerobic autotrophs or heterotrophs that can switch to anaerobic growth when nitrate is used as an electron acceptor (Bitton 1994). Denitrification can occur by two pathways. The dissimilative nitrate reduction pathway requires anoxic conditions and results in the liberation of nitrogen gas from the water column (Reed et al. 1988; Madigan et al. 1997). Under aerobic conditions denitrification results in the assimilative pathway or accumulation of nitrogen into biomass (Bitton 1994; Madigan et al. 1997). It is desirable to encourage the dissimilative pathway of denitrification so that nitrogen may be completely removed from the system in gaseous form rather than simply recycled through the system in biomass. In order for this to occur, there must be insufficient molecular or dissolved oxygen present so that the bacteria use the nitrate rather than the oxygen. The rate of the denitrification reaction is relatively fast when there is no free oxygen present (< 0.5 mg/l is ideal). The denitrification rate drops to zero when the dissolved oxygen level reaches 2.0 mg/l.

The denitrification process partially reverses the effects of the nitrification process in regards to alkalinity concentration. For every milligram of nitrate reduced to nitrogen gas, around 3.57 mg of alkalinity, in the form of $CaCO_3$, are created.

Denitrifiers also require the presence of organic matter (carbon source) to act as an electron donor (see carbon and nitrogen cycle diagrams below). The presence of a carbon source is the primary determinant of denitrification rates in water (Weier et al. 1994). Sources of such electron donors may be raw wastewater, methanol, and decomposing organic matter (Bowmer 1987; Bitton 1994; Weier et al. 1994). Alternatively, organic molecules resulting from solubilisation can be used, but are less efficient. If the main engine of dentrification is a subsurface flow constructed wetland, raw wastewater and decomposing plant matter provide the necessary carbon source for denitrification.

Denitrifiers belong to several genera including Pseudomonas, Bacillus, Spirillum, Hyphomicrobium, Agrobacterium, Acinetobacter, Propionobacterium, Rhizobium, Cornebacterium, Cytophata, Thiobacillus, and Alcaligenes. However, the most wide spread in water and wastewater are Pseudomonas fluorescens, P. Aeruginosa, P. denitrificans and Alcaligenes sp. (Smith et al. 1994; Bitton 1994). These organisms are ubiquitous and commonly found in natural soils and wetland

Approximate Sizing of SSFCWs to Treat BOD to 15 mg/l

Volume 200 l/pe 5 pe = 1 m3	BOD in mg/l	TSS in mg/l	NH4 in mg/l	WINTER Temp .C	Estimate of m2/pe	Area m2 Per m3 of sewage	Hydraulic Retention in days	BOD out mg/l	TSS out mg/l	NH3 out mg/l
1 m3	160	100	35	10	4.0	20.1	5.8	15	11.1	9.3
1 m3	160	100	35	15	3.0	15.0	4.3	15	11.2	13.2
1 m3	160	100	35	18	2.5	12.5	3.6	15	11.4	13.4
1 m3	160	100	35	20	2.25	11.2	3.2	15	11.5	13.6

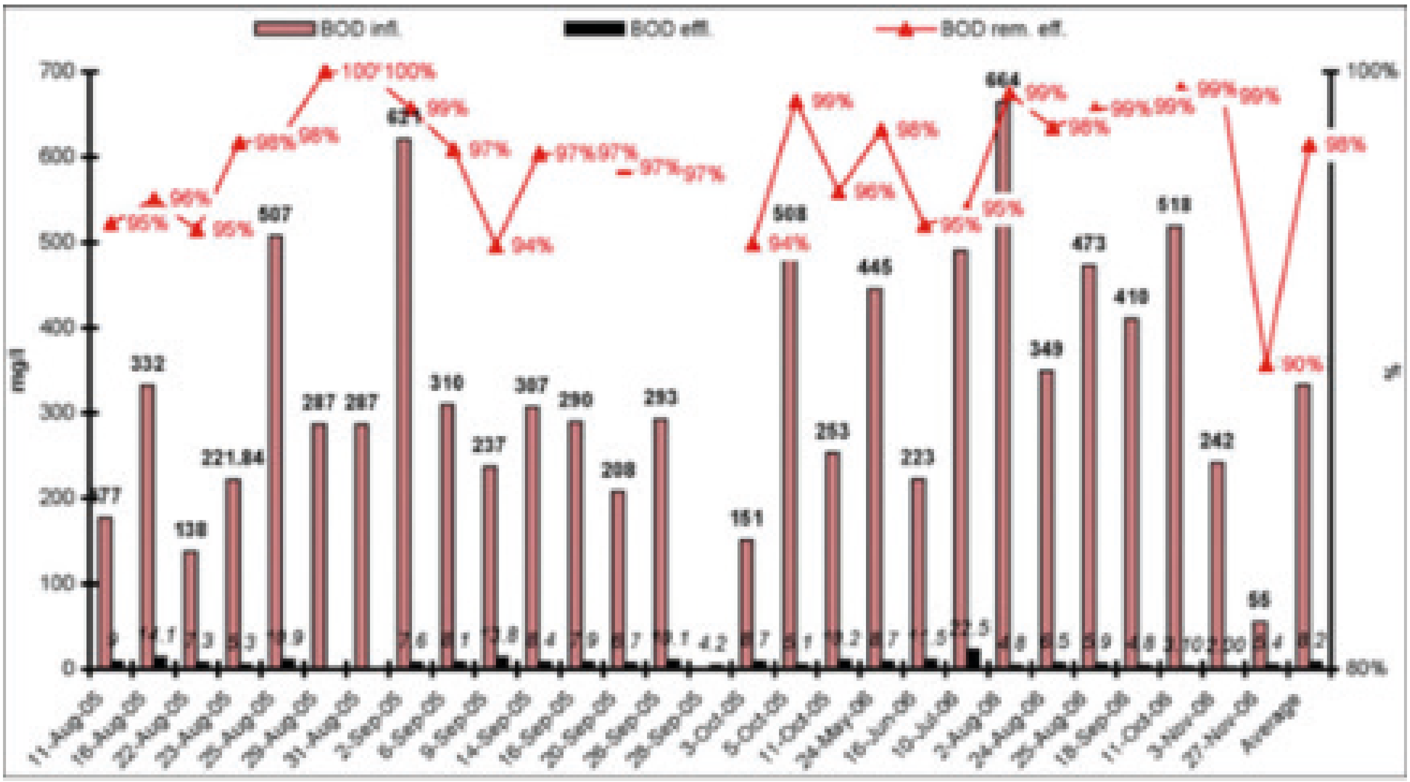
environments.

Sizing of Wetlands for Sewage Treatment Following Pre-Treatment in Septic Tanks

Constructed wetlands are sized using temperature dependent process equations. For an ecovillage application, the following table will provide a guide. This is only a guide and the process calculations should be checked by a qualified engineer before construction.

A person equivalent (pe) gives the daily wastewater influent to the treatment system. It is 60 grams of BOD per day, which is typically 200 litres with a BOD concentration of 300 mg/l (parts per million). For the same daily flow, typically the ammonia will be ~35 mg/l and the Total Suspended Solids (TSS) 250 mg/l.

As will be seen, the higher the temperature of the wastewater, the greater is the biological activity and so the more the treatment. Thus, a wetland in a tropical country will be smaller for the same level of treatment than one in a



Source: *Springer Link*

cold country.

The chart below gives the size of the working area of the wetland (between the manifolds) per person (pe) for four influent sewage water temperatures. The effluent treatment concentrations are also shown. It is recommended that at least 30% should be added to the size for berming of the edges, access and so on. Typically constructed wetlands are built 50 m to 100 m from the nearest house, although when properly built there is no odour. For very small wetlands (less than 50 people), the actual footprint should be calculated as berming can be a greater percentage of the total area required.

Further (Optional) Vertical Flow Reed Bed to Treat Septage

Sludge is the high solids, organic material that is a discharge from aerated tank-based systems. It is mainly composed of dead bacteria and some inorganics, such as sand and grit.

Septage is the sludge that settles at the bottom of septic tanks. Sludge and septage usually has a BOD of greater than 10,000 mg/l and often a strong odour. An economical way of treating

Comparison of three wastewater treatment technologies 03-marz-09

The numbers arte typical, rather than definitive.

Description	Constructed Wetland (without recycle)	Lagoon with floating ecologies & aeration	Tank-based system e.g. Organica FBR
Physical footprint/pe	4m2 + 30% = 5.2 m2	0.5 to 2 m2	0.07 to 0.14 m2
Typical capacity limits	50,000 pe	125,000 pe	>100,000 pe
Typical effluent standards	Tertiary	Tertiary	Tertiary
kWh/annum/pe for treatment	0	25 to 45	20
Construction cost comparison	Lowest	More than SSFCWs	More than lagoons
Engineering cost as %age of project	10%	10%	10%
O & M cost per m3 treated (approx.)	€ 0,10	€0.25 to €0.35	€ 0,25
Compexity of construction	Low	Moderate	High
Compexity of operations	Low	Moderate	High
Life cycle costs	Low	Moderate	Moderate
Suitabilty for rural ecovillages	High	Moderate	Low
Suitabilty for urban ecovillages	Low	High	High

Notes:

1. The numbers are for the wastewater temperatures in Northern Europe. Warmer temperatures will result in lower physical footprints. The working area of a SSFCW is ~4 m2/pe. With berming and access, typically the gross land area required is an additional 30%.
2. The Organica FBR systems are used for municipal and industrial applications.
3. Advanced standards are achieved by polishing with Recirculating San Filters or filtration, along with disinfection.
4. The higher figure for energy used in lagoons is for submersible venturi aerators.
5. The lagoon land area varies with depth and operations in either a fully mixed or partially mixed design.

sludge and septage is with a vertical flow reed bed. The bed is a simple planted sand filter, installed inside an impermeable liner. Leachate is the high BOD, but low TSS wastewater that collects at the low point in the bed. Typically, it is pumped to a wastewater treatment facility, if nearby, or alternatively to a specially built horizontal flow sub-surface constructed wetland.

The pores in the sand of the Vertical Flow Reed Bed are kept open by the plant stems, shoots and roots. The plants improve de-watering by seeking out moisture, and by keeping the septage open to air, as the reeds move with the wind. At the same time, roots treat biological slime in the sand.
Sludge, as organic solids, will accumulate over time on the surface of the bed. A typical loading rate is 50 kg dry weight of sludge per m2 of reed bed per annum. Continuous exposure of the sludge to air promotes the decomposition and oxidation of the sludge.

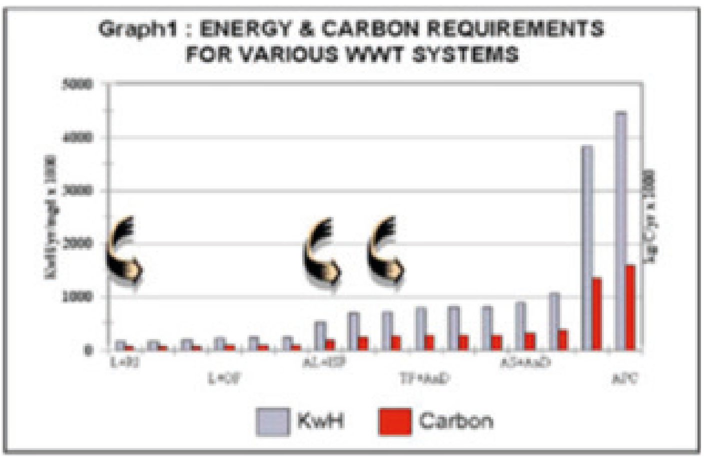
The volumes of sludge will be reduced between 90 to 98%. The principal form of reduction is de-watering. Mineralization is also significant (Kim 1993, Nielsen 1993, Reed et al 1995).

The bed is designed with a freeboard, which allows the sludge to accumulate for many applications. The bed can be designed for clearing every ten years. If and when clearing becomes necessary, the accumulated material is scraped off the surface of the bed. The treated sludge, which is now a stabilized composted material, is suitable for land application, particularly for landscaping and forestry. Sludge and septage treatment beds typically have odours generated during the loading of the bed. However, within 15 minutes to an hour, obnoxious odours are replaced by an earthy smell, similar to that of the soil and leaf litter on a forest floor. During the loading period, most of the odours are trapped by the leaves and plant stems. Most people cannot smell any odour when 50 to 100 metres down wind. The bed can be sited among trees to reduce further the possibility of unpleasant odours. No buildings should be within 100 metres of a septage treatment bed. Aeration of sludge or septage before bed application will stabilise the material and reduce odours significantly.

Food Chain Reactors provide high levels of treatment performance. Here the average annual BOD was 8.2 mg/l with a highly variable influent, demonstrating the robustness of the system.

For locations where land is expensive and there is a significant wastewater loading, a lagoon system or FCR is likely to be the most suitable technology. If there is room to use a lagoon, this will be less expensive than a FCR. In most major cities where the ecovillage is large, the more highly engineered FCR or similar will be the most cost-effective choice. (Note: Foodchain Reactors (FCR) used to be referred to as Feedback Batch Reactors (FBR) in the past.)

The table on the next page gives some approximate numbers and outlines comparisons of three wastewater treatment technologies. Costs will vary with the region. For example, where gravel prices are low, SSFCWs will be less expensive. Low excavation



Energy Chart, comparing treatment technologies

prices will favour lagoons and so on.

Note: this table offers only a guideline for initial design considerations at the community scale. Once the decision of what system to build is taken, the guidance of an expert and detailed engineering and costing is necessary for each project.

The Energy and Carbon Footprint of Sewage Systems

The chart below gives an indication of the energy used per 4,000 m3/d of sewage treated (in US terms, this is 1 MGD). Constructed wetlands use the lowest amount of energy and have the smallest carbon footprint of all the technologies in the table. It is hard to beat a SSFCW in life cycle cost. Numbers are also given for lagoon systems and FBRs and these are compared to conventional technologies.