# Biomimicry: Nature's Blueprint

*Filtering water by imitating life*

*Entry to the Stockholm Junior Water Prize 2020*

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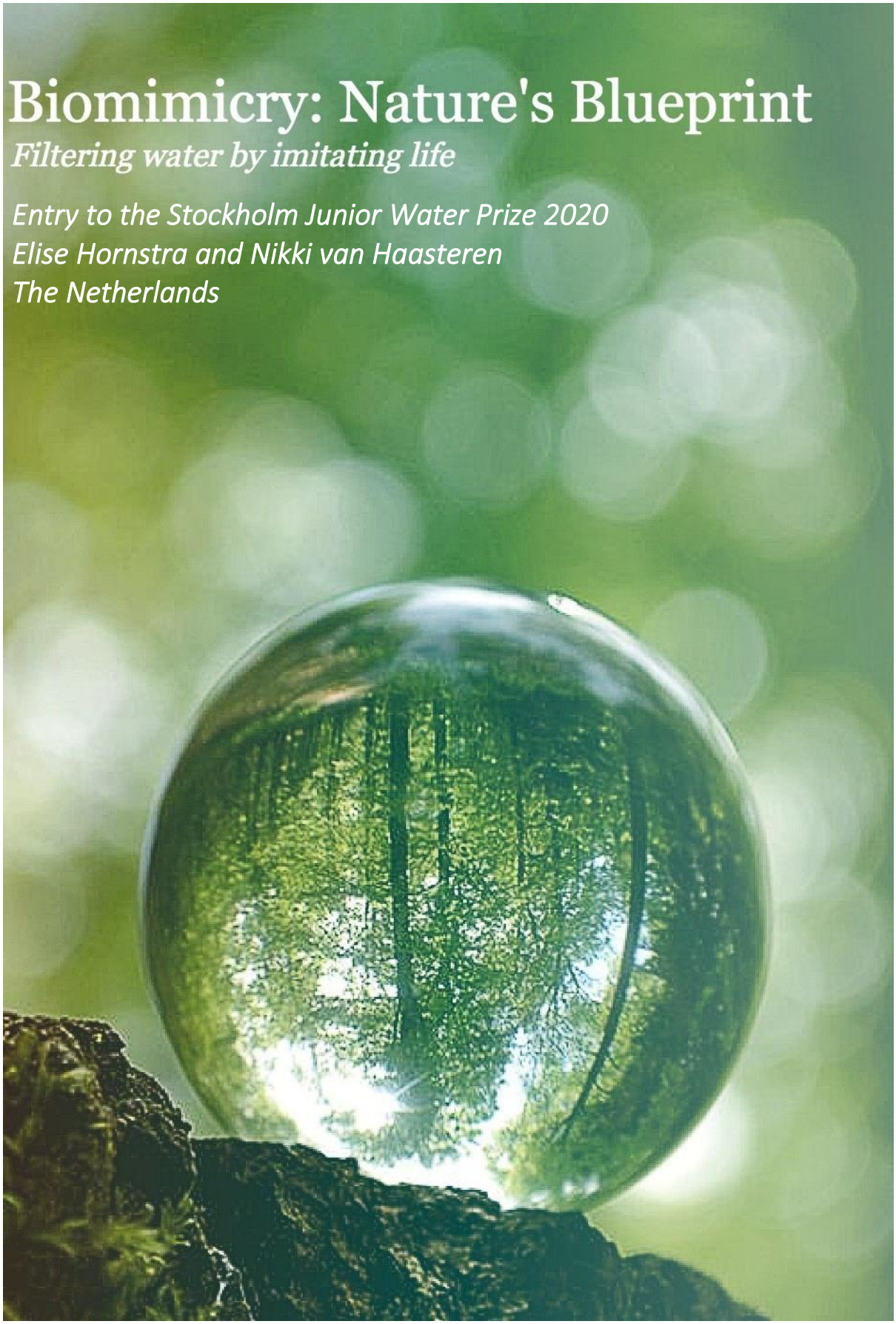

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*Summary*

Biomimicry is an art that uses patterns and processes that are found in nature to solve human problems. Biomimicry can be used to clean water. Our drinking water must be clean and safe to minimize the health risk of water consumption. This uncontaminated water is provided through filtration. During this research, the problem-driven approach is used. This approach starts with the essence of a problem and follows various research steps to find a solution. The steps that are followed for this paper: problem definition, reframing the problem, biological solution search, defining the biological solution, principle of extraction, and principle of application. The filtration processes that were put in practice were filtration through sedimentation, soil and plants. These processes showed the most potential from the biological processes that were researched. To create the setup of the experiment, 5 plastic 1L bottles where used. The 5 bottles where cut open and filled with a different material: soil and leaves, plants, Sedimentation, tap water, or ditch water. The bottles mimic the different natural filtration processes. The filtered water was then tested on various components.

Following the steps of the biomimicry problem-driven approach, the conclusion was that the design for a water filtration system that is broadly applicable and provides safe drinking water, that is at least 90% drinkable, to secure the health of society needs to be based on the filtration processes in the kidneys, soil and plants.

*Introduction*

This thesis paper is on the biomimicry design process of a water filtration system.
In this report, research has been conducted into how this design method can be applied to the problem of the effectiveness of water filtration systems and drinking water quality. The goal is to see which mechanism nature has that enable the filtration and purification of undrinkable water, to design a water filtration system that is broadly applicable and provides safe drinking water.

Plastic pollution is the inspiration behind this thesis paper. Undrinkable water is one of the reasons many plastic bottles are sold. By trying to find a solution for the undrinkable water, it is hoped that it will also contribute to the solution for the plastic problem.
The main question for the thesis is ‘How can water be efficiently filtered by applying biomimicry?’. The hypothesis is that one process will not be enough to filter the water sufficiently. Though a combination of multiple processes will filter the water efficiently and sufficiently. To formulate an answer to the main question an experiment is conducted, as well as literary research.

## *1. What is biomimicry?*

Biomimicry, also called biomimetics, uses the brilliance of nature.

Biomimicry originates from the Greek words βίος (bios), meaning life, and μίμησις (mimesis), meaning imitate.[1] Biomimicry is a method that mimics and learns from the models, systems, processes, and strategies found in nature to solve human problems and design challenges.[2]

Biomimicry views and values nature in a certain way. People need to look at nature as a model, as a measure, and as a mentor (figure 1.1). A society that imitates from nature learns how to optimize rather than to maximize.[3] Biomimicry uses a certain standard to deduce the sustainability of human innovations. These standards are based on the Nine Laws of Nature.[4]

1. Nature runs on sunlight
2. Nature uses only the energy it needs
3. Nature fits form to function
4. Nature recycles everything
5. Nature rewards cooperation
6. Nature banks on diversity
7. Nature demands local expertise
8. Nature curbs excesses from within
9. Nature taps the power of limit

Nature provides the mentor. Nature has been evolving for over 4,5 billion years and has gained enough experience in efficient and complex systems.

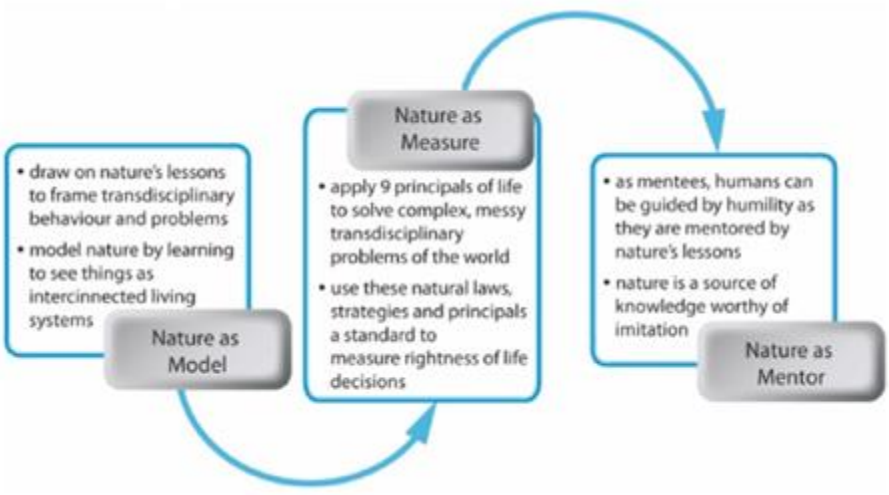



Figure 1.1, Nature provides people with a model, a measure and a mentor when trying to solve problems.

## *2. What are the requirements for drinking water?[5]*

Our drinking water must be clean and safe to minimalize the health risk of water consumption. When determining the drinking water quality water filtration companies and researchers look at the microorganism, chemicals and toxins and how appealing the water is to the consumers. The microbial and chemical constituents of water originate from nature and the industry present in a region. The guidelines of the WHO[5] provide a framework of the

basic and essential requirements to ensure the safety of drinking-water, comprising health-based targets established by a competent health authority, adequate and properly managed filtration systems. These guidelines on drinking water quality provided by the WHO are adopted and specified by the government of a country. Which and how the guidelines are implemented by a government is dependent upon the social, cultural, economic and environmental context and position of a country.

### *3. How is clean water provided using filtration?*

Most of the earth's water is not clean enough for human use, nearly 70 percent of the world is covered by water, but only 2.5 percent of it is fresh, this can be solved by filtering the water. Water filtration is the term that refers to all processes and systems that are used to remove pollutants from water. This removal is done by separating solids and fluids from a mixture using a filter. These filtered-out particles include parasites, unwanted chemicals, bacteria, biological contaminates and range of dissolved and particulate matter.[6] Water purification can only work to its full potential when temperature, pH, water pressure, the age of micro-organisms, properties of the liquid, and properties of the solid are all in its favour.

### *4. How can a problem be solved by applying biomimicry?[7]*

Bio-inspired design requires experts to go beyond their field of expertise and collaborate with experts from the biological and engineering domain. The researchers use functional modelling, graphs and abstraction or keywords to capture the essence of a biological mechanism in a way that can be understood by experts from different fields. During this research, the problem-driven approach (figure 4.1) will be used.

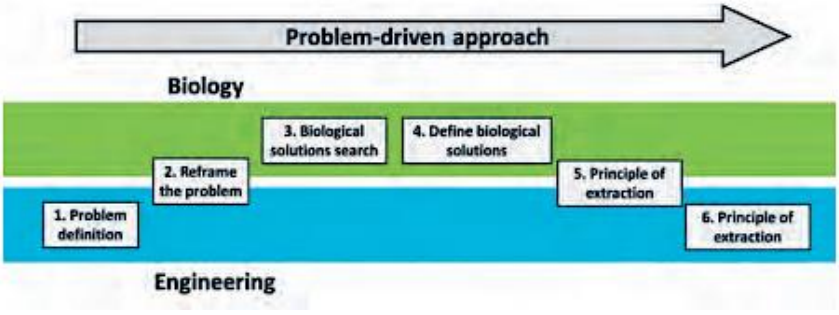



Figure 4.1: The problem- driven approach used biomimicry design

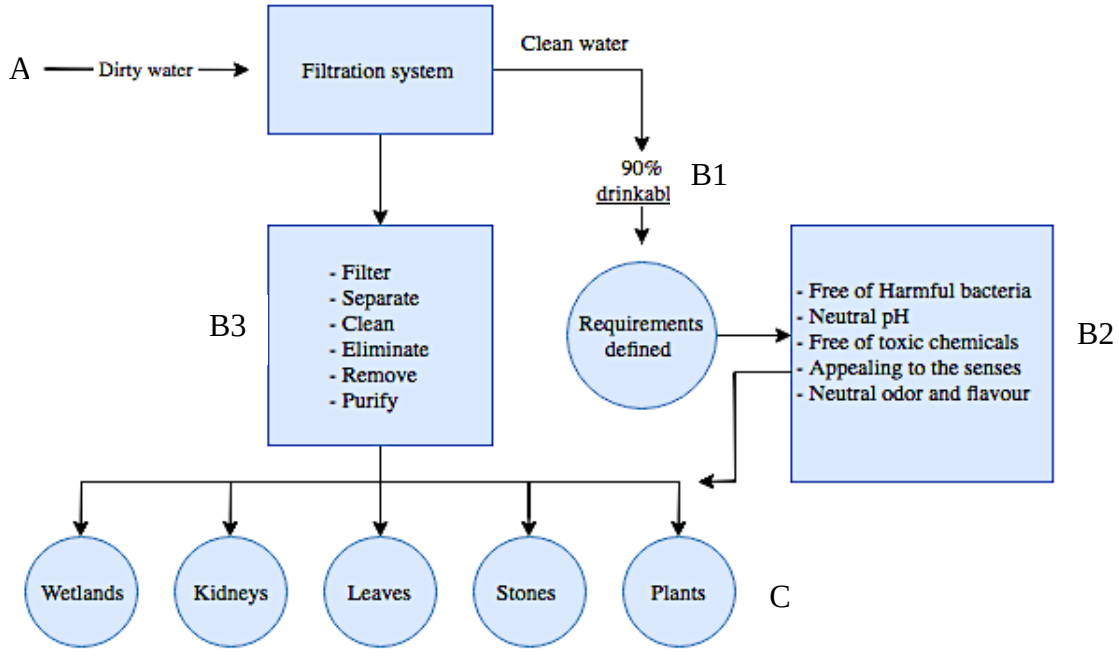
This approach starts with the essence of a problem and follows various research steps to find a solution. These steps include:

1. **Problem definition:** What needs to be solved?
2. **Reframing the problem.** The problem is translated into broadly applicable biologic terms, usually in to form of a question. 'How do biological solutions accomplish XYZ

function?'. Keywords are used to capture the essence of the problem. These keywords are usually verbs capable of capturing the main functions of the biological systems.

3. **Biological solution search.** Researchers look for biological systems that can be adopted to solve the problem. The use of commutating with various researchers from different and similar fields, databases such as Asknature.org and patterns from nature support the research process. They avoid subjectivity and provide lots of information about the systems.
4. **Defining the biological solution.** The systems that are selected during step 3 are thoroughly researched so that a deeper understanding of the system is created. This is called a functional decomposition.
5. **Principle of extraction. Principle of extraction.** Principles are extracted into a solution neutral form, which involves removing reference to structural and environmental entities of the biological domain. Neutralising the principles not only shows the basics of how the phenomenon works. The principle can now be used as inspiration for the design table, designs are based on the biological process.
6. **Principle of Application.** The biological principle is translated into the engineering domain. New affordances and constraints are introduced, after which the development of design starts.

## *5. Part 2 - Solving a problem using biomimicry*




*Scheme 1*

This scheme provides an overview of the design and research process of biomimicry.
It follows the six basic steps of the biomimicry design process.

### *6. Step 1 of the bio-inspired design – Problem Definition ( Scheme 1, A)*

A lot of countries, still do not have proper water filtration systems. Water from the tap cannot be consumed because it is not free of hazardous substances. This problem causes extra costs for water companies and consumers and increases plastics consumption. Bottled drinking water has to be bought. The problem is related to the social, cultural, economic, political and environmental conditions of a country. Countries such as Spain and Italy struggle with high temperatures and lots of sunlight that will speed up the development of microorganisms present in the water. Regions with intensive industry, such as mining and agriculture, struggle with the emission of pesticides and increased concentrations of nitrate and nitrogen into water bodies.

The problem of undrinkable water needs to be solved to reduce the consumption of plastics and pollution. However, the more pressing matter is that diseases and toxins spread very rapid amongst a population when the water is contaminated since water is used for everything. The problem needs to be solved to secure the health of a society.
This problem can be reframed as: which mechanisms does nature have that enable the filtration and purification of dirty water?

### *7. Step 2 of the Bio-inspired design – Reframing the Problem (Scheme 1, B)*

To design a water filtration system that is broadly applicable and provides safe drinking water, various natural filtration and purification mechanisms need to be researched and tested. It must be clear what is to be achieved from the solution. In this case, the solution must provide water that is at least 90% drinkable (scheme 1, B1). This means that a minimum amount of pollution can be detected in the drinking water after the filtration process. To check if the filtration system provides water that is 90% clean, requirements must be set (scheme 1, B2). Furthermore, it is determined which specific characteristics the solution needs to have to evaluate the potential that the natural filtration mechanisms have.

This way filtration systems with said characteristics can be found sooner in the databases (scheme 1, B3). Whether filtration systems have the required characteristics is determined through biological and chemical research. This research will be conducted in the next two steps of the design process.

## *8. Step 3 and Step 4 of the bio-inspired design – Biological solution search (Scheme 1, C) and Define the biological solution*

After a thorough search through the online database AsknNature.org, seven processes with quite some potential have been selected and looked into.

***Baleen whales***

The baleen whales, the Balaenoptera musculus, have special structures that allow an efficient consume of small organisms, especially tiny shrimp-like crustaceans called krill[8]. Baleen is similar to the bristles on a brush and is mostly made of keratin. The baleen replaces the teeth. When a baleen whale scoops up krill and water, it presses its tongue against its upper jaw to force the water through the baleen. This way the krill and fish are filtered from the water and ready for the consumption. Even though this filtration method can be very useful for filtering out large particles from water bodies, the method does not meet all the requirements. For instance chemicals cannot be filter out using this method.

***Basking shark[9]***

The Cetorhinus maximus or basking shark feeds by filtering water from zooplankton. It uses a mechanism which is similar to the mechanism of a sieve. If a fish opens its mouth the plankton-laden water will flow parallel to the filter. By opening its mouth and letting the water pass through gill slits on both sides of the head, filter-feeding fish collect the plankton for consumption. The fish's filters are composed of hard, rib-like structures called gill arches, which bear rows of smaller porous bottoms on either side of the fish's oral cavity. This process does not meet the requirements that the solution needs to match and it is difficult to remake a process like this. This method is not an option.

***Kidneys***

One of the best filtration systems, and water recycling technology, nature has provided are the kidneys. The human kidneys consist out two membranes, one with larger holes that filter out bacteria, the micro-organisms, and one with smaller holes that filters salt from the water.[10] The smaller holes have a specific filtration process. The kidneys have an assemblage of over a million lines, the nephrons (figure 8.1). The filtration system of the kidney.

The Glomerulus is where the blood that needs to be filtered enters. The blood gets filtered because of the small diameter, thus a high pressure, of the Glomerulus when it passes through the blood vessel. Fluids together with waste and small molecules can flow through the Bowman's Capsule, the blood vessel that holds the Glomerulus, but bigger molecules and red blood cells are left behind in the Glomerulus.[11] In the nephron, substances continue to filtrate.

In the nephrons, the water is filtered out through osmosis. When water descends into the ‘Loop of Henle’ it reaches the saltier part of the kidney, the hypotonic region, water flows out of the nephron back to the blood because it is hypotonic, un-salty. Now a lot of the ions, glucose, proteins and minerals are left in the nephron. The filtrate now travels through the ascending part of the ‘loop van Henle’ where more filtration takes place.[12] In these nephrons aquaporins are present. In the nephrons, aquaporins are responsible for the reabsorption of water.[13] In the end water, ions, proteins and small molecules have been separated from the blood and urine is produced. Waste and other excess substances are removed from the blood. All the molecules that are needed have been returned to the blood.

This process meets most of the requirement that is needed to solve the problem and it therefor a great option.

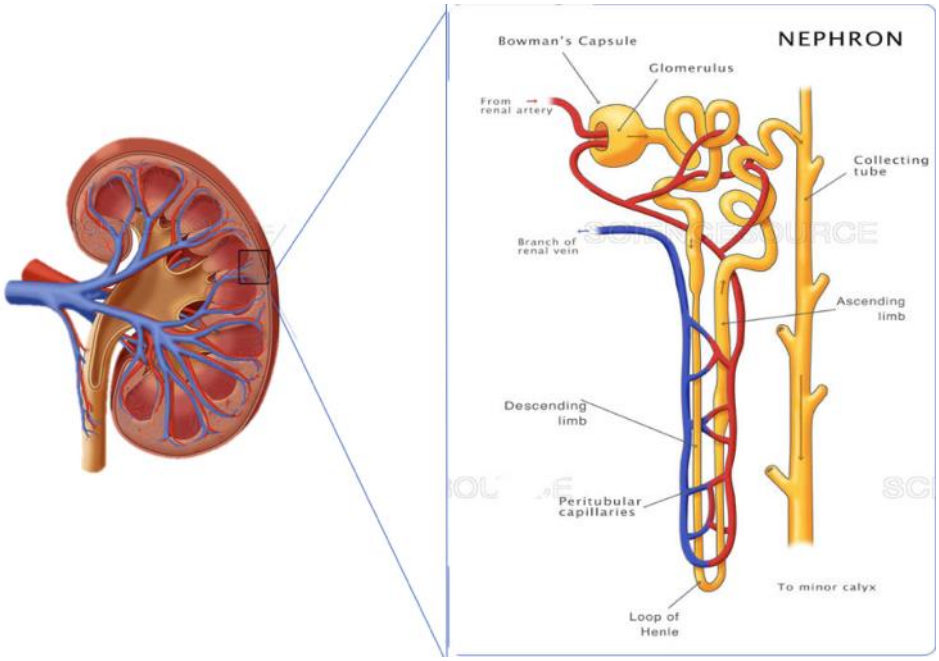



Figure 8.1, a nephron is an extremely small part of a kidney. The nephron is the part that filters the blood and produces urine.

***Plants***

Filtering contaminated water by using plant roots is process-wise relatively similar to filtering by use of kidneys. The wood barrels in the plant act akin with the blood vessels in the kidneys. Roots take up the water and the pollutants. The xylem, wood barrels, acts as a filtration system.[14] Xylem consists of nanoscale pores that are very helpful by the filtration of the water. Xylem can filter out viruses and bacteria because of their pit membranes. These pit membranes were small enough to not let any particles, bacteria or viruses, through them.[15] This process filters out 99,90% of the bacteria.

Another reason why the plant is a useful method of filtration is that roots take up the nutrients, the contaminations, and the micro-organisms. But these pollutants are stored in the leaf of the plants because it cannot fit through the leaf. When the water evaporates from the leaf, the contaminates will stay behind in the plant. Now water is filtered. However, other processes are needed to make filtration using this evaporation method possible, like a method that collects water vapour from the air. Because a second method is needed to get clean water plants are not the best option for a solution to the problem.

***Sand***

A well-known filtration method is the sedimentation process. Sedimentation is the process of deposition of solid material from a state of suspension or solution in a fluid. The most common form of sedimentation is the sedimentation in the rock cycle.

The sedimentation process starts with weathering and chemical and mechanical erosion which causes the rock to break down into smaller boulders. The smaller pieces can then be transported by air, ice or water. In this case, water is a means of transportation. During this transport, the rocks erode into smaller pieces, as the water from the stream flows along with the stones at high speed. The smaller the stones become, the faster the transport becomes. Sedimentation is a good natural means of filtration because the water travels past various barriers of different types and sizes of rocks as it flows from the source to the sea (figure 8.2). Some stones have the potential to purify the water as if travels along with the stones because of the minerals that are captured in the stone that slowly dissolve as the stone erodes. When the water is in the catchment area of the river, the stone particles as well as other particles, such as organic particles, sediment because of the slow current, which separates the water and provides water that is quite clean. This could be a great option to experiment with to see the extant of the filtration.

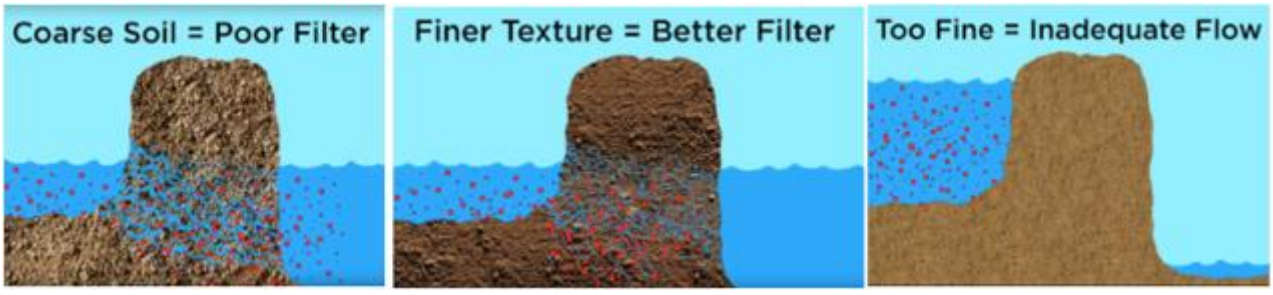



Figure 8.2: The size of the pores of the soil determine the filtration quality of the soil

***Leaves and soil***

Soil is the planet's biggest water filter and a great purifier. When water passes through the soil, it is cleaned via physical, chemical and biological processes, The soil contains important biota that helps transform and decompose certain chemicals and other contaminants from

soil, helping filter them out of the water. The leaves on top of the soil provide an extra barrier that starts the filtration of large particles from the water and is the source of the humus production. The purifying qualities differ per soil based on the components of the soil. The processes that remove or degrade the various constituents in water as it passes through the soil are the following.

The first filtration method of soil is through physical processes. These physical processes filter particles from the water with the help of the pores of the soil. The pores of the soil determine how effective the filtration is. A finer texture soil with many small pores holds back particles that are too large to pass through. However, soil that is too fine with too many small pores can block water from flowing through and prevent filtration. This characteristic is enhanced by the tortuous path that water takes through the soil, it provides numerous chances in pore sizes to capture constituents. This process can remove sediment and even bacteria.

Chemical processes also allow the soil to filter and purify water. The surfaces of soil particles are often chemically reactive. Contaminants can be absorbed and effectively removed. Clay soil has a negative charge that triggers the removal of positively charged ions in the water that passes through. Ions like calcium, magnesium and potassium are removed from the passing water and retained by the soil. Other chemicals are removed by covalent bonding, sharing electrons, that helps soil to retain many organic chemicals, pesticide and some inorganic constituents.

The biological process that helps soil filter water is influenced by the presence of bacteria and fungi that transform organic and inorganic substances and decompose certain chemicals in the soil. Then soil microorganisms can remove organic materials that have a high biological oxygen demand. Therefore, the nitrogen cycle is especially dependent on soil playing the role of a bioreactor soil. This method can be used for further investigation, but it could be a solution.

***Wetlands***

A wetland (figure 8.3) is a distinct ecosystem that is flooded by water, either permanently or seasonally, where oxygen-free processes prevail. Wetlands are located on the border between a rural area and water. They are, therefore, full of life with a large biodiversity. Therefore, the primary factor that distinguishes wetlands from other landforms or water bodies is the characteristic vegetation of aquatic plants, adapted to the unique hydric soil. This biodiversity, especially the wide range of plant species, along with the location enables wetlands to act as a natural filtration system. They remove sediments and nutrients from the soil and water in their surroundings.[16]


Figure 8.3: Wetlands

The numerous wetland plants consume the nutrients that are present in the water as they grow. Nutrients such as nitrogen and phosphorus are examples of nutrients that plants need to develop. Nutrients are also removed from the water by the physical processes like filtering and sedimentation because of the wetland structure. The wetlands consist of dense communities of wetland plants that slow down water flow, allowing sedimentation.

This filtration purifies the water as nutrients settle down. They can be consumed by the plants and bacteria in the wetlands, which provides temporary storage. The nutrients are not released until the plant decomposes. Furthermore, the rich vegetation in wetlands prevents erosion which leads to more sedimentation that prevents light from reaching aquatic plants and makes aquatic habitats unsuitable for aquatic animals.

Besides, microbes, such as bacteria, can adhere to the large surface area of the plants and roots. Most nitrogen is removed from the water in wetlands by the process of denitrification[17]. The nitrogen gas is then released into the atmosphere.

Nevertheless, there are limits to how much and what kinds of pollution wetlands can filter and purify. Nutrients, heavy metals and toxins are consumed by plants and enter the food web of the wetlands, causing the accumulation. However, the lack of nutrients in the water after the filtration makes sure that plants and algae grow at a slower rate.

Now, algal blooms that block out light and use up all the oxygen in an area of water cannot develop, protecting the aquatic life in the wetlands. It also prevents salts to move closer to the surface, which slows down the development of plants, Therefore, wetlands offer a great mechanism which can be used for biomimicry research and developments in terms of water filtration.

## *9. Step 5 of the Bio-inspired design – Principle of Extraction (Experiment)*

To create the setup of the experiment, 5 plastic 1L bottles where used. The 5 bottles where cut open and filled with a different material: soil and leaves, plants, Sedimentation, tap water, or ditch water, because these option showed the most potential after literary research. The bottles mimic the different natural filtration processes. A wooden shelf created a slope that helped the water flow through the systems. Buckets at the necks of the bottles caught the water (figure 9.1). The filtered water was then tested on various components, such as oxygen content, the presence of E. Coli bacteria, pH and phosphate content. Therefore, test tubes were filled with different types of filtrates. Then per tube, a tablet of chemicals that provided the necessary chemical reaction was added. Afterwards, the colours, which were created by the chemical reaction, of the substances, were compared to charts that show the corresponding value to the colour. These values were put into a table that provides an overview of the results (table 2).

Figure 9.1, the setup of the experiment

## *10. Step 6 of the bio-inspired design – Principle of Application (results)*

The tap water is used as a control test. The results that were conducted with this test were set as the standard, as the norm.

| | |
|---|---|
| E.coli → negative | Chlorine → < 0,8 °dH |
| Phosphate → 1 ppm | GH → > 8°dH |
| Nitrite → < 0,1 mg/L | KH → > 6°dH |
| Nitrate → 5 ppm | pH → 6,8-7,2 |

Table 1: This table shows the optimal values, values that are hoped the filtered water to have, these values were found on the bottle that held the tablets/ pills that were used to conduct this experiment.

| Tested elements | | | | | |
|---|---|---|---|---|---|
| | **Tap water, safe for consumption** | **Ditch water** | **Soil and leaves** | **Sedimentation** | **Plants** |
| **E. Coli** | Negative | Positive | Positive | Positive | Positive |
| **Phosphate** | 1 ppm | 4 ppm | 1 ppm | 1 ppm | 1 ppm |
| **Nitrite, $NO_2^-$** | 0 mg/L | 0 mg/L | 0 mg/L | 0 mg/L | 0 mg/L |
| **Nitrate, $NO_3^-$** | 10 ppm | 10 ppm | 0 ppm | 0 ppm | 0 ppm |
| **Chlorine** | 0 | 0,8 | 0 | 0,8 | 0 |
| **Common hardness** | >14°dH | >7°dH | >14°dH | >14°dH | >14°dH |
| **Carbonate hardness** | 10°dH | 6°dH | 10°dH | 15°dH | 10°dH |
| **pH** | 6,8 | 7,6 | 7,2 | 7,2 | 6,8 |

Table 2: This table shows all the values of the conducted experiments.

*Visual observations (figure 10.1):*

Tap water: Was very clear. No dirt particles or pollutants,

Ditch Water: Was clear, a little more yellowish than the tap water, dirt particles were present as well as organic material, like sticks, leaves and grass.

Sedimentation: Was turbid, unclear, but no dirt particles or organic material was found in the water.

Soil and leaves: Brownish, clear liquid. Lots of dirt particles, but little organic material.

Plants: Clear liquid, looks a bit brown. Little dirt particles were present in the water. No sign of organic material.

Figure 10.1, this figure shows the setup of the experiment as well as the visual examination of the water

## *11. Step 6 of the bio-inspired design – Principle of Application (conclusion)*

The main question for this thesis paper is 'How can water be efficiently filtered by applying biomimicry?' The answer to this question after literary research is that nature needs to be used as a foundation. To efficiently filter water using biomimicry one thing can be concluded, namely that particles need to be filtered out to make the water harmless for human consumption. The experiments and literary research have shown that the filtration mechanisms of kidneys, plants and soil should cooperate to finalize a product that filters water to its absolute potential.

Soil and plants provide physical, chemical and biological filtration mechanisms that filter and purify the water. Providing a strong cooperating with the filtration system of the kidneys. Soil and plants contain processes that filter the larger particles from the water. This provides the kidneys with water that only contains micro-particles that they can filter out. The chemical processes allow the removal of chemical constituents that the kidneys are unable to filter from the water. Also, the biological processes allow the removal of microbial hazards that are not microscopic. The kidneys consist of nephrons that separate water, ions, small molecules, and more from the blood. The nephrons are very effective in their waste and excessive substance filtration. Thus, combining these two filtration mechanisms will provide thorough water filtration and purification that provides safe drinking water.

By applying these natural processes the filtration won't be harmful to the environment and it will also be applicable everywhere because of these natural processes. People would also not have to buy bottled water anymore, because they can drink straight from the tap. The conclusions are not very different from the expected and predicted outcomes of the research. Since the filtration function of the kidneys has been discussed in biology class, It could, therefore, be predicted that the rigour of the systems makes that it provides the best filtration of water.

The conclusions that did not compare to the predictions were that soil provided cleaner water than expected. It was expected to provide darker coloured water with more chemicals in it. The experiments that have been conducted also provided conclusions that were not expected, they filtered and purified the water better than expected. It was expected to see more discolouration and measurements that would strongly differ from the standards. However, through this research, a lot of knowledge of nature's filtration and purification systems has been obtained.

A question that remains unanswered is how the filtration systems of the kidneys and plants and soil can be combined and converted into a design and product. To answer this

question, it is advised that further research is conducted. How they work and which factors are involved in the filtration processes needs to be known. How the systems coincide and differ needs to be known to find out how they can be connected to develop a combination of the filtration processes.

To know how this can be done new experiments have to be done that test a wider range of components in the water. Then, a prototype needs to be developed, tested and perfected. During this process, extra requirements concerning the realization of the design need to be added. Examples of these requirements are the size that the filtration system can and needs to be, what the budget for the realisation of the design is and how long the filtration process may take.

The measurements could be more accurate. The results are not as accurate as hoped, this is because unfortunately, there was not enough material to experiment twice. There is also no result you can compare the results with or from which you could take an average. The reliability of the experiment could increase by experimenting a few more times, than with different circumstances, such as different seasons, different temperatures and different times, for example, morning and evening.

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