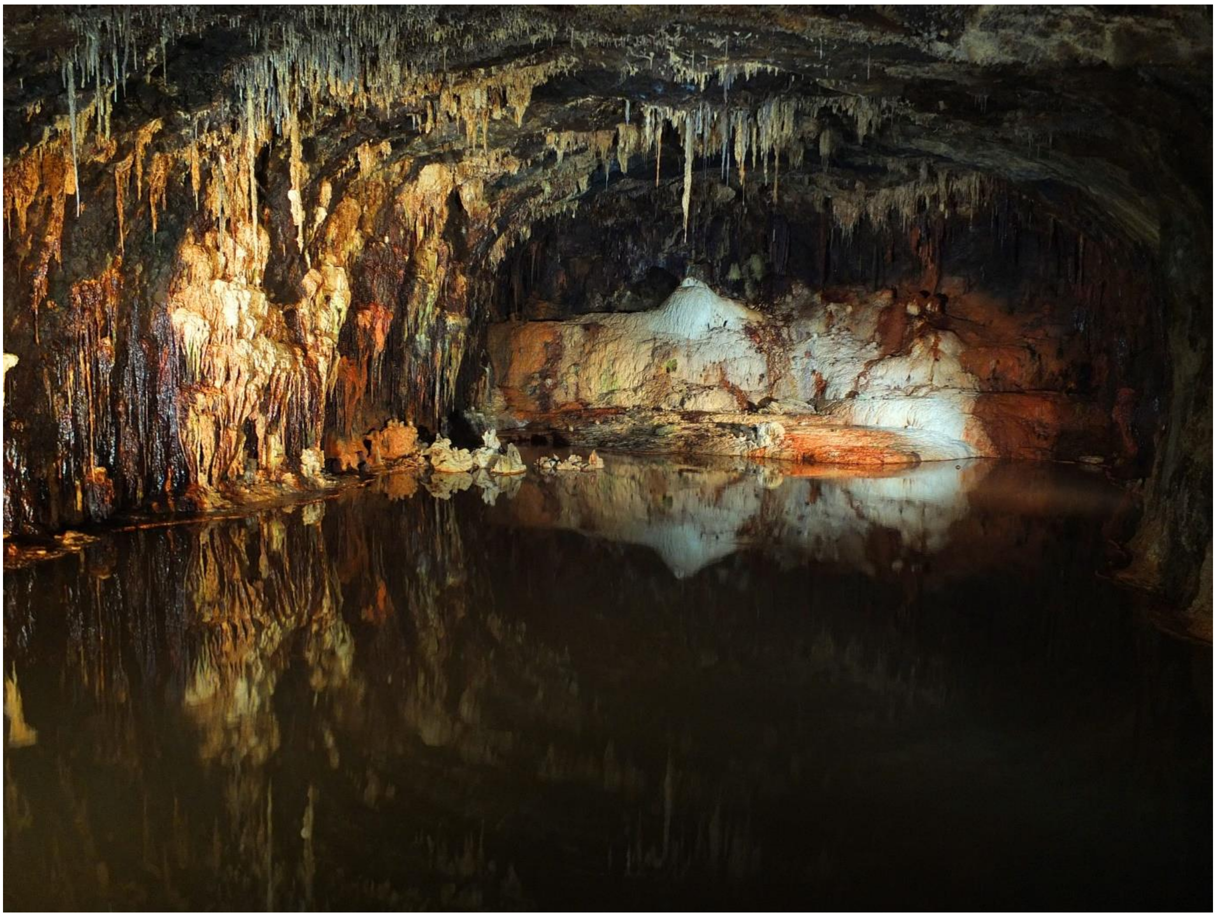
Aquifers

Mommy: Is there anything living in that stalactite cave we visited during the holidays?



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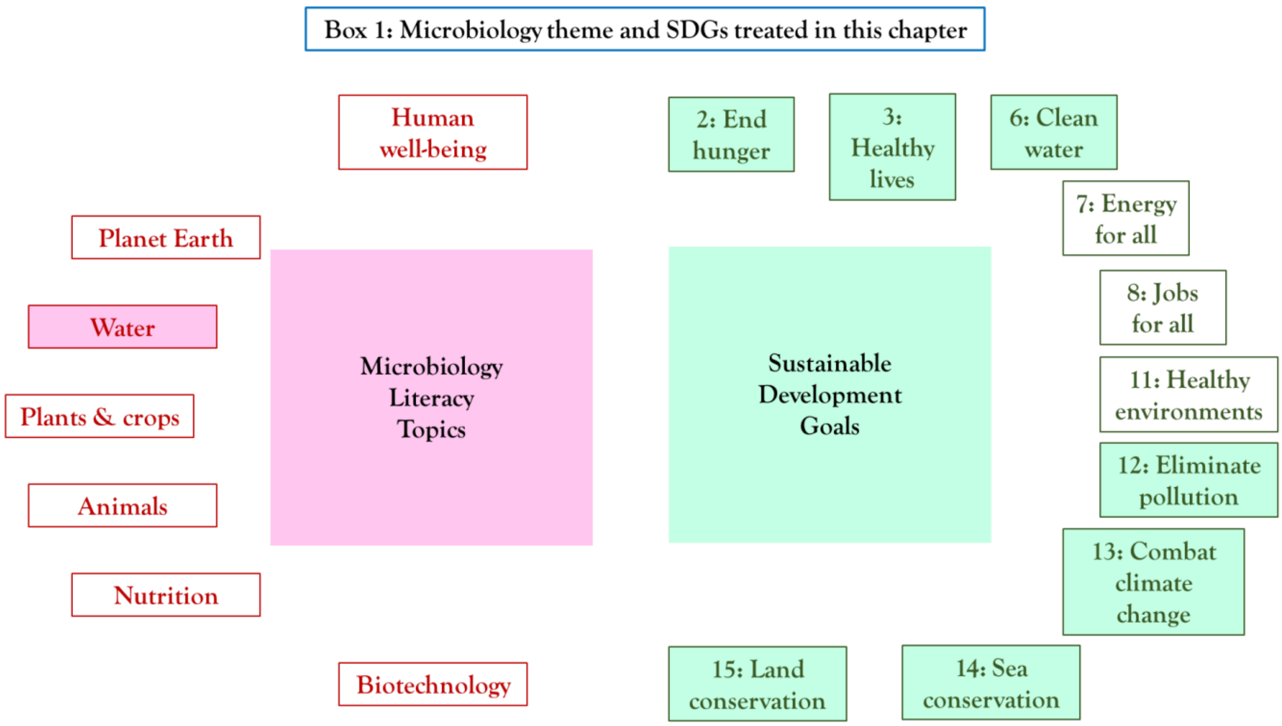
Storyline

Fresh, clean water is an essential resource for human life, as drinking water (see topic "Drinking water"), for general household use, agriculture and industry, and hence its availability strongly affects human well-being. While 70% of Earth's surface is covered by oceans, only 3% of the global water budget is fresh water. Of this small fraction, less than one hundredth is available as surface water, but almost one third is present in the underground, forming streams that flow through water-permeable layers of rock and sediment, so-called aquifers. More than 25% of the world's population depend on aquifers for water supply. Using water from aquifers has multiple advantages. It is possible over large areas, as aquifers span wide regions. Furthermore, biogeochemical processes in aquifers lead to purification of the water, so less treatment is required than for surface water. But aquifers are not unlimited sources of water, and are vulnerable to contamination. Human activity at the surface can have a drastic influence on the water quality underground, so aquifers need to be protected and managed in sustainable ways.

The Microbiology and Societal Context

The microbiology: microbial life in the subsurface; ecosystem services of aquifers; propagation of surface signals into aquifers; agricultural and industrial pollution; effect of climate change. *Sustainability issues*: health, food and water, environmental pollution, global warming, land conservation.



Aquifers: the Microbiology

1. ***Aquifers pose severe spatial restrictions to life.*** When looking at Earth's terrestrial surface, we get the impression that the ground below our feet is 'rock solid'. A visit in caves tells us that this is not necessarily true, and that vast, open spaces can exist underground. Often, streams of water can be seen flowing through such cave systems. Moreover, water dripping from the ceiling of the cave, potentially forming stalactites, tells us that even the solid rock above our heads must be partly permeable for water. Tight fractures and tiny pores in the rocks make the passage of water possible. Such water, originating from precipitation or water bodies at the surface, and now flowing through the underground, is called groundwater. While it is easy to imagine (and even to observe in the form of crustaceans and other small animals) that life has room in the large groundwater streams in a cave, the tiny fractures and pores only allow the passage of very small creatures, of microorganisms.

2. ***The geology and permeability of aquifers determines the flow of groundwater.*** Given that water flow depends on fractures, pores and caves in the rocks of an aquifer, it is obvious that the size of these spaces determines how fast water can enter and flow through the subsurface. Aquifers made up of loose, coarse sediments, only deposited during the last few hundred years, provide ample space for water flow, and thus can represent highly productive sources of groundwater. These aquifers are often connected to the surface, and hence called *unconfined*, allowing an easy infiltration of surface water. Sedimentary rocks, e.g., made from sandstone or limestone that can be hundreds of millions of years old, provide sufficient space for the groundwater flow through fractures, pores and caves, and hence can also be very productive. When they are topped by a rock layer with little (aquitard) or no (aquiclude) permeability for water, they are called *confined*. Confined aquifers can function like pressure pipes, leading water from an infiltration site to a different area where it can rise to the surface as an artesian spring. Older, crystalline rock often has only low permeability, and hence provides poor production of groundwater. Depending on the permeability, also the age of the groundwater can differ greatly. Surface-near groundwater in unconfined aquifers can have an age of days to years. Groundwater from deep, confined aquifers can be hundreds to millions of years old.

3. ***Microbial life in aquifers differs substantially from the surface.*** Imagine you are a microorganism in the subsurface. It is dark down there. You are alone, because pristine groundwater contains one hundred times fewer cells than, e.g., sea water. And you are starving, as there is very little to eat. At the surface, light is the driving power for life. The primary production of the organic compounds of cells from sunlight and carbon dioxide (CO_2), by photosynthetic organisms (plant and microbial phototrophs), forms the basis of many food webs. In the subsurface, photosynthesis is not possible. However, along with the water coming from the surface, a small part of the photosynthetically-produced organic carbon enters aquifers and feeds heterotrophic microorganisms. Such organic carbon can also be already present as deposits in the sedimentary rocks. When microbial activity slowly dissolves the rocks, this organic carbon is released and can act as an additional food source. Finally, some microbes can produce their own organic carbon by primary production. Instead of light, they use the chemical energy stored in certain minerals such as sulfides or ferrous iron to fix carbon, a process called chemolithoautotrophy. The organic carbon produced by them can also serve as food for other heterotrophic microbes.

4. ***Microbes must be particularly adapted to thrive in aquifers.*** Along with the water infiltrating from the surface, surface microorganisms also enter the groundwater. However, these

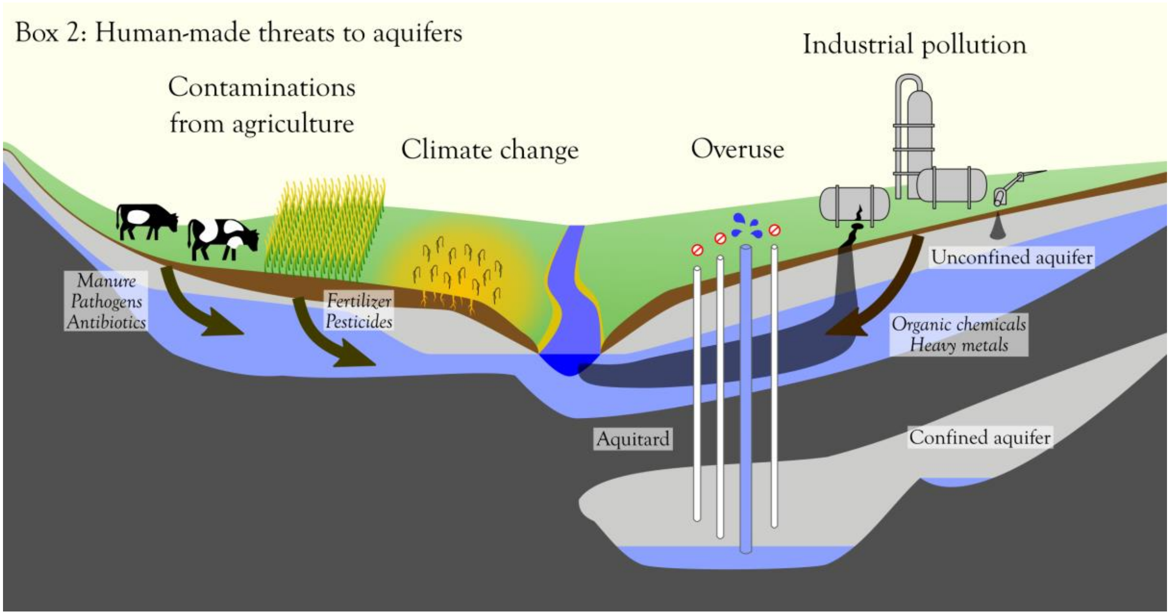
organisms are not adapted to the conditions there, and only a tiny fraction of them can survive and thrive. Most of them cannot deal with the low amounts and chemical diversity of nutrients. Under these conditions, versatility is key. To be successful, microbes must be able to use a wide range of different nutrients and metabolic strategies. Given the low concentrations of nutrients, the uptake mechanisms must be very efficient as well. Finally, also saving energy and nutrients is important. Microbes must be able to withstand periods where they don't find suitable nutrients, e.g., during times where no water comes from the surface. Many microbes in the groundwater have very small cells, far below 1 µm, as sustaining such small cells requires less energy and nutrients. Furthermore, smaller cells have a higher surface-to-volume ratio, which aids nutrient uptake. Many types of aquifer microorganism have also got rid of genes for metabolic functions they don't need, a process called genome streamlining, which further lowers maintenance energy costs. Some microbes have taken this to the extreme, and have lost essential functions, so that they now rely on partner organisms in order to carry out all necessary metabolic reactions. The tremendous saving of costs brought by this seems to compensate the challenge of finding the right partner in the groundwater.

5. ***The activity of microbes improves groundwater quality.*** While for the microorganisms in the groundwater, the input of organic and inorganic nutrients is essential to survive, for humanity, it represents an unwanted contamination. To obtain clean drinking water from groundwater, the removal of these contaminants is required. Luckily, microbes take over a large part of this work, as they take up the nutrients as food, and e.g. oxidize organic contaminants to CO_2. The release of this CO_2 makes the groundwater more acidic which, especially in limestone aquifers, leads to rock dissolution and improves the mineral composition of the water. Furthermore, pathogenic microbes coming from the surface are removed during the passage of the water through the tiny pores and fractures in the aquifer rock. Those that make it through are not adapted to the conditions in the subsurface and hence cannot survive, because they are outcompeted by the beneficial groundwater microorganisms.

6. ***Human-made surface signals will propagate into the aquifer.*** As described above, the subsurface is not disconnected from the land above. Water from the surface acts as the transport agent for dissolved compounds and gases, inorganic particles and microbial cells. These surface signals influence the conditions in the subsurface. Consequently, any human-made changes to surface environments will affect the function of life in the aquifer as well. Such changes might be local, like land-use for agricultural purposes or pollution from industry, or global, like climate change.

7. ***Agricultural land-use poses multiple challenges for microbially-mediated groundwater purification.*** Crop plant cultivation and animal husbandry strongly affect the input into the subsurface. Fertilizer and manure application lead to increased deposition of nitrates and phosphorus in soils. Herbicides and pesticides used in crop production are typically persistent over long periods of time in the environment. Livestock is a source of pathogens, and especially intensive animal husbandry often requires the use of antibiotics to prevent the spreading of diseases, posing a further environmental burden. All of these contaminations are transported into the subsurface as well (see topic "Agrochemicals"). As the microbial capacity for contaminant removal is not unlimited, an excess of such inputs will cause deterioration of groundwater quality. Moreover, the resulting changes in the subsurface conditions will affect the overall functioning of the groundwater ecosystem in potentially long-lasting ways.

8. ***Industrial pollution renders groundwater unsuitable for drinking water production.*** Besides agriculture, heavy industry and mining also pose threats to aquifer ecosystems. Accidental spillage from storage tanks or during production, as well as leaking pipelines, can introduce a chemically diverse range of organic contaminants into the environment. Especially surface-near unconfined aquifers, often featuring high groundwater production rates, are especially susceptible to pollution through such accidents, as contaminants can easily seep into them. Furthermore, heavy metal contaminations frequently occur through ore and coal mining, and the deposition of mining wastes on the surface. Many heavy metals (see topic "Heavy metals") and organic chemicals (see topic "Industrial pollutants") are toxic for humans, preventing the use of contaminated groundwater as drinking water. Contaminant plumes in the groundwater often lead to a drastic change in the microbial community. Specialized microbes able to degrade the pollutants may grow rapidly, but their activities deplete other nutrients. The 'natural' processes in the groundwater ecosystem are often suspended due to these limitations, and might only continue when the contaminants are removed. While microorganisms have shown to be able to degrade and detoxify most chemical compounds produced by humanity, these natural bioremediation processes can take a long time, rendering the aquifers unusable for decades or centuries.

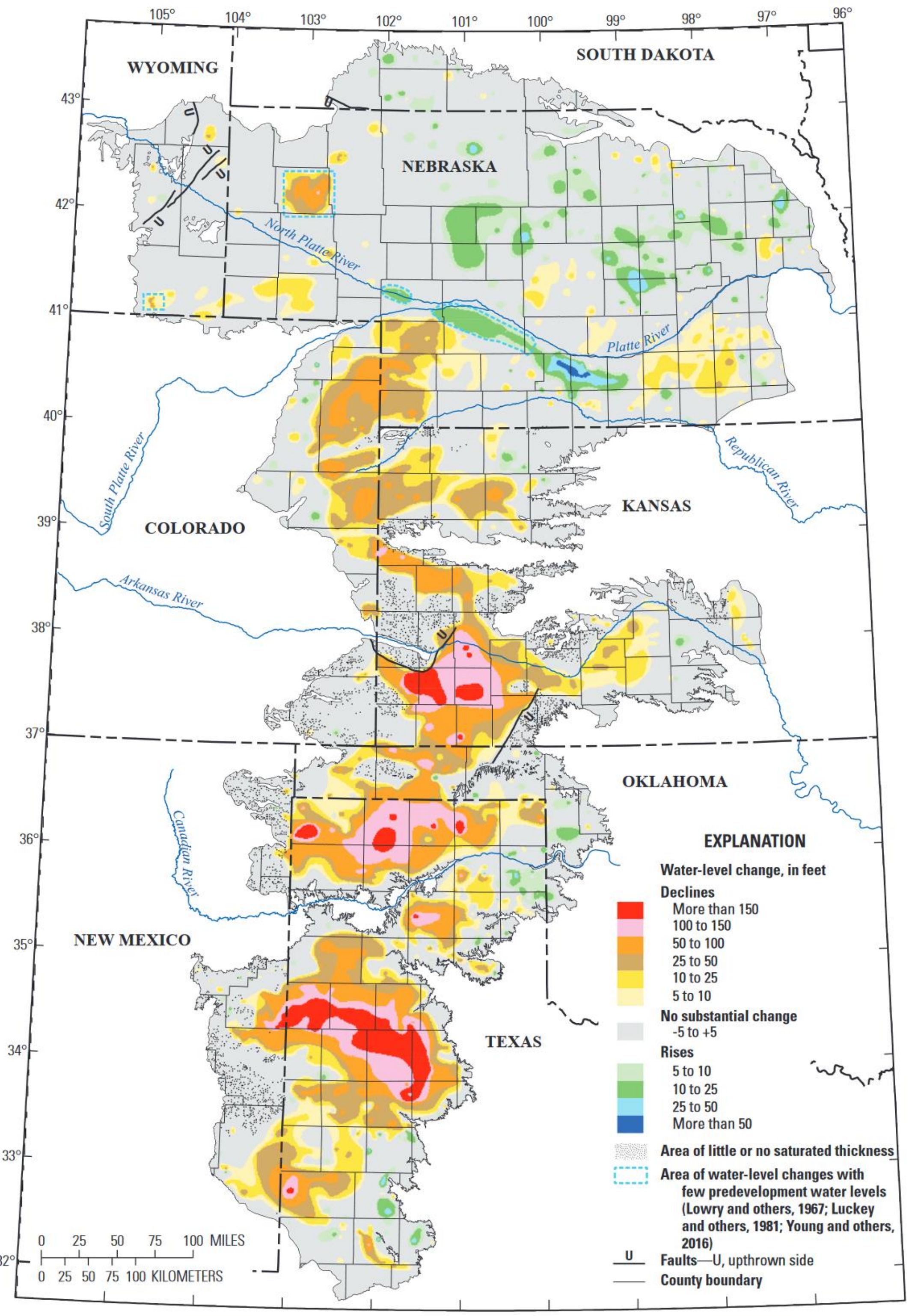


9. ***Natural contaminations are amplified by human activity.*** Groundwater resources can also be contaminated from natural sources. Arsenic, for example, is the 20th most common element in the Earth's crust, and can be released into groundwater when the rock material dissolves. As arsenic can cause cancer and other diseases, drinking water is required to contain less than 10 µg/L of it. Microbes mediate the release of arsenic from rocks into the water, but human activities such as mining can drastically accelerate this process. Microbes, on the other hand, might also be used to remove arsenic from water during drinking water production, but currently this process is still mainly achieved using challenging chemical methods.

10. ***Groundwater recharge and use need to be balanced.*** Not just the quality, but also the quantity of groundwater can be threatened by human activity. Aquifers are not unlimited groundwater reservoirs, and are characterized by the rate of inflow (recharge) and outflow – loss to other water bodies and extraction by humans. Excessive withdrawal of groundwater, for drinking water production, agricultural or industrial use, can lead to lowering groundwater tables.

This can result in wells and springs drying up, hence cutting off peoples' access to clean water. Furthermore, sinking levels of groundwater near the surface can also restrict the access of plants and animals, subsequently threatening the whole ecosystem. Water-level changes can differ substantially even between different regions of the same aquifer. Groundwater resources therefore need to be managed and used sustainably at the local as well as global level.

Box 3: Water-level changes of the High Plains Aquifer, USA, from 1950 to 2015. U.S. Geological Survey/map by Virginia McGuire; Source: Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2015 and 2013–15



11. ***Climate change will affect aquifer ecosystems in unprecedented ways.*** Human-caused global warming and associated extreme weather events lead to changes in precipitation and soil drying patterns, directly altering the water regimes of the affected regions. These changes are progressing so rapidly that many ecosystems cannot withstand them, leading to their destruction e.g. by desertification processes. Hence, global warming will strongly affect both the transport of signals from the surface into the subsurface, as well as the recharge of groundwater. Furthermore, raising atmospheric temperatures themselves will lead to an increase of the temperature in the subsurface. As these ecosystems are not usually exposed to high seasonal variations in temperature, this is likely to affect their functioning in unpredictable ways.

Relevance for Sustainable Development Goals and Grand Challenges

The microbial role in aquifers relates to several SDGs, including:

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.** Clean water is essential not just for drinking, but also for the production of food. But while agriculture requires water as a resource, it also threatens aquifers through contamination and overuse, interfering with the ecosystem services in water purification they provide. In sustainable agriculture, groundwater use needs to be balanced with recharge, and contamination has to be limited. Especially meat production requires a large amount of water and leads to higher contamination, and thus should be reduced in favor of crop production.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** Contaminations in groundwater such as antibiotics and pathogens from animal husbandry, or heavy metal and organic contaminants from industry, can negatively affect human health. The groundwater purification mediated by microbes can reduce such contaminants, but the capacity of this process is limited. On the other hand, microbial activity in groundwater leads to rock dissolution and hence the enrichment of minerals in the groundwater, leading to the formation of mineral waters with potential health benefits.
- **Goal 6. Ensure availability and sustainable management of water and sanitation for all.** The balance of groundwater use and recharge, as well as contamination and microorganism-mediated purification is essential for a sustainable management of groundwater resources. Reduced groundwater quality requires additional purification steps, leading to increased costs. Testing groundwater quality can already be challenging in developing countries or rural areas.
- **Goal 12. Ensure sustainable consumption and production patterns.** The various threats posed to aquifers, from agriculture, industry, overuse and global warming, need to be counteracted by regulations for water use and by protection of groundwater recharge areas. Remediation of damages and pollutions in aquifers are highly time- and cost-intensive.
- **Goal 13. Take urgent action to combat climate change and its impacts.** The aquifer is a delicate ecosystem, and we know little about how it actually works. Raising temperatures, changing precipitation patterns and loss of biodiversity are all signals that are not restricted to Earth's surface, but will propagate into the subsurface and change its functioning in ways we cannot predict. Considering that these systems adapted and evolved over a long time, such rapid changes might have devastating, irreversible effects on the ecosystem services aquifers provide!
- **Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development.** Input of contaminants into aquifers that exceeds the purification capacity of the groundwater microbiome will end up in rivers and streams, ultimately leading to the transport of the contaminants to marine systems.

- **Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.** Reduction of forest ecosystems and increase of agriculture, as well as land degradation and biodiversity loss, will alter the surface signals reaching the subsurface, and thus will also affect the functioning of aquifer ecosystems.

Potential Implications for Decisions

1. ***Individual***

a. Reduction of personal greenhouse gas emissions and ecological footprint can help to restrict global warming and limit its effect on aquifers and other ecosystems.

b. Stop or reduce meat consumption will reduce both water use and aquifer contamination.

c. Reduce household water use can protect groundwater resources (depending whether water shortage is a problem in your region)..

2. ***Community policies***

a. Establishment of protected groundwater recharge areas will prevent contamination.

b. Encourage sustainable agriculture by providing benefits for organic farming can help to reduce water use and contamination from food production.

3. ***National policies regarding aquifer protection***

a. Banning pesticides and other compounds that are harmful to groundwater organisms, are recalcitrant to biodegradation or accumulate in the environment will reduce the environmental burden for subsurface ecosystems.

b. Provide and/or support unified systems for assessment of aquifer health, such as the Water Framework Directive of the European Union.

c. Weighing up different purposes of groundwater utilization and land use.

Pupil Participation

1. ***Class discussion of the threats and protective measures for aquifers***

2. ***Pupil stakeholder awareness***

a. Is there an aquifer below our feet? Do we do anything that could pollute it (pets)

b. Where does your drinking water come from? Is it sourced from aquifers?

c. How much water do you use each day? How much water do you think is used in the production of food, clothing, furniture etc.?

d. Can you think of anything you might personally do to protect groundwater resources?

e. What kind of regulations are in place in your community to protect groundwater resources?

3. ***Exercises***

a. Bring a bottle of tap water to school; the teacher will also bring a bottle and, in addition, several different examples of bottled water from different sources, including glaciers. Taste all of them and comment on the intensity and type of flavor. (Flavor comes from the aquifer chemistry (e.g. dissolved salts), the purification process, additions made to make the water safe to drink). Which water tastes the best?

b. Find out the geographic location and dimensions of aquifers, as well as protected areas, agricultural and industrial sites in your area, to create a map showing these locations.

c. Construct a model aquifer to illustrate groundwater flow and the distribution of pollutants.

The Evidence Base, Further Reading and Teaching Aids

https://www.e-education.psu.edu/earth103/node/701; Bralower, T. and Bice, D. “Distribution of Water on the Earth’s Surface”. Retrieved 2020-09-24.

Gleeson, T., Wada, Y., Bierkens, M. F. P., van Beek, L. P. H. (2012) “Water balance of global aquifers revealed by groundwater footprint”. Nature. 488 (7410): 197–200. doi:10.1038/nature11295

Flemming, H. C. and Wuertz, S. (2019). Bacteria and archaea on Earth and their abundance in biofilms. *Nature Reviews Microbiology*, 17(4), 247-260.

Griebler, C. and Lueders, T. (2009). Microbial biodiversity in groundwater ecosystems. *Freshwater Biology*, 54(4), 649-677.

Akob, D. M. and Küsel, K. (2011). Where microorganisms meet rocks in the Earth's Critical Zone. *Biogeosciences*, 8(12), 3531.

Stevens, T. (1997). Lithoautotrophy in the subsurface. *FEMS Microbiology Reviews*, 20(3-4), 327-337.

https://www.epa.gov/ground-water-and-drinking-water/drinking-water-activities-students-and-teachers

Glossary

Antibiotics – Compounds that inhibit microbial growth or kill microbes.

Bioremediation – Utilization of organisms like bacteria and archaea, fungi and plants for the biologic detoxification of ecosystems.

Chemolithoautotrophy – Lifestyle that employs CO_2 as carbon source and obtains energy from the oxidation of inorganic compounds.

Ecosystem services – Benefits that humanity receives from ecosystems.

Ecological footprint – The natural ecological capital required to sustain the personal lifestyle of a human.

Fertilizer – Compounds to supplement the nutrient supply for cultivated plants.

Greenhouse gas – Trace gasses in Earth’s atmosphere that contribute to the greenhouse effect.

Groundwater reservoirs – The entirety of the available groundwater in the context of the water cycle.

Herbicides – Compounds designed to kill unwanted plants in the application area.

Heterotrophy – Lifestyle that employs organic carbon compounds as carbon source.

Microbiome – Entirety of the microorganisms living in a specific habitat.

Nitrates – Minerals containing nitrogen in its most oxidized form.

Pathogen – Organism with the ability to cause disease.

Pesticides – Compounds employed to kill or disperse undesirable or harmful organisms, or prevent their reproduction or growth.

Phototrophy – Lifestyle that obtains energy from light.

Pollution – Exposure of ecosystems to waste materials and emissions.

Remediation – Removal of contaminants or pollution from the environment, to restore its natural state.

Sustainable Development Goals – Seventeen interlinked goals set by the United Nation in 2015 for a better and more sustainable future for all human beings.