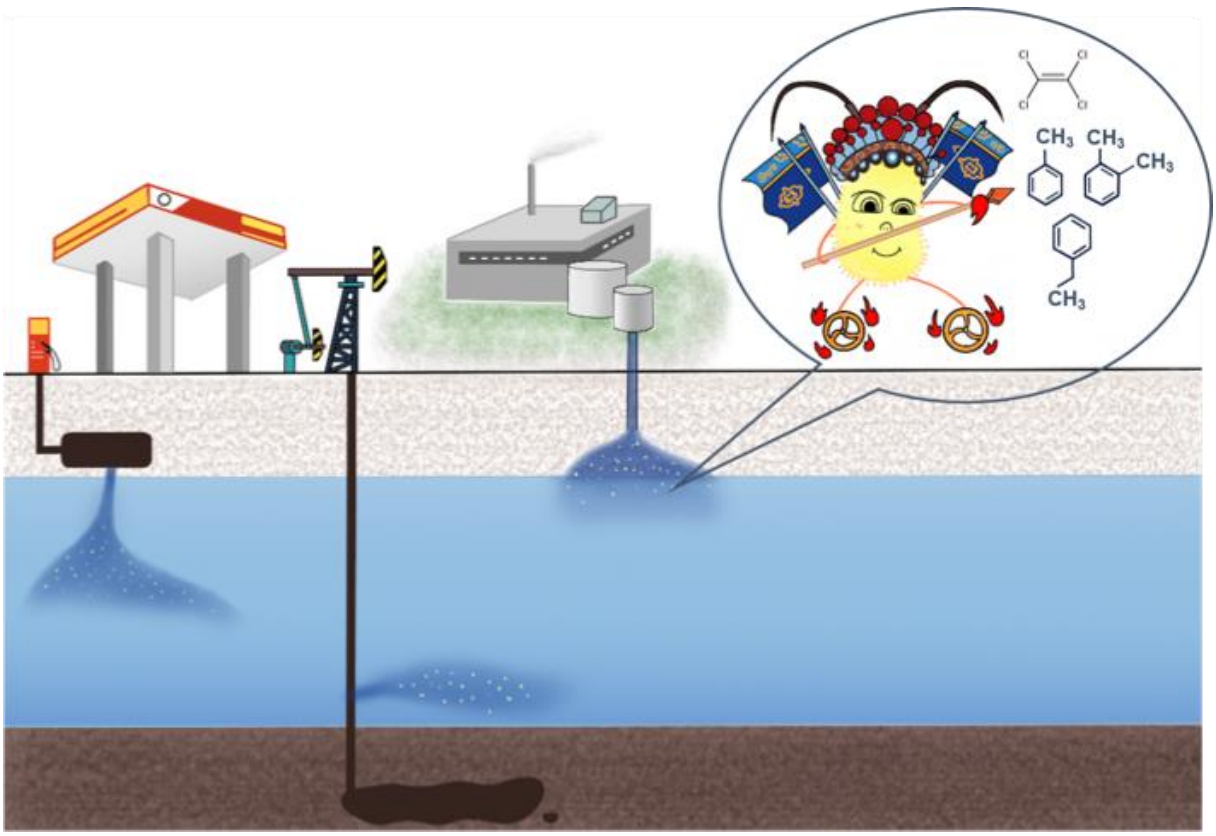
Groundwater:
the place where pollutants go to die

Daddy: what happens to all that water on the fields brought by the spring floods?



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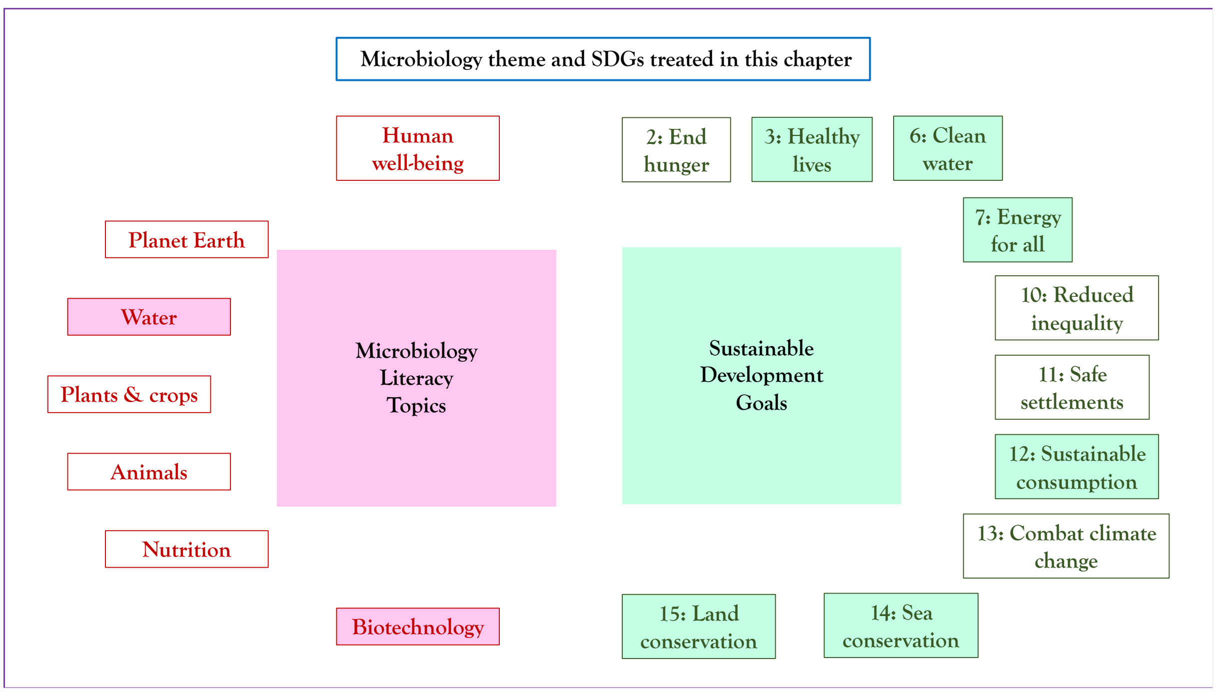
Groundwater: the place where pollutants go to die

Storyline

Groundwater, the water found underground, is a valuable fresh water source for human beings. However, natural processes or improper waste disposal have introduced a variety of pollutants from industry and agriculture into groundwater, including some carbon-based ones or organic contaminants. Fortunately, some microorganisms inhabiting groundwater can develop catalytic strategies to "breathe" these organic contaminants, which act as the food and energy source to support their growth and reproduction. These natural biodegradation activities are used by biotechnologists to develop technical processes known as bioremediation which have been shown to be feasible and economical approaches for groundwater contamination clean-up. To ensure success of bioremediation, it is critical to understand both the environmental conditions in groundwater and the degrading organisms involved.

The Microbiology and Societal Context



The microbiology: groundwater pollution; biodegradation; catalytic enzymes; bioremediation; bioaugmentation; bioaugmentation. *Sustainability issues:* human health; clean water; energy; sustainable consumption; conservation of groundwater resources.

Groundwater: the place where pollutants go to die: the Microbiology

1. What is groundwater? Groundwater accounts for more than 99 % of the fresh, unfrozen water on earth. Located below us, it has been used as public and private water supplies globally. It is also a gigantic reservior that receives hazardous chemicals released from human activities (e.g., industry and agriculture). Among the known groundwater contaminants, many are carbon-based and thus are called organic contaminants. For example, the energy production industry alone produces large amounts of waste during the processing of oil, coal and nuclear energy. In our daily life, millions of underground storage tanks globally distributed are mostly employed for gasoline storage under gas stations. Accidental releases of gasoline due to serious corrosion of these "hidden" tanks can cause relatively small scale but a large number of "plumes" known as point source contamination. In contrast, pesticides and fertilizers applied over large agriculture areas can be washed off and permeate into groundwater. This type of contamination is considered as a nonpoint source. Because surface and underground water systems are often connected, contaminated groundwater will potentially pollute surface waters such as streams and lakes. Thus, the clean-up of groundwater contamination is critical to protect this precious and invisible water source, as well as human health. Groundwater is more than a dark, isolated and sterile world. It is also the habitat for large numbers of microorganisms. Some of these organisms can act as the "warriors" and fight against the contaminants introduced into their territories.

2. ***The microorganisms living in groundwater can break down organic contaminants***. Biodegradation is the breakdown of organic contaminants mediated by microbial activity. Many groundwater organisms can "munch" these organic contaminants as food or substrates. In this case, microorganisms obtain carbon and energy to build their "muscles" and reproduce, creating daughter cells.

3. ***How do microorganisms degrade organic groundwater contaminants?*** Because of the complex molecular structure of contaminants, their complete degradation usually needs multiple reaction steps, each one catalyzed by a specific protein or enzyme. Although the pathways for degrading different organic contaminants vary, microorganisms typically first break down macromolecules into smaller subunits. Then, the subunits are transported into cells for further degradation. Complete removal of groundwater contaminants needs all the enzymes for the multiple steps of reactions in the degradation pathways. A lack of key enzymes is one common reason for long-term persistence of some contaminants, or their partially broken down products.

4. ***Biodegradation can be a teamwork***. Under aerobic conditions, organic contaminants can be completely degraded to carbon dioxide (CO_2), a process termed mineralization. However, one organism may not contain all the enzymes needed to completely degrade an organic groundwater contaminant, but a group of organisms with different enzymes can collaborate to supply the missing degradation steps. In this collaborative effort, one organism partially degrades the contaminant and then releases the part of the molecule that it cannot deal with. This is then taken up and metabolized by new microbes. They may also only degrade part of the molecule and another group is then needed to finish the job.

Microbes are opportunists: they continually seek new sources of food. If they have enzymes that can degrade part of a chemical that is being released by another microbe, they migrate to the chemical and form teams with the original microbe in order to extract maximum collective benefit. Such "relay race" interactions continue until no further degradation is possible or the contaminants have been completely broken down.

5. ***Why can groundwater microorganisms break down human-made contaminants they have never met?*** Most of the natural organic carbons that microorganisms can consume are photosynthetically fixed (e.g. plant material). However, the groundwater contaminants introduced by industry and agriculture (e.g. petroleum products, organic solvents, and pesticides) are usually synthetic, i.e. created by humans, and thus completely new to nature. The organisms living in groundwater have not met or used these synthetic substrates during their long history of evolution. Fortunately, however, some of the chemicals are similar in structure to natural organic compounds, so the biodegrading organisms' existing enzymes can recognize the unusual chemical structures and attack them. Secondly, some enzymes can evolve to degrade new substrates – they become re-purposed to take advantage of a new food source. And, thirdly, some organisms have rather unspecific enzymes that can coincidently degrade a particular contaminant in addition to the target substrate(s). In this situation, the organisms can also break down the contaminants but do not obtain energy in the process, which is called co-metabolism.

6. ***Some representative groundwater contaminants that can be biodegraded***. A variety of organic groundwater contaminants can be degraded by microorganisms. For example, a group of volatile organic substrates, collectively known as BTEX, comprising benzene, toluene, ethylbenzene and xylene are common in the gasoline-contaminated groundwater. Tetrachloroethylene (PCE) and trichloroethylene (TCE) that have been commonly used as dry cleaning and metal degreasing reagents are also among the most common groundwater contaminants in the USA. Microorganisms can partially or completely degrade these contaminants. While some of the contaminants are long-lasting and difficult to be completely removed, commercial success for bioremediation of other more biodegradable ones has been reported.

7. ***Challenges for groundwater bioremediation.***

a. *Growth-limiting prevailing environmental conditions.* To grow active biodegrading organisms in groundwater is not an easy thing. For example, some organisms need to breathe oxygen and contaminants at the same time, but others "hate" oxygen when they do a similar job. Thus, appropriate oxygen concentration is important for success of biodegradation. Meanwhile, the subsurface is typically poor in nutrients. Without enough carbon- and nitrogen-containing nutrients, the biodegrading organisms cannot be healthy and get enough reducing force to break down the contaminants. In addition, many organic contaminants are water-hating or hydrophobic, so they do not dissolve in water well enough to be supplied as food for microorganisms.

b. *Creating the right environment.* In order to remove organic groundwater contaminants via biodegradation, engineers can modify the underground environments, e.g. by adding/removing oxygen, supplying nutrients, or injecting reagents to help the hydrophobic contaminants to dissolve, in order to enhance activity of the native microorganisms. This kind of intervention is called biostimulation.

c. If appropriate biodegrading microorganisms are not present, or if the toxicity of the contaminants inhibits microbial populations or their activities, specific microorganisms with the needed activities and/or toxicity-tolerances can be introduced to achieve the desired biodegradation. This intervention is known as bioaugmentation. The introduced organisms can be "superbugs" that exhibit active contaminant-degrading capacity and are developed through adaptations under laboratory conditions or through genetic engineering.

Relevance for Sustainable Development Goals and Grand Challenges

Groundwater, groundwater pollution and contaminant bioremediation are relevant to a number of sustainable development goals, including

- **Goal 3. Ensure healthy lives.** Groundwater is a major source of drinking water and polluted groundwater yielding polluted drinking water negatively impacts human health. Microbial degradation of pollutants in groundwater counteracts this and hence contributes to human health.
- **Goal 6. Achieve access to safe drinking water.** Groundwater is a major source of drinking water and polluted groundwater yielding polluted drinking water is not safe. Bioremediation of contaminated groundwater increases its quality as drinking water.
- Goal 7. **Achieve access to clean energy.** Fossil-fuels are neither clean nor sustainable, and contribute to greenhouse gas emissions and thus global warming. Transiting to clean, renewable energy sources will reduce pollution of groundwater reservoirs.
- **Goal 12. Significantly reduce the release of chemicals and waste to air, water and soil.** A number of industries release chemicals into the environment, some of which end up in groundwater. Groundwater microbes that degrade these chemicals, and bioremediation processes based upon them, significantly reduce the impact of such pollution.
- **Goals 14 and 15.** Reduce marine pollution/ensure sustainable use of terrestrial and inland freshwater ecosystems. Pollutants are typically discharged into soil and freshwater systems and, from these, may migrate to groundwater. Groundwater systems are often connected to surface waters, some of which drain into the oceans. Hence, pollutants migrate to and contaminate soils, surface and underground freshwaters, and marine systems. Contaminant-degrading microbes in groundwater thus play a role in mitigating contaminant spread among connected systems.

Potential Implications for Decisions

1. ***Individual***

a. You have some chemical waste, such as left-over paint or garden pesticide. What will you do with it: flush it down the toilet? pour it on the soil in a corner of the garden? take it to a recycling centre?

b. You have a gorgeous dog that you regularly take for a walk. When it poops, do you look the other way? pick up the poop in a poop bag and dispose of it in the prescribed manner?

2. ***Community policies***
    a. Education of the community about the importance of groundwater, its pollution and pollution prevention
    b. Provision of accessible recycling facilities for chemical wastes
    c. Monitoring chemical pollution of public spaces and local groundwater reservoirs
    d. Remediation of polluted local groundwater reservoirs

3. ***National policies***
    a. Auditing of national groundwater systems, creation of detailed pollution maps
    b. Development of groundwater protection policies and monitoring systems
    c. Assuring supplies of clean drinking water

Pupil Participation

1. ***Class discussion*** of the issues associated with the known groundwater contamination accidents/cases and the possible microbial treatment methods (Teachers can provide the examples for discussion).

The Evidence Base, Further Reading and Teaching Aids

Pepper, I.L., Gerba, C.P., and Gentry, T.J. (2015). Environmental Microbiology. Academic Press, London, U. K., 703p.
Francis H. Chapelle, (2020), Ground-Water Microbiology and Geochemistry, 2nd Edition, Wiley, NJ, U. S., 495 p.

Glossary

Bioaugmentation: The practice of adding cultured microorganisms into the subsurface for the purpose of biodegrading specific soil and groundwater contaminants.
Biodegradation: The degradation of the materials into environmentally acceptable products such as water, carbon dioxide, and biomass, by the action of naturally available microorganisms under normal environmental conditions.
Biostimulation: The modification of the environment to stimulate existing bacteria capable of bioremediation.
Co-metabolism: Simultaneous degradation of two compounds, in which the degradation of the second compound (the secondary substrate) depends on the presence of the first compound (the primary substrate).
Enzyme: The proteins that act as biological catalysts (biocatalysts) that accelerate chemical reactions.
Groundwater: The water found underground in the cracks and spaces in soil, sand and rock.
Hydrophobic: The physical property of a molecule that is seemingly repelled from a mass of water (known as a hydrophobe).

Nonpoint source contamination: Diffuse contamination (or pollution) of water or air that does not originate from a single discrete source.
Molecular structure: From a structural point of view, a molecule consists of an aggregation of atoms held together by valence forces.
Mineralization: The process by which chemicals present in organic matter are decomposed or oxidized into easily available forms to plants.
Organic contaminants: Chemicals that are carbon based, such as organic solvents, pesticides, petroleum-based wastage, timber, and gas or liquid phase volatile compounds.
Point source contamination: Contaminants that enter the environment from an easily identified and confined place.
Substrate: The chemical species being observed in a chemical reaction, which reacts with a reagent to generate a product.