

## The pollution crisis



Figure 1. The industrial shore of Arthur Kill, New Jersey-New York, USA.

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## The pollution crisis

**Pollution**, the introduction of harmful materials into the air, land and water, occurs as a result of our daily activities, knows no boundaries and is a global problem. Pollution includes trash and harmful materials that we can see (Figure 2) but also dissolved, hidden, **pollutant** chemicals. These pollutants are problems virtually anywhere throughout the world; from the Gobi Desert to the Midway Atoll, from the snow peak of Mount Everest to ice sheets in Antarctica. The ubiquity of pollutants, far from their sites of production and use, is due to efficient natural and human-created global connectivity processes. These pollutants may include new or **emerging pollutants** such as man-made plastic **nurdles** (pellets used in the production of plastic items) that have the ability to join together with **legacy persistent organic pollutants**, or pollutants that remain in the environment for prolonged periods of time, to form super-toxic particles. We also observe naturally occurring **heavy metals** that become concentrated from human activities and may seep into our drinking water supply, as well as **gases** and **chemicals** that affect our local and global **climate**. We find **microorganisms**, **life forms too small to be seen by the unaided human eye**, at the center of our pollution problem, sometimes serving as a source of this pollution but also possessing great potential to solve our pollution problems.



Figure 2: Costal harbor pollution, Phu Quoc, Vietnam.

1. **Watersheds.** We can see the impact of human activities in our neighborhoods and local waterways. Take note of the amount of garbage and debris you observe around your neighborhood. The **debris** present on land or in a small stream may be transported to larger rivers and eventually the ocean. This connection between our local lands and waterways can be explained through the concept of a **watershed** (Figure 3). We all live within our local watershed, an area of land that drains all the streams and rainfall to a common waterbody. When we experience a rain event or storm, the **stormwater** that falls on land travels to a **storm drain** and empties into the nearest body of water, taking pollutants from the land along with it. ([PBS Watershed Video](#)). We see this occurring with pollutant chemicals in watersheds throughout our world.

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Conceptual diagram illustrating the environmental impacts of agriculture, mining, and development pressures in the Upper Potomac Headwaters region.

Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Upper Potomac Headwaters Report Card 2015, IAN Press, December 2015.

ian.umces.edu

Figure 3: Conceptual diagram of a watershed.

Attribution: Jane Hawkey, Integration and Application Network Image Library.

2. *Where pollutants go to die.* Eventually these pollutants are transported to the oceans. We can see the devastating effects of land and water pollution when we take a look at our ocean gyres, areas where the world's ocean currents converge, that encircle areas of calm water with no currents. It is here that we find massive floating masses of rubbish often referred to as great garbage patches ([NOAA Great Pacific Garbage Patch Video](#)). Seas and bays, where land may restrict water passage, also serve as pollutant hotspots where improperly disposed trash collects.

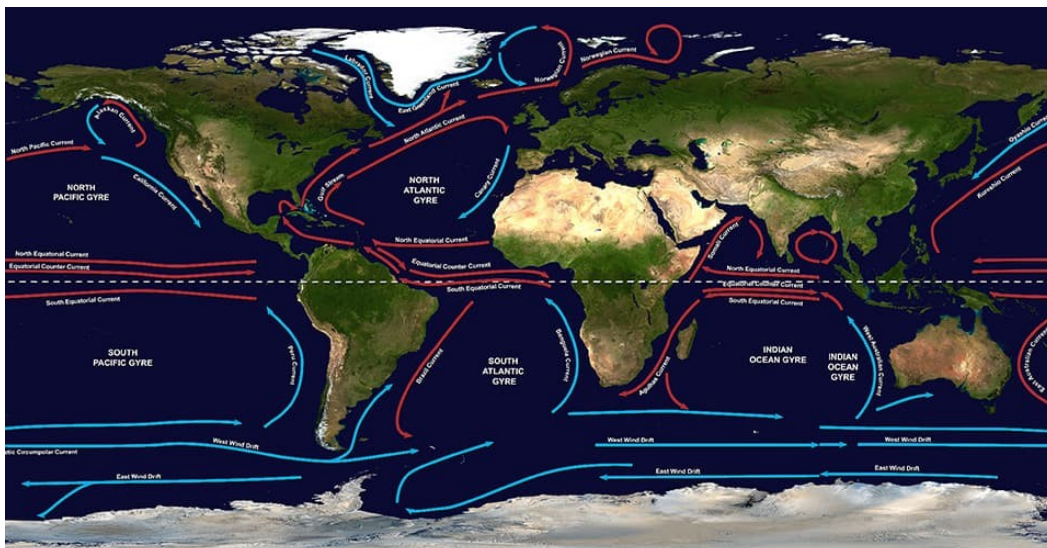


Figure 4: Map depicting the five major ocean gyres.

Attribution: National Oceanic and Atmospheric Administration

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Over time, **marine debris**, any persistent solid material, carried by ocean currents, makes its way into the centers of these gyres or bays where it becomes trapped (Figure 4). These floating garbage patches contain large debris as well as tiny particles, smaller than the size of a pencil eraser, and often too small to be seen by the naked eye. Accumulation of debris as well as **photodegradation** in the presence of sunlight and **biodegradation** by microorganisms of the trapped material contribute to the toxic soup-like nature of these areas ([Learning Junction Degradation of Waste Video](#)).

3. **Influence of pollutants on wildlife and us.** All pollutants, by definition, are harmful and, no matter the size, pose a threat to the wonderful creatures that inhabit our planet. The large debris that make up **macroscopic** pollutants such as fishing nets, bottles and cans, bags, diapers, and foam can harm sea birds, fishes, and other **aquatic** life. We all too often see animals such as albatross, leatherback sea turtles, or curvier beaked whales mistakenly ingest pollutants as food or find these animals tangled in the debris and stranded (Figure 5).

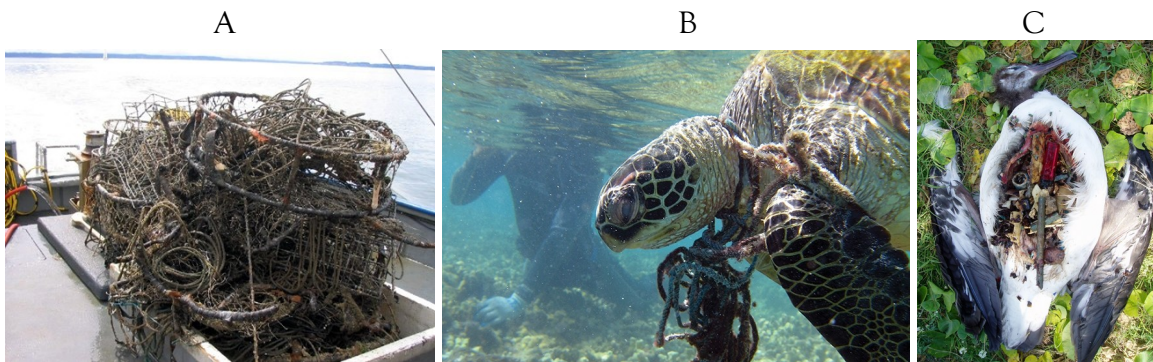
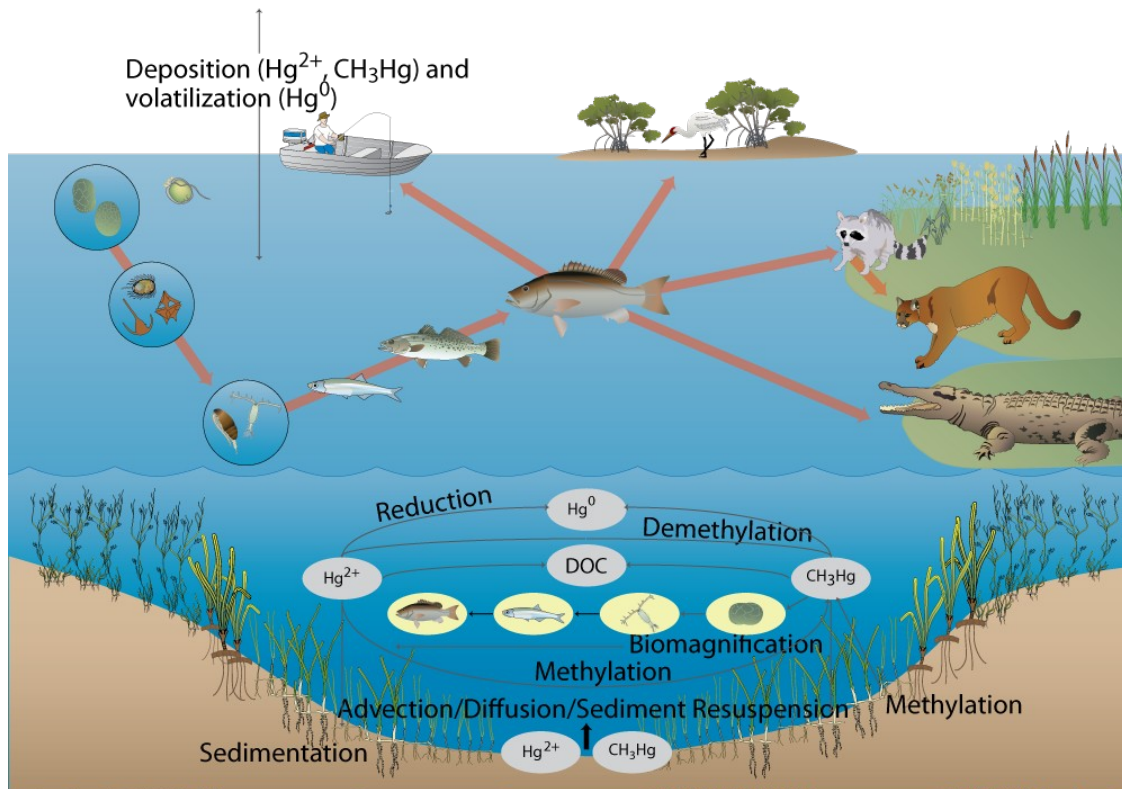


Figure 5: Heavy derelict crab pots (A), Entangled Hawksbill seaturtle in Hawaii, USA (B), Deceased albatross on Midway Atoll (C). Attribution: National Oceanic and Atmospheric Administration.

When the pollutant is too small to see, such as a dissolved chemical molecule, we may not even know our water is polluted. **Agrochemicals**, chemicals associated with agricultural practices, **heavy metals** which may accumulate during mining activities, are examples of **industrial pollutants** that are not always visible to the naked eye. Water that contains these “hidden” pollutants can still harm aquatic life and make us very sick. Heavy metals such as **mercury**, and long-lasting organic pollutants including, **polycyclic aromatic hydrocarbons** (PAH’s), **polychlorinated biphenyls** (PCB’s), and **dioxins** are often found in high levels in the fatty tissues of top or **apex predators** such as tuna and swordfish (covered in more detail under *Heavy metals* by Geoff Gadd). Harmful **toxins** accumulate over time in aquatic animals in a process known as **bioaccumulation**. Zooplankton, tiny animals that help form the base of aquatic food webs, may ingest these small pollutants and chemicals as they sort through tiny particles in search of **diatoms** and other **phytoplankton** that serve as their food source ([Zooplankton Ingesting Plastic Video](#)). Biomagnification, the increased concentration of a toxic chemical in higher trophic animals, as zooplankton are consumed by larger predators (Figure 6). **Microplastics**, smaller than 5 mm in size, and other **persistent synthetic polymers** make their way up the food chain as they are incorporated into the tissues of predators.

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Conceptual diagram illustrating mercury biomagnification within the aquatic food chain. Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Kruczynski, W.L., and P.J. Fletcher (eds.). 2012. *Tropical Connections: South Florida's marine environment*. IAN Press, University of Maryland Center for Environmental Science, Cambridge, Maryland. 492 pp.

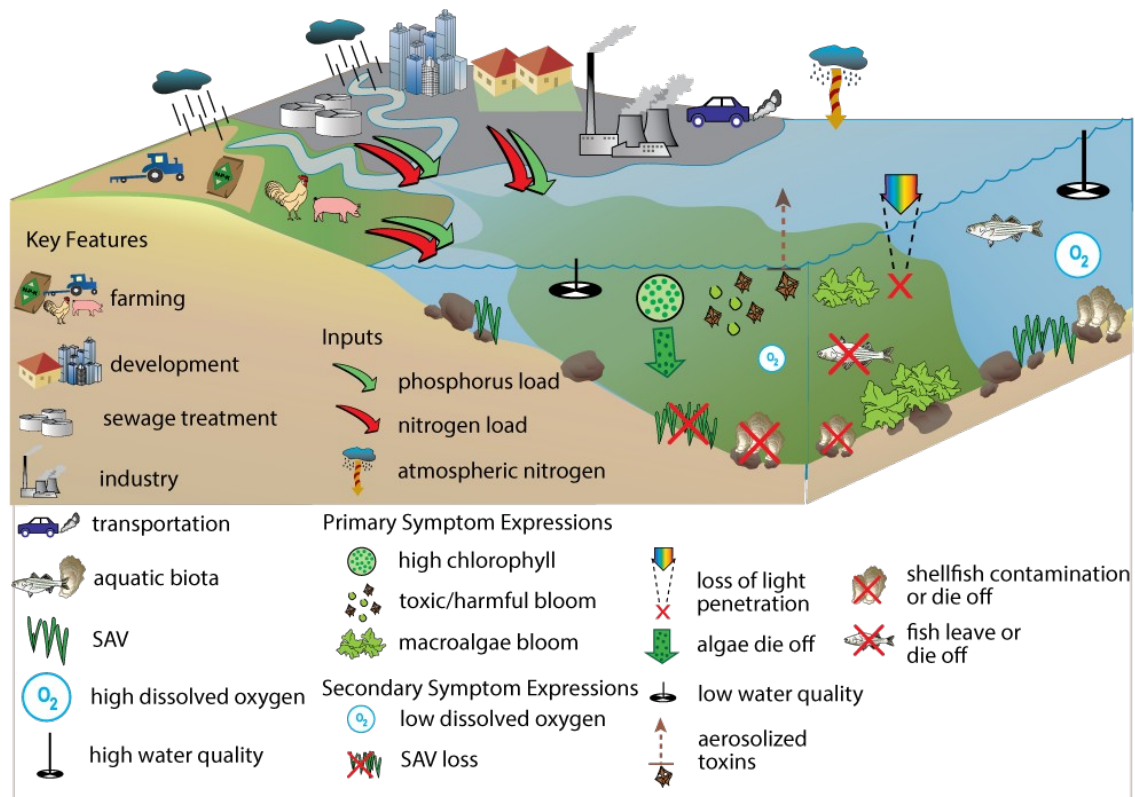
Figure 6. Biomagnification of mercury in the aquatic food chain.

Attribution: Kate Bentsen, Integration and Application Network Image Library.

4. **Point and non-point sources of pollution.** It is typically easier to detect and control pollutants that enter our environment through a so-called **point-source**, let's say from a pipe carrying waste from an industrial manufacturing plant or **wastewater treatment plant (WWTP)**. Other times, we may have non-point source pollution where we are unsure of the exact location from where the pollutants are entering a system. It can be extremely difficult to locate the problem and find a solution of a non-point source pollutant. We will start with a discussion on the more difficult of the two.

Chemicals such as **pesticides**, **herbicides**, and **fertilizers**, collectively known as **agrochemicals** (covered in more detail under *Agrochemicals* by Gary Bending), can enter directly into rivers from what we call non-point sources because we cannot always pinpoint the original source of the pollutant. Farmers will use these chemicals to ensure higher yields and that their crops will be safe from pests and plentiful enough to feed our growing global population ([TED Ed Do we really need pesticides?](#)). Agrochemicals such as pesticides and herbicides are designed to kill pests and weeds, respectively. Fertilizers are applied to help plants grow by providing essential **nutrients**, such as **nitrogen** and **phosphorous**. Problems occur as these agrochemicals are washed away with rain and enter into a local **waterbody** that people use for drinking, recreation, or fishing (Figure 7).

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Eutrophication is one of the major factors contributing to the increase in harmful algal blooms in the Chesapeake Bay.

Diagram courtesy of the Integration & Application Network, University of Maryland Center for Environmental Science.

Figure 7: Point, nonpoint source pollution, and eutrophication.  
Attribution: Jane Hawkey, Integration and Application Network.

5. **Eutrophication.** When an excess of nutrients enter into our coastal waters, it can lead to a process called **eutrophication**, an increase in the supply of organic matter into a system (covered in more detail under *Eutrophication: algal blooms* by Hans Paerl). Excess nutrients, or **nutrient pollution**, can cause disruptions with the natural **biogeochemical cycling** that regulates and balances an ecosystem. Biogeochemical cycling, the biological cycling of nutrients, is primarily controlled by diverse groups of **microorganisms** ([Khan Academy Biogeochemical Cycling](#)). These tiny, single celled organisms can utilize nutrients, such as carbon, nitrogen, and phosphorous, and make them available for plants and animals to use. A balance in this cycle is beneficial to the system since the **growth rate** or doubling of **primary producers** is equal to a process called **remineralization**. Primary producers such as **cyanobacteria** and other **phytoplankton** form the base of our aquatic **food web** (covered in more detail under *Microbial Interactions* by William Orsi) by using energy from sunlight to turn **inorganic** nutrients into **organic** biomass and oxygen. The biomass and oxygen produced through primary production provides support to the entire **ecosystem** which may include zooplankton, crabs, oysters and clams, fishes, birds, and mammals (including people). Remineralization is essentially the reverse of this process (minus the sunlight) where other microorganisms such as **heterotrophic bacteria** take the **biomass** from phytoplankton and convert it back into inorganic nutrients while consuming oxygen. The biogeochemical cycle

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continues, and, in the process, a balance exists between the production of biomass and oxygen and the consumption of biomass and oxygen.

When nutrients are supplied to a system in excess, which happens when rainwater washes fertilizers into a waterway, the cycle can be thrown out of balance. Too much nitrogen or phosphorous, for example, can support an overgrowth of algae and lead to **algal blooms** ([Fuse School Eutrophication](#)). If certain cyanobacteria or dinoflagellates such as *Karenia brevis* are present in very high numbers, they can produce toxins that are harmful to humans and aquatic life. An increase in **harmful algal blooms (HABs)** across the globe has been observed as a result of excess nutrients in coastal waterways which can have a cascading effect and cause further harm to these systems ([WHOI Map](#)).



Figure 8: Cyanobacterial bloom in the Baltic Sea

6. **Oxygen minimum zones – dead zones.** We also see the devastating effects of low oxygen events such as hypoxia and **anoxia** following algal blooms in impaired systems. Heterotrophic bacteria present in the water break down the excess organic material of the algal cells after they die. This process of remineralization uses up the dissolved oxygen in the water as the biomass is broken down. If low oxygen is persistent, **dead zones** may form causing massive die-offs of crabs, oysters and clams, and the fish that live in these waters ([Our Changing Climate Dead Zones](#)). Unfortunately, these hypoxic events happen increasingly all around the world leading to the creation of dead zones along most coastal waters, globally (Figure 9).

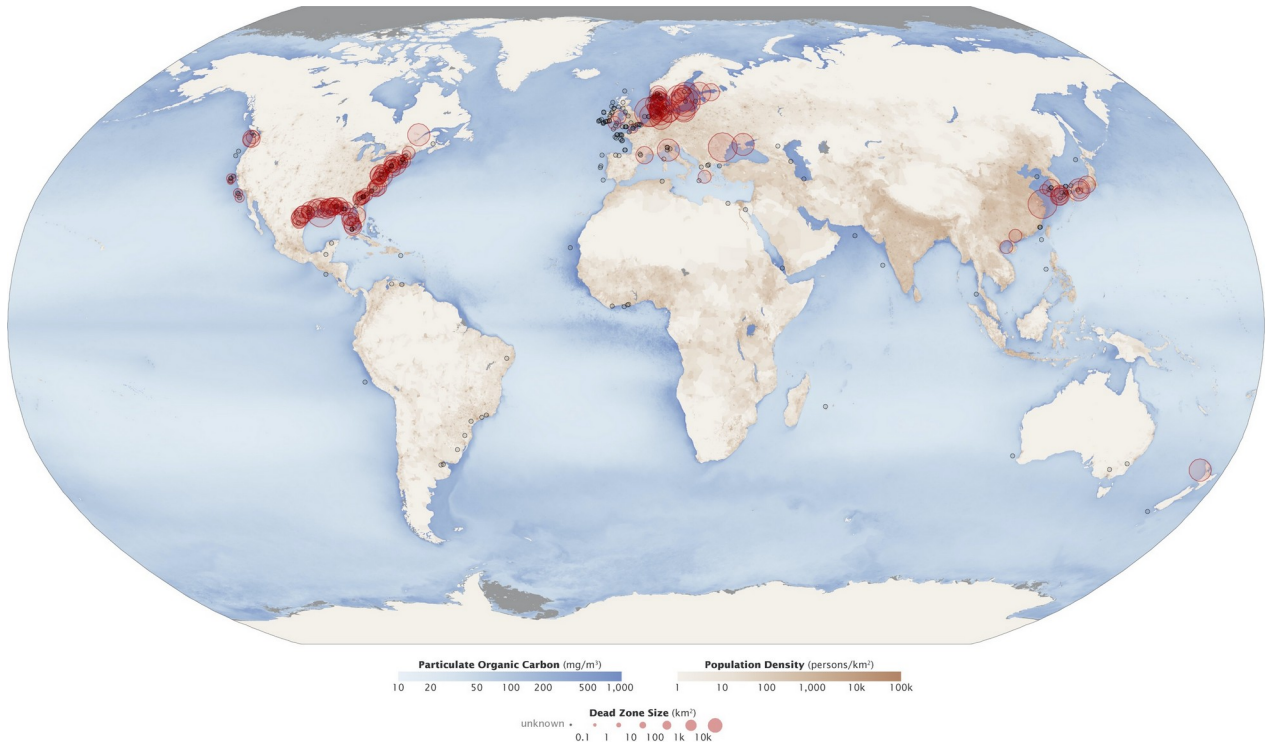


Figure 9. Aquatic dead zones. Attribution: [NASA Earth Observatory Map](#).

7. **Wastewater treatment plants: imperfect barriers between human-generated waste and the environment.** One of the most successful examples of pollution control is the wastewater treatment plant (WWTP). Prior to the development and widespread implementation of these facilities, human and animal sewage, storm water runoff, and industrial wastes entered directly into waterways. WWTPs have been an integral part of water pollution prevention through the reduction of pathogens, heavy metals, nutrients, and organic material that would otherwise enter the receiving waterways. WWTPs take advantage of natural microbial processes where heterotrophic bacteria break down organic matter through a series of screening and aeration stages. In this structured biological breakdown of waste, pollutant levels are significantly reduced before effluent is discharged to the natural systems ([National Geographic WWTP Operations Video](#)). Water quality monitoring of pipes leaving a wastewater facility occurs to as a way to regulate pollutants entering natural systems. Local regulations may determine the amount of organic material and nutrients that can be discharged from a wastewater treatment facility to ensure that local waterways remain safe for swimming, fishing, or other recreational activities. WWTPs are engineered biological interfaces between humans and the environment acting as barriers that prevent much human-generated waste from entering the environment.

Unfortunately, not all pollutants are removed during the traditional wastewater treatment process. Emerging pollutants such as microplastics (MPs) as well as pharmaceutical and personal care products (PPCPs) are not effectively removed during the traditional wastewater treatment process, initially designed to remove nutrients and reduce readily biodegradable organic matter. Pharmaceuticals, chemicals primarily used to treat and prevent infections or illness, and personal care products, chemicals used to improve the quality of life, are now widespread throughout the natural environment due to their extensive use (Figure 10). MPs and PPCPs, what we would

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consider point-source pollutants since we know the exact location where the pollutant enters a waterway, are also often not regulated or monitored in wastewater effluent. Additional treatment stages are known to be effective in the removal of these products, but these upgrades to WWTPs are costly and rare. In any case, WWTPs cannot keep up with the rapid development of new personal care and wellness products; although these may be subject to environmental impact analysis before introduction, possible long term environmental effects only emerge after a considerable period of time.

While point source pollutants may be easy to identify, they have proven to be extremely difficult to control and prevent due to the origins of the pollutants and their chemical behavior in the environment. Microorganisms play a central role in the breakdown of these compounds, however transformation into potentially more harmful byproducts add to the complexity of this pollution problem and have harmful impacts on the biota within these local waterways (covered in more detail under *Industrial Pollutants* by Jessica Lisa and Max Häggblom).

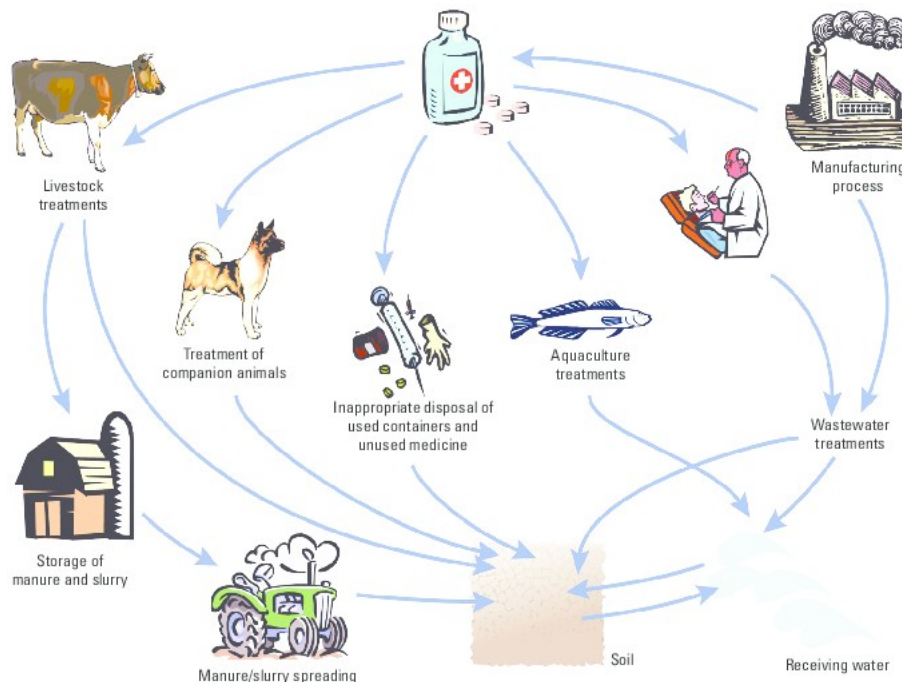


Figure 10: Major pathways of PPCP release into the environment.

Attribution: Boxall, A, et al. 2012, *Pharmaceuticals and Personal Care Products in the Environment: What Are the Big Questions?* *Environmental health perspectives*:120(9):1221-9 (10.1289/ehp.1104477).

### Kid Friendly Resources

Watershed resources:

<https://nj.pbslearningmedia.org/resource/ket09.sci.ess.water.wshed/what-is-a-watershed/>

<https://www.neefusa.org/nature/water/lesson-1-watershed-basics>

<https://time.com/5554027/dead-whale-plastic-philippines/>

<https://www.nytimes.com/2019/03/18/world/asia/whale-plastics-philippines.html>

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### Eutrophication Resources:

<https://oceanservice.noaa.gov/facts/eutrophication.html>  
<https://www.nationalgeographic.org/encyclopedia/dead-zone/>

### Pollution Resources

<https://link.springer.com/content/pdf/10.1007%2F978-3-319-73250-3.pdf>  
[https://www.pbs.org/now/classroom/classroom\\_kids1.html](https://www.pbs.org/now/classroom/classroom_kids1.html)  
<https://www.npr.org/sections/thesalt/2013/12/12/250438904/how-plastic-in-the-ocean-is-contaminating-your-seafood>  
<https://www.pnas.org/content/113/9/2430> (oysters)  
[https://www.pnas.org/content/112/38/11899?ijkey=1b0b05c4b6adb754d9040f184cc68a03d61e79f2&keytype=tf\\_ipsecsha](https://www.pnas.org/content/112/38/11899?ijkey=1b0b05c4b6adb754d9040f184cc68a03d61e79f2&keytype=tf_ipsecsha) (sea birds)  
<https://www.bbc.com/future/article/20141104-is-anywhere-free-from-pollution> (general)  
<https://www.nationalgeographic.org/encyclopedia/pollution/>  
<https://www.epa.gov/international-cooperation/persistent-organic-pollutants-global-issue-global-response>  
[https://ec.europa.eu/environment/integration/research/newsalert/pdf/326na6\\_en.pdf](https://ec.europa.eu/environment/integration/research/newsalert/pdf/326na6_en.pdf)  
[https://www.iucn.org/sites/dev/files/marine\\_plastics\\_issues\\_brief\\_final\\_0.pdf](https://www.iucn.org/sites/dev/files/marine_plastics_issues_brief_final_0.pdf)

### WWTPs

<https://www3.epa.gov/npdes/pubs/bastre.pdf>  
[https://www.usgs.gov/special-topic/water-science-school/science/wastewater-treatment-water-use?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/special-topic/water-science-school/science/wastewater-treatment-water-use?qt-science_center_objects=0#qt-science_center_objects)  
[https://www.usgs.gov/special-topic/water-science-school/science/a-visit-a-wastewater-treatment-plant?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/special-topic/water-science-school/science/a-visit-a-wastewater-treatment-plant?qt-science_center_objects=0#qt-science_center_objects)  
[https://academickids.com/encyclopedia/index.php/Sewage\\_treatment](https://academickids.com/encyclopedia/index.php/Sewage_treatment)  
<https://www.funkidslive.com/learn/marina-venturas-inside-water/marina-venturas-inside-water-the-sewage-treatment-process/#>  
<https://www.frontiersin.org/articles/10.3389/fenvs.2019.00064/full>  
<https://www.britannica.com/technology/wastewater-treatment-chemmatters> (video)

## Resources

Conley DJ, HW Pearl, RW Howarth, DF Boesch, SP Seitzinger, KE Havens, C Lancelot, GE Likens. 2009 Controlling Eutrophication: Nitrogen and Phosphorus. *Science* 323: 1014-1015 (DOI: 10.1126/science.1167755)  
Diaz RJ and R Rosenberg. 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* 321: 926-929 (DOI: 10.1126/science.1156401)  
Kuypers, MM, HK Marchant, and B Kartal. 2018. The microbial nitrogen-cycling network. *Nature Reviews Microbiology*. 16: 263-276.

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### Glossary

**agrochemical** (noun): a substance used in agriculture, including chemical fertilizers, herbicides, and insecticides

**algal blooms** (noun): a rapid growth of microscopic algae or cyanobacteria in water, often resulting in a colored scum on the surface

**anoxia** (noun): absence of oxygen

**apex predators** (noun): animals at the top of a food chain, not preyed upon by any other animal

**aquatic** (adjective): relating to water

**bioaccumulation** (noun): the accumulation over time of a substance and especially a contaminant (such as a pesticide or heavy metal) in a living organism

**biodegradable** (adjective): capable of being decomposed by the action of living organisms

**biodegradation** (noun): the gradual breakdown of a material mediated by specific biological activity

**biogeochemical cycling** (noun): the circulation of essential elements of living matter

**biota** (noun): the animal and plant life of a particular region, habitat, or geological period

**byproducts** (noun): incidental or secondary compounds made in the manufacture or synthesis of something else

**chemicals** (noun): any basic substance that is used in or produced by a reaction involving changes to atoms or molecules

**climate** (noun): the average course or condition of the weather at a place usually over a period of years as exhibited by temperature, wind velocity, and precipitation

**cyanobacteria** (noun): a group of microscopic, photosynthetic organisms found naturally in all types of water

**dead zone** (noun): regions of a waterbody where there is so little oxygen that almost no life exists beneath the surface waters

**diatoms** (noun): a major group of single-celled algae that have a cell walls composed of silica and can be found in the oceans, waterways and soils of the world

**dioxins** (noun): any of several persistent toxic heterocyclic hydrocarbons that occur especially as by-products of various industrial processes (such as pesticide manufacture and papermaking) and waste incineration

**effluent** (noun): liquid waste discharged into a river or the sea

**emerging pollutants** (noun): contaminants that are increasingly being detected in the environment and have the potential to impact human health and the environment, but are not yet widely regulated; also known as contaminants of emerging concern (CEC's)

**eutrophication** (noun): the increase in the rate of supply of organic matter to an ecosystem. Most commonly fueled by excess nutrients that supports an increase in primary productivity in estuaries and coastal systems

**fertilizers** (noun): natural or artificial substances containing the chemical elements that improve growth and productiveness of plants

**food web** (noun): a system of interlocking and interdependent food chains

**gas** (noun): a fluid substance that has neither independent shape nor volume but tends to expand indefinitely; plural gasses

**growth rate** (noun): the time it takes for single-cell organism to divide

**gyre** (noun): a large system of rotating ocean currents

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**harmful algal bloom:** a rapid growth of microscopic algae or cyanobacteria in water, resulting in the production of toxins

**heavy metals** (noun): naturally occurring elements that have a high atomic weight and a density at least 5 times greater than that of water

**herbicides** (noun): substances or mixtures of substances intended for preventing, destroying, repelling, or mitigating unwanted plants

**industrial pollutant** (noun): a substance, produced during the processing of raw materials and manufacture of goods in factories, that has undesired effects

**inorganic** (adjective): of, relating to, or denoting compounds which are not derived from living organisms or do not contain carbon

**legacy pollutants** (noun): contaminants that are strongly associated with industrial processes (intentional and unintentional production) and remain in the environment long after their introduction, posing long-term effects and stress on human health and the environment

**macroscopic** (adjective): observable to the naked eye

**marine debris** (noun): any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into an aquatic environment or the Great Lakes

**mercury** (noun): the chemical element of atomic number 80, a heavy silvery-white metal which is liquid at ordinary temperatures

**microscopic** (adjective): too small to be seen by the unaided eye

**microorganisms** (noun): life forms too small to be seen by the unaided human eye

**microplastics** (noun): plastic particles that measure less than five millimeters

**nitrogen** (noun): the chemical element of atomic number 7

**non-point source pollutant** (noun): pollutants released in a wide area

**nurdles** (noun): small plastic pellets which serve as raw material in the production of plastic products

**nutrients** (noun): substances that provide nourishment essential for growth and the maintenance of life

**nutrient pollution** (noun): the process by which excess nutrients, mainly nitrogen and phosphorus, contaminate bodies of water causing challenging environmental problems

**organic** (adjective): of, relating to, or denoting compounds which are derived from living organisms or contain carbon compounds

**organisms** (noun): life forms

**pathogen** (noun): a specific causative agent of disease

**persistent organic pollutants** (noun): ubiquitous environmental contaminants that are not readily degraded in the environment

**persistent synthetic polymers** (noun): human-made substances composed of very large molecules that are multiples of simpler chemical units that are not readily degraded in the environment

**personal care products** (noun): items mainly used to improve the quality of daily life

**pesticides** (noun): substances or mixtures of substances intended for preventing, destroying, repelling, or mitigating any pest

**pharmaceuticals** (noun): prescription or over the counter therapeutic drugs used to prevent or treat human and animal diseases

**phosphorous** (noun): the chemical element of atomic number 15

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**photodegradation** (noun): the process by which a molecule is altered by the absorption of photons, particularly those wavelengths found in sunlight

**phytoplankton** (noun): flora of freely floating, often minute organisms, that drift with water currents and convert sunlight, water and carbon dioxide to algal biomass

**point-source pollutant** (noun): any contaminant that enters the environment from an easily identified and confined place

**pollution** (verb): the introduction of harmful materials into the air, land and water

**pollutant** (noun): something introduced into the environment that harmfully disrupts it

**polycyclic aromatic hydrocarbons** (PAH's; noun): a class of hydrocarbon molecules that have multiple fused aromatic carbon rings, and that include carcinogenic substances and environmental pollutants. PAH's occur naturally in coal, crude oil, and gasoline and are also produced when coal, oil, gas, wood, garbage, and tobacco are burned.

**polychlorinated biphenyls** (PCB's; noun): any of several compounds that are produced by replacing hydrogen atoms in biphenyl with chlorine, have various industrial applications, and are toxic environmental pollutants which tend to accumulate in animal tissues

**primary producers** (noun): organisms capable of converting an abiotic source of energy (e.g. light) into energy stored in organic compounds

**regulate** (verb): to control or maintain

**reminerzalization** (noun): the process by which organic matter is broken down or transformed into its simplest inorganic forms

**storm drain** (noun): a means (such as a pipe) by which usually liquid matter (such as rainwater) is carried away

**stormwater** (noun): rainwater or melted snow that runs off streets, lawns and other sites

**trophic level** (noun): each of several hierarchical levels in an ecosystem, comprising organisms that share the same function in the food chain and the same nutritional relationship to the primary sources of energy

**toxins** (noun): biologically produced chemical substance that is capable of causing harm to cells or living organisms

**wastewater treatment plant** (WWTP; noun): a facility in which a combination of various processes (e.g., physical, chemical and biological) are used to treat municipal and industrial wastewater and remove pollutants

**water quality monitoring** (noun) the sampling and analysis of water and physical, chemical, and biological characteristics conditions of the waterbody

**waterbody** (noun): any significant accumulation of water such as a river, lake or a bay

**watershed** (noun): an area of land from which all water drains into one common waterbody such as a river, lake, estuary, or ocean