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Introduction to Environmental Science

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Chapter 1- Introduction to Environmental sciences

At the end of this section, students will be able to:
1. Define environment, ecosystems, and environmental sciences
2. Understand the interdisciplinary nature of environmental science
3. Define sustainability and sustainable development
4. Understand the complex relationship between natural and human systems
5. Understand scientific approach and begin to apply the scientific method

Environment and environmental science

Viewed from space, Earth (Figure 1.1) offers no clues about the diversity of life forms that reside there. The first forms of life on Earth are thought to have been microorganisms that existed for billions of years in the ocean before plants and animals appeared. The mammals, birds, and plants so familiar to us are all relatively recent, originating 130 to 200 million years ago. Humans have inhabited this planet for only the last 2.5 million years, and only in the last 200,000 years have humans started looking like we do today. It took thousands of years for the human population to reach 1 billion (1800) but only 130 years to reach 2 billion (1930). It took only 30 years to reach 3 billion (1960), 15 years to reach 4 billion (1975), 12 years to reach 5 billion (1987), 12 years to reach 6 billion (1999) and 13 years to reach 7 billion (2012, Population Reference Bureau). There are around 7.3 billion people today (http://www.breathingearth.net/).

Figure 1.1 This NASA image is a composite of several satellite-based views of Earth. To make the whole-Earth image, NASA scientists combine observations of different parts of the planet. (credit: NASA/GSFC/NOAA/USGS)
The word ‘environment’ describes living and nonliving surroundings relevant to organisms. It incorporates physical, chemical and biological factors and processes that determine the growth and survival of organisms, populations, and communities. All components fit within the ecosystem concept as a way to organize all of the factors and processes that make up the environment. The ecosystem includes organisms and their environment within a specific area. The flow of energy and matter through the ecosystems influences abundance and distribution of organisms within them. Today, human activities influence all of the Earth’s ecosystems. Earth’s natural systems provide ecosystem services required for our survival such as: air and water purification, climate regulation, and plant pollination. We have degraded nature’s ability to provide these services by depleting resources, destroying habitats, and generating pollution. The benefits people obtain from ecosystems are essential for life. Supporting services include: nutrient cycling, soil formation, and primary production. Another important service of natural ecosystems is provisioning like food production, maintenance of clean water, production of wood, fibers and fuel. Ecosystems are responsible for climate regulation, flood regulation together with disease regulation, also water purification from natural and anthropogenic impurities. Finally ecosystems provide cultural and esthetic services. As humans we gain strength and positive energy from observing natural habitats, recreation in waters and mountains. Nature is also a source for poets and writers. It is a source of aesthetics, religious and other nonmaterial benefits. Studying ecosystem structure in its original state is the only way we can make anthropogenic systems like agricultural fields, reservoirs, fracking operations, and dammed rivers working for human benefit with minimal impact on ours and other organisms’ health. For more details on chemical and biological organization see Supplement to Chapter 1-foundations of life.

**Environmental sciences** study all aspects of the environment in a multidisciplinary / interdisciplinary way. It requires the knowledge of various other subjects like biology, chemistry, physics, statistics, microbiology, bio-chemistry, geology, economics, law, sociology etc. It is a relatively new field of study that has evolved from integrated use of many disciplines. Environmental engineering is one of the fastest growing and complex disciplines of engineering. It creates awareness and understanding of environmental concepts that may be scientific, social and ecological systems thereby providing a platform for solution to various environmental problems.

**Sustainability and Sustainable Development**

In 1983 the United Nations General Assembly passed resolution 38/161 entitled - Process of Preparation of the Environmental Perspective to the Year 2000 and Beyond3, - establishing a special commission whose charge was:

a. To propose long-term environmental strategies for achieving sustainable development to the year 2000 and beyond;

b. To recommend ways in which concern for the environment may be translated into greater co-operation among developing countries and between countries at different stages of economic and social development and lead to the achievement of common and mutually supportive objectives which take account of the interrelationships between people, resources, environment and development;
c. To consider ways and means by which the international community can deal more effectively with environmental concerns, in light of the other recommendations in its report;
d. To help define shared perceptions of long-term environmental issues and of the appropriate efforts needed to deal successfully with the problems of protecting and enhancing the environment, a long-term agenda for action during the coming decades, and aspirational goals for the world community, taking into account the relevant resolutions of the session of a special character of the Governing Council in 1982.

Although the Report did not technically invent the term ‘sustainability’, it was the first credible and widely disseminated study that used the term sustainability in the context of the global impacts of humans on the environment. Its main and often quoted definition refers to sustainable development as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The report uses the terms ‘sustainable development’, ‘sustainable’, and ‘sustainability’ interchangeably, emphasizing the connections among social equity, economic productivity, and environmental quality (Figure 1.2).

Figure 1.2. Overlapping Themes of the Sustainability Paradigm A depiction of the sustainability paradigm in terms of its three main components, showing various intersections among them. Source: International Union for the Conservation of Nature.

Preserving the environment for humans today and in the future is a responsibility of every generation and a long-term global goal. Currently, we are drawing down Earth’s natural capital, its accumulated wealth of resources. Today’s search for sustainable solutions is centered on sustainable development. Sustainability and the triple bottom line (meeting environmental, economic, and social goals simultaneously) require that we limit our environmental impact, while promoting economic well being and social equity.

Many human activities can be sustainable. For example, sustainable agriculture is agriculture that does not deplete soils faster than they form and does not destroy the biodiversity of the area.
Sustainable farming and ranching do not reduce the amount of healthy soil, clean water, genetic
diversity of crop plants and animals. Maintaining as much ecological biodiversity as possible in
the agro-ecosystem is essential to long-term crop and livestock production.

In the United States, we typically expect each new generation to be better off than their parents.
Decades of technological advancement and economic growth have created a mindset not
satisfied with ‘mere’ sustainability. We might call it turbo-materialism or a cornucopian
worldview (see Figure 1.3): namely that the Earth's resources, adapted to our use by human
ingenuity, guarantees a perpetual growth in goods and services. At the root of the cornucopian
worldview lies a brand of technological triumphalism, an unshakeable confidence in
 technological innovation to solve all social and environmental problems, be it world hunger,
climate change, or declining oil reserves. In sustainability discourse, there is a wide spectrum of
opinions from the extremes of cornucopian optimism on one side and to the doom-and-gloom
scenarios that suggest it is already too late to avert a new Dark Age of resource scarcity and
chronic conflict on the other.

For every generation entering a Dark Age, there were parents who enjoyed a better life, but who
somehow failed to pass along their prosperity. No one wants to fail their children in this way. To
this extent, biology dictates multi-generational thinking and ethics. Though it might not always
be obvious, we are all already the beneficiaries of multi-generational planning. The world-
leading American higher education system, for example, depends upon an intergenerational
structure and logic—a financial and human investment in the future committed to by multiple
generations of Americans going back to the 19th century. But conversely, in terms of
vulnerability, just as higher education in the United States is neither necessarily permanent nor
universal, but a social institution built on an unwritten contract between generations, so the
lifestyle benefits of advanced society as we know it will not simply perpetuate themselves
without strenuous efforts to place them on a sustainable footing.
The IPAT Equation

As attractive as the concept of sustainability may be as a means of framing our thoughts and goals, its definition is rather broad and difficult to work with when confronted with choices among specific courses of action. One way of measuring progress toward achieving sustainable goals can be with the application of the IPAT equation.

\[ I = P \times A \times T \]

- \( I \) represents the impacts of a given course of action on the environment;
- \( P \) is the relevant human population for the problem at hand;
- \( A \) is the level of consumption per person;
- \( T \) is impact per unit of consumption.

Impact per unit of consumption is a general term for technology, interpreted in its broadest sense as any human-created invention, system, or organization that serves to either worsen or uncouple consumption from impact. The equation is not meant to be mathematically rigorous; rather it provides a way of organizing information for a first-order analysis. Suppose we wish to project future needs for maintaining global environmental quality at present day levels for the mid-twenty-first century. For this we need to have some projection of human population (\( P \)) and an idea of rates of growth in consumption (\( A \)).
The Process of Science

Environmental sciences is a science, but what exactly is science? Science (from the Latin scientia, meaning “knowledge”) can be defined as knowledge that covers general truths or the operation of general laws, especially when acquired and tested by the scientific method. Science may be better defined as fields of study that attempt to comprehend the nature of the universe. The scientific method is a method of research with defined steps that include experiments and careful observation. One of the most important aspects of this method is the testing of hypotheses by means of repeatable experiments. A hypothesis is a suggested explanation for an event, which can be tested. A theory is a tested and confirmed explanation for observations or phenomena that is supported by many repeated experiences and observations.

The scientific method

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed. Let’s think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives in class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: “Why is the classroom so warm?”

Proposing a Hypothesis

Recall that a hypothesis is a suggested explanation that can be tested. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, “The classroom is warm because no one turned on the air conditioning.” But there could be other responses to the question, and therefore other hypotheses may be proposed. A second hypothesis might be, “The classroom is warm because there is a power failure, and so the air conditioning doesn’t work.” Once a hypothesis has been selected, the student can make a prediction. A prediction is similar to a hypothesis but it typically has the format “If . . . then . . . .” For example, the prediction for the first hypothesis might be, “If the student turns on the air conditioning, then the classroom will no longer be too warm.”

Testing a Hypothesis

A valid hypothesis must be testable. It should also be falsifiable, meaning that it can be disproven by experimental results. Importantly, science does not claim to “prove” anything because scientific understandings are always subject to modification with further information. This step — openness to disproving ideas — is what distinguishes sciences from non-sciences. The presence of the supernatural, for instance, is neither testable nor falsifiable. To test a hypothesis, a researcher will conduct one or more experiments designed to eliminate one or more of the hypotheses. Each experiment will have one or more variables and one or more controls. A variable is any part of the experiment that can vary or change during the experiment. The control group contains every feature of the experimental group except it is not given the manipulation that is hypothesized about. Therefore, if the results of the experimental group differ
from the control group, the difference must be due to the hypothesized manipulation, rather than some outside factor. Look for the variables and controls in the examples that follow. To test the first hypothesis, the student would find out if the air conditioning is on. If the air conditioning is turned on but does not work, there should be another reason, and this hypothesis should be rejected. To test the second hypothesis, the student could check if the lights in the classroom are functional. If so, there is no power failure and this hypothesis should be rejected. Each hypothesis should be tested by carrying out appropriate experiments. Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (Figure 1.4). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

**Figure 1.4.** The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed.
The scientific method may seem too rigid and structured. It is important to keep in mind that, although scientists often follow this sequence, there is flexibility. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests. Notice, too, that the scientific method can be applied to solving problems that aren’t necessarily scientific in nature.

Global perspective

The solution to most environmental problems requires a global perspective. Human population size has now reached a scale where the environmental impacts are global in scale and will require multilateral solutions. Example: Famines in Africa. There is plenty of food produced on earth to adequately feed everyone. The problem is food distribution. Better food distribution—global perspective can solve this problem.

Urbanization

Human population currently is about seven billion. That number might not seem particularly jarring on its own; after all, we all know there are lots of people around. But consider the fact that human population grew very slowly for most of our existence, then doubled in the span of half a century to reach six billion in 1999. And now, just over ten years later, we have added another billion. A look at the graph of projected population indicates that growth is not only going to continue, but it will continue at a rapid rate.

The proportion of people living in cities has greatly increased over the past 50 years. Environmental solutions need to include the urban environment. When the impact of technology is combined with the impact of population, the impact on the environment is multiplied. In an increasingly urban world, we must focus much of our attention on the environments of cities and on the effects of cities on the rest of the environment.

Urbanization is the study of the social, political, and economic relationships in cities, and someone specializing in urban environments would study those relationships. In some ways, cities can be microcosms of universal human behavior, while in others they provide a unique environment that yields their own brand of human behavior. There is no strict dividing line between rural and urban; rather, there is a continuum where one blends into the other. However, once a geographically concentrated population has reached approximately 100,000 people, it typically behaves like a city regardless of what its designation might be. According to sociologist Gideon Sjoberg (1965), there are three prerequisites for the development of a city. First, good environment with fresh water and a favorable climate; second, advanced technology, which will produce a food surplus to support non-farmers; and third, strong social organization to ensure social stability and a stable economy. Most scholars agree that the first cities were developed somewhere in ancient Mesopotamia, though there are disagreements about exactly where. Most early cities were small by today’s standards, and the largest city at the time was most likely Rome, with about 650,000 inhabitants. The factors limiting the size of ancient cities included
lack of adequate sewage control, limited food supply, and immigration restrictions. For example, serfs were tied to the land, and transportation was limited and inefficient. Today, the primary influence on cities' growth is economic forces. Since the recent economic recession has reduced housing prices, researchers are waiting to see what happens to urban migration patterns in response. In the United States the trend of more urban life styles has been increasing (Figure 1.5).

![Percent of U.S. Population](chart.png)

**Figure 1.5.** As this chart illustrates, the shift from rural to urban living in the United States has been dramatic and continuous. (Graph courtesy of the U.S. Census Bureau)

The development of factories brought people from rural to urban areas, and new technology increased the efficiency of transportation, food production, and food preservation. For example, from the mid-1670s to the early 1900s, London increased its population from 550,000 to 7 million (Old Bailey Proceedings Online 2011). The most recent phenomenon shaping urbanization around the world is the development of post-industrial cities whose economic base depends on service and information rather than the manufacturing industry. The professional, educated class populates the post-industrial city, and they expect convenient access to culturally based entertainment (libraries, museums, historical downtowns, and the like) uncluttered by factories and the other features of an industrial city. Global favorites like New York, London, and Tokyo are all examples of post-industrial cities. As cities evolve from industrial to post-industrial, gentrification becomes more common. The practice of gentrification refers to members of the middle and upper classes entering city areas that have been historically less affluent and renovating properties while the poor urban underclass are forced by resulting price
pressures to leave those neighborhoods. This practice is widespread and the lower class is pushed into increasingly decaying portions of the city.

The precautionary principle

The precautionary principle or the precautionary approach is one perspective of environmental risk management. The precautionary principle stakes that “When the health of humans and the environment is at stake, it may not be necessary to wait for scientific certainty to take protective action”. In other words, better to be safe than sorry. Proponents of the precautionary principle believe that the burden of proof should be on the individual, company or government who is proposing the action, not on the people who will be affected by it. For example, if environmental regulations concerning pesticides were based on the precautionary principle (in the US, they are not), then any pesticide that could potentially harm the environment or human health would not be widely used.

What is the environment worth to you?

The environment, and its benefits to individuals or groups, can be viewed and justified from multiple perspectives. A Utilitarian justification for environmental conservation means that we should protect the environment because doing so provides a direct economic benefit to people. For example, someone might propose not developing Georgia’s coastal salt marshes because the young of many commercial fishes live in salt marshes and the fishers will collapse without this habitat. An Ecological justification for environmental conservation means that we should protect the environment because doing so will protect both species that are beneficial to other as well as other species and an ecological justification for conservation acknowledges the many ecosystem services that we derive from healthy ecosystems. For example, we should protect Georgia’s coastal salt marshes because salt marshes purify water, salt marshes are vital to the survival of many marine fishes and salt marshes protect our coasts from storm surges. An Aesthetic justification for conservation acknowledges that many people enjoy the outdoors and do not want to live in a world without wilderness. One could also think of this as recreational, inspirational, or spiritual, justification for conservation. For example, salt marshes are beautiful places and I always feel relaxed and calm when I am visiting one, therefore we should protect salt marshes. And finally a moral justification represents the belief that various aspects of the environment have a right to exist and that it is our moral obligation to allow them to continue or help them persist. Someone who was arguing for conservation using a moral justification would say that it is wrong to destroy the coastal salt marshes.

Parts of this chapter have been modified from the OpenStax textbooks.

Questions:
1. Why there was a need to study the impact of human population growth on the environment!
2. What does sustainability mean to you?

In class activities:
1. What are the consequences of unsustainable vs. sustainable living? What quality of life do we want for us and our children?
2. Think of an environmental problem that requires a global perspective for a solution?
3. List various justifications for environmental protection.

**Approaches to Knowledge and Thinking**

How can I break this problem into parts?
How can I approach this differently?
How can deductive reasoning help?
What am I trying to do?
What does it all mean?

**Websites for more information and further discussion**


"Process" of science [http://undsci.berkeley.edu/](http://undsci.berkeley.edu/)


See excel file with terminology introduced in this chapter
Chapter 2: Population Ecology

Learning Outcomes - At the end of this section, students will be able to:

- Define the variables in the exponential and logistic growth equations.
- Use the exponential and logistic equations to predict population growth rate.
- Compare the environmental conditions represented by the exponential growth model vs. the logistic growth model.
- Define carrying capacity and be able to label the carrying capacity on a graph.
- Compare density-dependent and density-independent birth and death rates. Give examples of each.
- Interpret survivorship curves and give examples of organisms that would fit each type of curve.

Chapter outline

1. What is population ecology?
3. Exponential growth.
4. Logistic growth.
5. Density-dependent and independent rates.

What is population ecology?

A population can be generally defined as a group of individuals of the same species occupying a given area at a given time. Populations change over time. Populations grow and shrink and the age and gender composition also change through time and in response to changing environmental conditions. Population ecology is the study of populations and their changes over time.

Population Size and Density

The study of any population usually begins by determining how many individuals of a particular species exist, and how closely associated they are with each other. Within a particular habitat, a population can be characterized by its population size (N), defined by the total number of individuals, and its population density, the number of individuals within a specific area or volume. Population size and density are the two main characteristics used to describe a population. For example, populations with more individuals may be more stable than smaller populations based on their genetic variability, and thus their potential to adapt to the environment. Alternatively, a member of a population with low population density (more spread
out in the habitat), might have more difficulty finding a mate to reproduce compared to a population of higher density.

**Exponential Growth**

Charles Darwin, in his theory of natural selection, was greatly influenced by the English clergyman Thomas Malthus. Malthus published a book (An Essay on the Principle of Population) in 1798 stating that populations with unlimited natural resources grow very rapidly. This accelerating pattern of increasing population size is called **exponential growth**. According to the Malthus model, once population size exceeds available resources, population growth decreases dramatically.

The best example of exponential growth is seen in bacteria. Bacteria are prokaryotes that reproduce by prokaryotic fission. This division takes about an hour for many bacterial species. If 100 bacteria are placed in a large flask with an unlimited supply of nutrients (so the nutrients will not become depleted), after an hour, there is one round of division and each organism divides, resulting in 200 organisms - an increase of 100. In another hour, each of the 200 organisms divides, producing 400 - an increase of 200 organisms. After the third hour, there should be 800 bacteria in the flask - an increase of 400 organisms. The important concept of exponential growth is that the **population growth rate** (dN/dt) the number of organisms added in each reproductive generation— is accelerating; that is, it is increasing at a greater and greater rate. After ½ a day and 12 of these cycles, the population would have increased from 100 to more than 24,000. When the population size, \( N \), is plotted over time, a J-shaped growth curve is produced (Figure 2.1).

![Figure 2.1: The “J” shaped curve of exponential growth for a hypothetical population of bacteria. The population starts out with 100 individuals and after 11 days there are over 24,000 individuals. As time goes on and the population size increases, the rate of increase also increases (each step up becomes bigger). In this figure “r” is positive.](image-url)
This is the equation for exponential population growth:

\[
\frac{dN}{dt} = rN
\]

- \(\frac{dN}{dt}\) = population growth rate
- \(N\) = population size
- \(r\) = per capita rate of increase

\(dN/dt\) is the population growth rate, it is the change in population size over the change in time. The population growth rate (\(dN/dt\)) depends on population size (\(N\)) and the per capita rate of increase (\(r\)). “\(r\)” is the per capita rate of increase, and it is equal to the birth rate subtracted from the death rate for a population. “\(r\)” can be positive, meaning the population is increasing in size; or negative, meaning the population is decreasing in size; or zero, where population size is unchanging, a condition known as zero population growth. “\(r\)” varies depending on the organism, for example a population of bacteria would have a much higher “\(r\)” than an elephant population.

In the exponential growth model, population size is multiplied by the per capita rate of increase. So a larger population size (larger \(N\)) will result in a larger population growth rate.

**Logistic Growth**

Exponential growth cannot continue forever because resources (food, water, shelter) will become limited. Exponential growth may occur in environments where there are few individuals and plentiful resources, but when the number of individuals gets large enough, resources will be depleted, slowing the growth rate. When resources are limited, populations exhibit logistic growth.

In logistic growth, population growth rate decreases as resources become scarce. When the population size equals the carrying capacity of the environment, population growth rate levels off at zero, resulting in the logistic growth curve (Figure 2.2). This population size, which represents the maximum population size that a particular environment can support, is called the carrying capacity, or \(K\).
Figure 2.2: Shows logistic growth of a hypothetical bacteria population. The population starts out with 10 individuals and then reaches the carrying capacity of the habitat which is 500 individuals.

This is the equation for the logistic growth model:

$$\frac{dN}{dt} = rN \left[1 - \frac{N}{K}\right]$$

- $N$ = population size
- $\frac{dN}{dt}$ = population growth rate
- $r$ = per capita rate of increase
- $K$ = carrying capacity

In the logistic growth model, a population starts out small with plenty of resources; the population size is much lower than the carrying capacity of the environment. Population size increases and population growth rate initially increases. But then as population size grows larger resources become more limited and population growth rate begins to slow down. When the population size is at the carrying capacity of the environment ($N = K$) then population growth rate is zero and the population stays at a constant size.

Yeast, a microscopic fungus used to make bread and alcoholic beverages, exhibits the classical S-shaped logistic growth curve when grown in a test tube (Figure 2.3). Its growth levels off as the population depletes the nutrients that are necessary for its growth. In the real world, however, there are variations to this idealized curve. For example, a population of harbor seals may exceed the carrying capacity for a short time and then fall below the carrying capacity. This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation, the logistic model is exhibited.
Figure 2.3: Graph (a) plots amount of yeast versus time of growth in hours. The curve rises steeply, and then plateaus at the carrying capacity. Data points tightly follow the curve. Graph (b) plots the number of harbor seals versus time in years. Again, the curve rises steeply then plateaus at the carrying capacity, but this time there is much more scatter in the data. A micrograph of yeast cells, which are oval in shape, and a photo of a harbor seal are shown.

Density-dependent and density-independent rates

Population size can be affected by density-dependent factors, in which the density of the population at a given time affects birth and death rates, and density-independent factors, which influence population size regardless of population density. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

Density-dependent birth rates and death rates depend on the population size. Most density-dependent factors are biological in nature (biotic), and include predation, inter- and intraspecific competition, accumulation of waste, and diseases such as those caused by parasites. Usually, higher population density results in higher death rates and lower birth rates. For example, as a population increases in size food becomes scarcer and some individuals will die from starvation meaning that the death rate from starvation increases as population size increases. Also as food becomes scarcer, birth rates decrease due to fewer available resources for the mother meaning
that the birth rate decreases as population size increases. For density-dependent factors, there is a feedback loop between population density and the density-dependent factor.

An example of density-dependent regulation is shown in Figure 2.4 with results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite of humans and other mammals. Denser populations of the parasite exhibited lower fecundity (fewer eggs). One possible explanation for this is that females would be smaller in more dense populations because of limited resources and smaller females produce fewer eggs.

![Fecundity as a Function of Population](image)

**Figure 2.4**: Graph of fecundity, which is the number of eggs per female, as a function of population size. The number of eggs decreases rapidly at first, then levels off between 30 to 50 worms. In this population of roundworms, fecundity (number of eggs) decreases with population density.

Density-independent birth rates and death rates do NOT depend on population size; these factors are independent of, or not influenced by, population density. Many factors influence population size regardless of the population density, including weather, natural disasters, pollution and other abiotic factors. For example, an individual deer may be killed in a forest fire regardless of how many deer happen to be in the forest. The forest fire is not responding to deer population size. As the weather grows cooler in the winter, many insects die from the cold. This doesn’t change whether there is a population size of 100 mosquitoes or 100,000 mosquitoes, most mosquitoes will die from the cold regardless of the population size and the weather will change irrespective of mosquito population density.

In real-life situations, density-dependent and independent factors interact. For example, a devastating earthquake occurred in Haiti in 2010. This earthquake was a natural geologic event that caused a high human death toll from this density-independent event. Then there were high densities of people in refugee camps and the high density caused disease to spread quickly, representing a density-dependent death rate.
Survivorship Curves

We can compare different species, or populations within the same species, by comparing survivorship curves. Survivorship curves summarize patterns of survival over time. A survivorship curve plots age along the x-axis and number of survivors, or % surviving, along the y-axis. All survivorship curves start along the y-axis intercept with all of the individuals in the population (or 100% of the individuals surviving). As the population ages, individuals die and the curves goes down. A survivorship curve never goes up.

Survivorship curves generally fall into one of three typical shapes, Types I, II and III (Figure 2.5). Organisms that exhibit **Type I** survivorship curves have the highest probability of death in old age. In Type I survivorship curves, juvenile survivorship is high and most mortality (death) occurs during old age. Humans are an example of a species with a Type I survivorship curve. Elephants are another example. Many species that have few offspring and lots of parental care are species with a Type I survivorship curve. Species with **Type III** survivorship patterns have the greatest probability of death at young ages. In Type III survivorship curves, juvenile survivorship is very low and many individuals die young. However, any individuals that make it to maturity are likely to live long time. Dandelions are an example of a species with a Type III survivorship curve. Many frogs also fit this pattern. A female frog may lay hundreds of eggs in a pond and these eggs produce hundreds of tadpoles. However, predators eat many of the young tadpoles and competition for food also means that many tadpoles don’t survive. But the few tadpoles that do survive and metamorphose into adults then live for a relatively long time (for a frog). **Type II** survivorship is intermediate between the others and suggests that such species have an even chance of dying at any age. Many birds and small reptiles, like lizards, have a Type II survivorship curve.
**Figure 2.5:** Survivorship curves show the distribution of individuals in a population according to age. Humans and most mammals have a Type I survivorship curve because death primarily occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive the younger years, but after a certain age, individuals are much more likely to survive.

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This material has been modified from the OpenStax Biology textbook.
Chapter 3: Human demography

By the end of this chapter, you will be able to:

- State the current size of the human population.
- Interpret age-structure diagrams.
- Explain what the demographic transition model represents and describe the societal changes that cause the demographic transition.
- Describe what happens to birth rates, death rates, population growth rate, and population size as a country moves through the stages of the demographic transition model.
- Give examples of countries in the different stages of the demographic transition models and match age-structure diagrams with the stages of the demographic transition model.
- Define life expectancy and explain how it changes as a country moves through the demographic transition model.
- Define fertility and explain how it changes as a country moves through the demographic transition model.

Chapter outline

1. The human population
2. Demography
3. Age structure diagrams
4. The demographic transition model
5. Life expectancy
6. Fertility

You should also read the National Geographic Article: Population 7 billion along with this chapter. http://ngm.nationalgeographic.com/2011/01/seven-billion/kunzig-text

3.1 The human population.

The human population is growing rapidly. For most of human history, there were fewer than 1 billion people on the planet. During the time of the agricultural revolution, 10,000 B.C., there were only 5-10 million people on Earth - which is basically the population of New York City today. In 1800, when the Industrial Revolution began, there were approximately 1 billion people on Earth (Figure 3.1). We’ve added 6 billion people to the human population in just a little over 200 years. This demonstrates the capacity of the human population to exhibit exponential growth (Chapter 2).

What is the current human population? Use this World population clock link to determine the current human population: http://math.berkeley.edu/~galen/popclk.html
Figure 3.1: Shows the increase in human population size starting in 1750 and predicted out to 2050. The orange area represents the human population in industrialized countries and the blue/green area represents the human population in less-industrialized (developing) countries. The greatest amount of human population growth will be in less-industrialized countries.

3.2 Demography
Demography applies the principles of population ecology (chapter 2) to the human population. Demographers study how human populations grow, shrink, and change in terms of age and gender compositions. Demographers also compare populations in different countries or regions.

3.3 Age structure diagrams
One of the tools that demographers use to understand populations is the age structure diagram. This diagram shows the distribution by ages of females and males within a certain population in graphic form. Figure 3.2 shows a diagram for the United States population. In this diagram, the ages are arranged so that age ranges are grouped together, for example: 0 – 4 years, 5 – 9 years, and so on. The population of each group is represented as a bar extending from a central vertical line, with the length of each bar dependent upon the total population for that particular group. The centerline separates the females from the males. The female and male populations for each group are represented by the distance from the centerline, with females on the right and males on the left.
By looking closely at the age structure diagram, one will notice slightly more boys in the younger age groups than girls; however, the ratio tends to reverse in the upper age groups, when females tend to outnumber males. Many countries have a female majority as a result of the longer life expectancy for females.

The following age structure diagrams (Figure 3.3) show the United States in 2005 and 2010. Please note the slightly different x-axes scale on these diagrams compared to the 2000 diagram above (Figure 3.2). You can see the aging group of baby boomers move upward when you compare these 3 age structure diagrams. There are also more elderly (80+) individuals, especially women, in 2005 and 2010.

An age-structure diagram provides a snapshot of the current population and can represent information about the past and give potential clues about future problems. When you are interpreting age-structure diagrams, it is important to compare the width of the base to the rest of the population. If the base is very wide compared to the upper parts of the diagram, then this indicates a lot of young people in the population compared to older generations i.e. a high birth rate and a rapidly growing population. If the base is smaller than the upper parts of the diagram, then this indicates few young people in the population compared to older generations. This population has low birth rates and is shrinking.
3.4 The Demographic Transition Model

The demographic transition model shows the changes in the patterns of birth rates and death rates that typically occur as a country moves through the process of industrialization or development. The demographic transition model was built based on patterns observed in European countries as they were going through industrialization. This model can be applied to other countries, but not all countries or regions fit the model exactly. And the pace or rate at which a country moves through the demographic transition varies among countries.

![Demographic Transition Model Diagram](image)

**Figure 3.4:** The demographic transition model shows how birth rates and death rates change over time as a country becomes more developed. The demographic transition model is typically divided into four stages. The green line represents death rates and the dashed red line represents birth rates.

In the demographic transition model, a country begins in Stage 1, the preindustrial stage. In Stage 1 (Figure 3.4), both birth rates and death rates are high. The high death rates are because of disease and potential food scarcity. A country in Stage 1 of the demographic transition model does not have good health care; there may not be any hospitals or doctors. Children are not vaccinated against common diseases and therefore many children die at a young age. Infant and childhood mortality rates (death rates) are very high. A society in Stage 1 is likely based upon agriculture and most people grow their own food. Therefore, droughts or flood can lead to widespread food shortages and death from famine. All of these factors contribute to the high death rate in Stage 1. Partly to compensate for the high death rates, birth rates are also high. High birth rates mean that families are large and each couple, on average, has many children. When death rates are high, having many children means that at least one or two will live to adulthood. In Stage 1, children are an important part of the family workforce and are expected to work growing food and taking care of the family.

As you are examining the stages of the demographic transition model, remember that:

**Population Growth Rate = Birth Rate – Death Rate**
In Stage 1, birth rates are high, but death rates are high as well. Therefore, population growth rate is low or close to zero (Figure 3.5).

As a country develops, medical advances are made such as access to antibiotics and vaccines. Sanitation improvements, such as proper waste and sewage disposal, and water treatment for clean drinking water also progress. Food production also increases. Together these changes lead to falling death rates which marks the beginning of Stage 2 (Figure 3.4). Death rates continue to fall throughout Stage 2 as conditions improve. This means that people are living longer and childhood mortality drops. However, birth rates are still high in Stage 2. There is a time lag between the improving conditions and any subsequent changes in family size, so women are still having many children and now more of these children are living into adulthood. In Stage 2, the birth rate is higher than the death rate, so population growth rate is high. This means that population size increases greatly during Stage 2 of the demographic transition model (Figure 3.5).

A falling birth rate marks the beginning of Stage 3 in the demographic transition model. As a country continues to industrialize, many women join the workforce. Additionally, raising children becomes more expensive and children no longer work on the family farm or make large economic contributions to the family. Individuals may have access to birth control and choose to have fewer children. This leads to a drop in birth rates and smaller family sizes. Death rates also continue to drop during Stage 3 as medicine, sanitation and food security continue to improve. Even though both birth rates and death rates are falling throughout Stage 3, birth rates are higher than death rates. This means that population growth rate is high and that population size continues to increase in Stage 3 of the demographic transition model (Figure 3.5).

Birth rate and death rates drop to low, stable, approximately equal levels in Stage 4. Death rates are low because of medical advances, good sanitation, clean drinking water and food security. Birth rates are low because of access to birth control and many women delay having their first child until they have worked. Childhood mortality is low, life expectancy is high, and family size is approximately two children per couple. With low birth rates and low death rates, population growth rate is approximately zero in Stage 4 (Figure 3.5).

Figure 3.5: This figure repeats the demographic transition model of Figure 3.4, with the changes in population size (y-axes on the far right) shown by the black line. Population size is low and stable in Stage 1, increases
rapidly in Stage 2 and 3 because birth rates are higher than death rates, and then is high and stable again in Stage 4.

3.5 Life expectancy
Life expectancy is the average number of years that a person in a particular population is expected to live. Life expectancy at birth is the number of years a newborn infant would live if mortality rates at the time of its birth did not change. For example, the life expectancy at birth for someone born in 2014 in Japan is 84.46 years while the life expectancy at birth for someone born in the United States in 2014 is 79.56 years (source: https://www.cia.gov). As a country moves through the demographic transition model, life expectancy increases. Overall, life expectancy has increased for most countries and regions over the past 100 years. However, there is still a significant amount of variation in life expectancy in different regions of the world.

Use this World Health Organization interactive map to compare life expectancy among different countries: http://gamapserver.who.int/gho/interactive_charts/mbd/life_expectancy/atlas.html

What other countries have a life expectancy at birth similar to the United States? List two countries that have a higher life expectancy and two countries that have a lower life expectancy than the United States.

3.6 Fertility
Fertility is the actual level of reproduction of a population per individual, based on the number of live births that occur. Total fertility is the average number of children born to each woman, over the woman’s lifespan, in a population. Birth rate and fertility are closely linked terms. As a country moves through the demographic transition model, fertility rates decrease. Overall, fertility rates have decreased for most countries and regions over the past 50 years (Figure 3.6). However, there is still a significant amount of variation among different regions of the world.
Figure 3.6: Shows the total fertility of different regions of the world. The blue bars are the total fertility estimates from 1950-1955. The red bars are the total fertility estimates from 2010-2015. More developed regions include Europe, Northern America (US and Canada), Australia, New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia. Oceania includes Australia, New Zealand, Melanesia, Micronesia and Polynesia. Data are from the United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects, 2015 Revision. UN http://esa.un.org/unpd/wpp/DVD/
CHAPTER 4: NON-RENEWABLE ENERGY

Chapter outline
4.1 What is Energy?
4.2 Fossil Fuels
4.3 Coal
4.4 Oil
4.5 Natural gas
4.6 Fossil fuels and greenhouse gases
4.7 Nuclear energy

Learning Objectives
By the end of this chapter, students will be able to
  • List specific examples of non-renewable energy sources
  • Explain what makes an energy source non-renewable
  • Describe the main types of fossil fuels and how they formed
  • Explain the environmental impacts associated with exploration, extraction and use of the different types of fossil fuels
  • Explain nuclear energy, how it works, its benefits and risks
4.1 What is Energy?

**Energy** is the ability of a system to do work. A system has done work if it has exerted a force on another system over some distance. When this happens, energy is transferred from one system to another. At least some of the energy is also transformed from one type to another during this process. One can keep track of how much energy transfers into or out of a system. There are two categories that all energy falls into: kinetic and potential. **Kinetic** energy refers to types of energy associated with motion (Figure 4.1, top). For example, a rock rolling down a hill, the wind blowing through trees, water flowing over a dam, and a cyclist riding a bicycle are just a few examples of kinetic energy. **Potential** energy is energy possessed by an object or system due to its position in space relative to another object or system and forces between the two (Figure 4.1, bottom). Examples include a rock poised at the top of a hill and water stored behind a dam. Some forms of energy are part kinetic and part potential energy. **Chemical** energy is the potential of a chemical substance to undergo a transformation through a chemical reaction to transform other chemical substances, hence it is a form of potential energy. Examples include energy stored in the food you eat and the gasoline that you put in your car.

![Examples of different forms of kinetic energy](image1)

![Examples of different forms of potential energy](image2)

**Figure 4.1**: Examples kinetic (top) and potential (bottom) forms of energy. *All images were obtained from Wikimedia commons (public domain).*

Living organisms need energy to perform life-sustaining “work” in order to survive. For nearly all plants and animals living on the Earth’s surface, the sun is the ultimate source of that energy. Over time, we humans have developed an understanding of energy that has allowed us to harness it for uses well beyond basic survival. The development and evolution of human society is attributed to energy. The first major advancement in human understanding of energy
was the mastery of fire for cooking and heating. Modern civilization is especially dependent on energy and some of its most distinct characteristics such as population growth, environmental impact and climate change are all a consequence of energy use. We use energy to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the comforts and conveniences to which we have grown accustomed in the industrial age. Societal complexity, affluence, and the gap between poor and rich peoples are all related to energy.

4.2 Fossil Fuels

Fossil fuels is the term given to energy sources with a high hydrocarbon content, found in the Earth’s crust, that formed in the geologic past and can be burned to release their energy. They were formed from prehistoric plants and animals that lived hundreds of millions of years ago (100 – 500 million years ago). When these ancient living organisms died they were quickly buried and subjected to immense pressure from overlying earth materials including layers of mud, rock, sand, and sometimes surface water bodies such as oceans and lakes.

During the millions of years that passed, the dead plants and animals slowly decomposed in anaerobic (very low to no oxygen) conditions and their chemical energy became concentrated. The organic compounds that once made up tissues of these organisms were chemically changed under high pressures and temperatures. While some fossil fuels may be in the process of formation today, the amount of time required for usable quantities to form is measured in millions of years and these fuels will not ever be available for us. Thus for all practical purposes we consider fossil fuels to be finite and non-renewable.

4.2.1 Fossil Fuel Types and Formation

There are three main types of fossil fuels – natural gas, oil, and coal – and the specific type formed depends on the combination of organic matter that was present, how long it was buried and what temperature and pressure conditions existed when they were decomposing. Oil and natural gas were created from organisms that lived in water and were buried under ocean or river sediments. Long after the great prehistoric seas and rivers vanished, heat, pressure, and bacteria combined to compress and transform the organic material under layers of silt or shale rock (Figure 4.2). In most areas, a thick liquid called oil formed first, but in deeper, hot regions underground, the transformation process continued until natural gas was formed. Over time, some of this oil and natural gas began working its way upward through the earth’s crust until they ran into rock formations called “caprocks” that are dense enough to prevent them from seeping to the surface. It is from under these caprocks in what we call reservoirs that most oil and natural gas is retrieved today.
Coal is a fossil fuel that formed from the remains of trees, ferns, and other plants that lived 300 to 400 million years ago (Figure 4.3). In some areas, such as portions of what is now the eastern United States, coal was formed from swamps covered by sea water. The sea water contained a large amount of sulfur, and as the seas dried up, the sulfur was left behind in the coal. Scientists are working on ways to take the sulfur out of coal because when coal burns, the sulfur is released in to the atmosphere as an air pollutant (see Chapter 6). Some coal deposits, however, were formed from freshwater swamps which had very little sulfur in them. These coal deposits, located largely in the western part of the United States, have much less sulfur in them.

4.2.2 Consumption

Historically, human prosperity has been directly correlated with energy use. The health and vitality of world societies critically depends on energy, most of which comes from fossil fuels (Figure 4.4). Energy resources, however, are unevenly distributed throughout the world, and so are the consumption rates. Developed regions generally consume far more energy than the developing regions. For example, the United States has only about 5% of the world’s population but consumes over 20% of the world’s energy. Additionally, developing countries

Figure 4.2: Oil and natural gas (petroleum) formation. Source: U.S. Energy Information Administration. [http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_home](http://www.eia.gov/energyexplained/index.cfm?page=natural_gas_home)

Figure 4.3: The process of coal formation. Source: U.S. Energy Information Administration.
devote a larger proportion of energy consumption to subsistence activities such as growing and preparing food, and heating homes. Industrialized nations rely more on mechanized equipment and technology and, therefore, a greater proportion of their energy consumption goes to transportation and industry.

Fossil fuels can be utilized in their crude form without being converted or transformed to another form, this is referred to as **primary energy consumption**. In their primary form, these fossil fuels can be used for transportation, heating and cooking, or used to generate electricity. **Electricity** is a secondary energy source that is easier to transfer over long distances and apply to a variety of uses. There are four major sectors that consume energy: 1) The **industrial sector** which includes facilities and equipment used for manufacturing, agriculture, mining, and construction; 2) The **transportation sector** includes vehicles that transport people or goods including cars, trucks, buses, motorcycles, trains, aircraft, boats, barges, and ships; 3) The **residential sector** consists of homes and apartments; 4) The **commercial sector** includes offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, places of worship, and more. Each of these sectors also consumes electricity produced by the electric power sector.

**Figure 4.4**: U.S. primary energy consumption, 2014 showing that about 80% of our energy consumption comes from fossil fuels. Based on data obtained from U.S. Energy Information Administration.

### 4.3 Coal

Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified into four main types, or ranks depending on the types and amounts of carbon present and on the amount of heat energy the coal can produce. These ranks starting from the highest ranked to the lowest ranked are anthracite, bituminous, subbituminous, and lignite (Figure 4.5). The rank of a deposit of coal is determined by the amount of pressure and heat that acted on the plants over time. The greater the heat and pressure, the higher the rank.
4.3.1 Mining, Processing, and Electricity Generation

Surface mining or strip mining involves using large machines to remove the top soil and layers of rock known as overburden to expose the coal seam and is used when the coal is less than 200 feet underground. Mountaintop removal is a form of surface mining where the tops of mountains are blasted with dynamite and removed to access coal seams. After the mining is finished, the disturbed area is covered with topsoil, and the area is replanted.

Underground mining, sometimes called deep mining, is used when the coal is several hundred feet below the surface. Some underground mines are 1,000 feet deep, and extend for miles. Miners ride elevators down deep mine shafts and travel on small trains in long tunnels to get to the coal. The miners use large machines that dig out the coal. Once mined, the coal may go to a preparation plant located near the mining site where it is cleaned and processed to remove rocks and dirt, ash, sulfur, and other unwanted materials. This process increases the amount of energy that can be obtained from a unit of coal (heating value).

After coal is mined and processed, it is transported to the market, which can be more expensive than the cost of mining it. Nearly 70% of coal delivered in the United States is transported, for at least part of its trip to market, by train. Coal can also be transported by barge, ship, truck, and even by pipeline. It is often cheaper to transport coal on river barges, but barges are unable to take coal everywhere it is needed. If the coal is used near the coal mine, it can be moved by trucks and conveyors. Coal can also be crushed, mixed with water, and sent through a slurry pipeline. Sometimes, coal-fired electric power plants are built near coal mines to lower transportation costs.

Once at the power plant, coal is first pulverized into a fine powder then mixed with hot air and blown into a furnace (boiler). Burning in suspension, the coal/air mixture provides the most complete combustion and maximum heat possible. Purified water, pumped through pipes inside a boiler, is turned into steam by the heat from the combustion of coal. The high pressure of the steam pushing against a series of giant turbine blades turns the turbine shaft. The turbine shaft is connected to the shaft of the generator, where magnets spin within wire coils to produce electricity. After doing its work in the turbine, the steam is drawn into a condenser, a large chamber in the basement of the power plant. In this important step, millions of gallons of cool water from a nearby source (such as a river or lake) are pumped through a network of tubes running through the condenser. The cool water in the tubes converts the steam back into water that can be used over and over again in the plant. The cooling water is returned to its source.
without any contamination except at a higher temperature than when first extracted from the river or lake. Figure 4.6 below is a schematic diagram showing a typical layout of a coal-fueled power plant. You can also watch a short video of a virtual tour of a coal power plant at the URL provided below.

https://www.youtube.com/watch?v=2IKECt4Y3RI

Figure 4.6: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Image by US Tennessee Valley Authority – Public domain. www.tva.com

4.3.2 Impacts of coal use
Impact on the environment

A majority of the coal mined in the United States (about 66%) is from surface, or strip mines which leave highly visible impacts at the surface. Strip mining operations generally involve removing soils, rock, and other material to access shallow deposits of coal and therefore
leave permanent scars on the landscape. It also involves the destruction of substantial amounts of forests and other ecosystems, destroying natural habitats and threatening biodiversity.

Mountaintop removal, the extreme form of strip mining, has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. The tops of mountains are removed using a combination of explosives and mining equipment and the material is deposited into nearby valleys. This technique not only alters the landscape (Figure 4.7) but affects the health and quality of nearby streams by depositing rocks, dirt, and pollutants that can harm aquatic wildlife. While mountaintop mining has existed since the 1970s, its use became more widespread and controversial beginning in the 1990s. U.S. laws require that dust and water runoff from areas affected by coal mining operations be controlled, and that the area be reclaimed close to its original condition.

![Figure 4.7: A) Strip mine for lignite coal at Garzweiler near Koln, Germany. Image from Wikimedia commons](https://commons.wikimedia.org/wiki/File:Garzweiler.strip.mine.jpg) B) Mountaintop removal in Eunice WV, photo by Roston, obtained from [https://commons.wikimedia.org/wiki/File:Euniceblast3.JPG](https://commons.wikimedia.org/wiki/File:Euniceblast3.JPG)

The largest environmental impact of **underground mining** may be the methane gas that must be vented out of mines to make the mines a safe place to work. Methane is a strong greenhouse gas, meaning that on an equal-weight basis, its global warming potential is much higher than most other greenhouse gases (see chapter 7). Other impacts include the collapse of the ground above mine tunnels and draining of acidic water from abandoned mines to nearby streams. Acidic water lowers the pH which is detrimental to aquatic organisms. This **acid mine drainage** is an environmental impact associated with both underground mining and strip mining.

In the United States and most of the world, most of the coal consumed is used as a fuel to generate electricity. Burning coal produces emissions such as sulfur dioxide (SO₂), nitrogen oxides (NOₓ) that are associated with acid rain (more on this in chapter 6). Carbon dioxide (CO₂), another emission resulting from burning coal, is a major greenhouse gas that is associated with global warming (see chapter 7).

Fly ash and bottom ash are residues created when coal is burned at power plants. In the past, fly ash was released into the air through the smokestack, but laws now require that much of the fly ash now be captured by pollution control devices, like scrubbers. In the United States, fly
ash is generally stored at coal power plants or placed in landfills. Pollution leaching from ash storage and landfills into groundwater and the rupture of several large impoundments of ash are environmental concerns.

**Impact on human health**

In the United States, most of the coal consumed is used as a fuel to generate electricity. Burning coal produces emissions that impact human health. Emissions such as sulfur dioxide (SO₂), nitrogen oxides (NOₓ) and particulates contribute to respiratory illnesses. Particulates also contribute to a condition among coal miners and other coal workers known as coal workers' pneumoconiosis (CWP) or black lung disease, which results from long exposure to coal dust. Inhaled coal dust progressively builds up in the lungs and is unable to be removed by the body; this leads to inflammation, fibrosis, and in worse cases, tissue death (necrosis).

Coal is the largest source of mercury and also a source of other heavy metals many of which have been linked to both neurological and developmental problems in humans and other animals. Mercury concentrations in the air usually are low and of little direct concern. However, when mercury enters water, either directly or through deposition from the air, biological processes transform it into methylmercury, a highly toxic chemical that accumulates in fish and the animals (including humans) that eat fish.

**4.3.3 Reducing the environmental impacts of coal use**

Regulations such as the Clean Air Act and the Clean Water Act require industries to reduce pollutants released into the air and water. Below are some actions that have been taken to reduce the negative impacts of coal:

- **Industry** has found several ways to reduce sulfur, NOₓ, and other impurities from coal. They have found more effective ways of cleaning coal after it is mined, and coal consumers have shifted toward greater use of low sulfur coal.
- **Power plants** use flue gas desulfurization equipment, also known as *scrubbers*, to clean sulfur from the smoke before it leaves their smokestacks. In addition, industry and the U.S. government have cooperated to develop technologies that can remove impurities from coal or that can make coal more energy-efficient so less needs to be burned.
- **Equipment** intended mainly to reduce SO₂, NOₓ, and particulate matter can also be used to reduce mercury emissions from some types of coal. Scientists are also working on new ways to reduce mercury emissions from coal-burning power plants.
- **Research** is underway to address emissions of carbon dioxide from coal combustion. Carbon capture separates CO₂ from emissions sources and recovers it in a concentrated stream. The CO₂ can then be sequestered, which puts CO₂ into storage, possibly underground, where it will remain permanently (see chapter 7).
- **Reuse and recycling** can also reduce coal’s environmental impact. Land that was previously used for coal mining can be reclaimed and used for airports, landfills, and golf courses. Waste products captured by scrubbers can be used to produce products like cement and synthetic gypsum for wallboard.
4.4 Oil

Oil is currently the most widely used fossil fuel and accounts for about one third of global energy consumption. Crude oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the oil.

Oil is made up of hydrocarbons which are molecules that contain hydrogen and carbon in various lengths and structures, from straight chains to branching chains to rings. Hydrocarbons contain a lot of energy and many of the things derived from crude oil like gasoline, diesel fuel, paraffin wax and so on take advantage of this energy.

4.4.1 Extraction

Oil is mainly obtained by drilling either on land (onshore) or in the ocean (offshore). Early offshore drilling was generally limited to areas where the water was less than 300 feet deep. Oil and natural gas drilling rigs now operate in water as deep as two miles. Floating platforms are used for drilling in deeper waters. These self-propelled vessels are attached to the ocean floor using large cables and anchors. Wells are drilled from these platforms which are also used to lower production equipment to the ocean floor. Wells have been drilled in water depths of 10,000 feet or greater using floating rigs. Some drilling platforms stand on stilt-like legs that are embedded in the ocean floor. These platforms hold all required drilling equipment as well as housing and storage areas for the work crews.

Offshore oil producers are required to take precautions to prevent pollution, spills, and significant changes to the ocean environment. Offshore rigs are designed to withstand hurricanes. Offshore production is much more expensive than land-based production. When offshore oil wells are no longer productive enough to be economical, they are sealed and abandoned according to applicable regulations.

4.4.2 Processing and Refining

When extracted, crude oil consists of many types of hydrocarbons as well as some unwanted substances such as sulfur, nitrogen, oxygen, dissolved metals, and water all mixed together. Unprocessed crude oil is therefore, not generally useful in industrial applications and must first be separated into different useable products at a refinery (Figure 4.8). All refineries perform three basic steps: separation, conversion, and treatment in the processing and refining of crude oil.
During **separation**, the various products (hydrocarbons) are separated into different components (called *fractions*), by taking advantage of the differences in boiling temperature of the components. This process is called **fractional distillation** and involves heating up the crude, letting it vaporize and then condensing the vapor. The lightest components have the lowest boiling temperature and rise to the top while the heaviest, which also have the highest boiling temperature, remain at the bottom.

**Conversion** is the chemical processing in which some of the fractions are transformed into other products, for example, a refinery can turn diesel fuel into gasoline depending on the demand for gasoline. Conversion can involve breaking larger hydrocarbon chains into smaller ones (cracking), combining smaller chains into larger ones (unification) or rearranging the molecules to create desired products (alteration).

**Treatment** is done to the fractions to remove impurities such as sulfur, nitrogen and water among others. Refineries also combine the various fractions (processed and unprocessed) into mixtures to make desired products. For example, different mixtures of hydrocarbon chains can create gasolines with different octane ratings, with and without additives, lubricating oils of various weights and grades (10W-40, 5W-30, etc.), heating oil, and many others. The products are stored on-site until they can be delivered to various markets such as gas stations, airports and chemical plants.

A 42 U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. This increase in volume is similar to what happens to popcorn when it is popped. Gasoline makes up the largest fraction of all petroleum products obtained (Figure 4.9). Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks, waxes, lubricating oils, and asphalt.

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**Figure 4.8**: Tesoro Corporation Oil Refinery in Anacortes, Washington. Photo by Walter Siegmund.  [https://commons.wikimedia.org/wiki/Oil_refinery#/media/File:Anacortes_Refinery_31904.JPG](https://commons.wikimedia.org/wiki/Oil_refinery#/media/File:Anacortes_Refinery_31904.JPG)
4.4.3 Fracking for oil

Hydraulic fracturing, informally referred to as “fracking,” is an oil well development process that typically involves injecting water, sand, and chemicals under high pressure into a bedrock formation via the well. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. Hydraulic fracturing is a well-stimulation technique used commonly in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil flow to a well from petroleum-bearing rock formations (Figure 4.10).

Energy development often requires substantial amounts of water, and hydraulic fracturing is no exception. Water is needed not only for the traditional drilling process, but also for the actual fracturing as well. Water is first mixed with chemicals and fine sands, then pumped at extremely high pressure into the shale rock to fracture it, forming pathways for the oil and gas to reach the well. The water is then recovered, along with the oil and gas.

There are concerns regarding the potential contamination of fresh groundwater resources from oil and gas extraction wells that use hydraulic fracturing; either from the petroleum resource being produced or from the chemicals introduced in the fracturing process. Fracking fluid flowback – the fluid pumped out of the well and separated from oil and gas – not only contains the chemical additives used in the drilling process but also contains heavy metals, radioactive materials, volatile organic compounds (VOCs) and hazardous air pollutants such as benzene, toluene, ethylbenzene and xylene (BTEX). In some cases, this contaminated water is
sent to water treatment plants that are not equipped to deal with some of these classes of contamination.

Figure 4.10: Schematic cross-section of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing. Source: US EPA (Public Domain)

4.4.4 Environmental Impacts of Oil

Burning petroleum products releases emission such as carbon monoxide (CO), sulfur dioxide (SO$_2$), nitrogen oxides (NO$_x$), and particulate material all of which are air pollutants that impact the environment as well as human health (see more on air pollution in Chapter 6). Petroleum also emits carbon dioxide which is a greenhouse gas.

Exploring and drilling for oil may disturb land and ocean habitats. On land, extensive infrastructure such as road networks, transport pipelines and housing for workers are needed to support a full-scale drilling operation. These can pollute soil and water, fragment habitats, and disturb wildlife.

Human-caused oil spills in rivers and oceans harm ecosystems. Natural seeps do occur and may be a significant source of oil that enters the environment globally, but they are slow, small, and spread out over large areas, and the ecosystem has adapted to them. Spills from tankers or well spills have more catastrophic impacts. The quantity of oil spilled during accidents has ranged from a few hundred tons to several hundred thousand tons but even small spills have been shown to have a great impact on ecosystems.

Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin oil slick which can cover beaches with a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill site before most of the oil escapes, and land animals can avoid the oil more easily. The
amount of oil spilled from ships dropped significantly during the 1990s partly because new ships were required to have a "double-hull" lining to protect against spills.

Leaks also happen when we use petroleum products on land. For example, gasoline sometimes drips onto the ground when people are filling their gas tanks, when motor oil gets thrown away after an oil change, or when fuel escapes from a leaky storage tank. When it rains, the spilled products get washed into the gutter and eventually flow to rivers and into the ocean. Another way that oil sometimes gets into water is when fuel is leaked from motorboats and jet skis.

When a leak in a storage tank or pipeline occurs, petroleum products can also get into the ground, and the ground must be cleaned up. To prevent leaks from underground storage tanks, all buried tanks are supposed to be replaced by tanks with a double lining.

4.5 Natural Gas

Crude oil is frequently found in reservoirs along with natural gas. In the past, natural gas was either burned or allowed to escape into the atmosphere. Now, technology has been developed to capture the natural gas and either reinject it into the well or compress it into liquid natural gas (LNG).

Natural gas is predominately composed of methane (CH$_4$). Some of the gases that are produced along with methane, such as butane and propane (by-products), are separated and cleaned at a gas processing plant. The by-products, once removed, are used in a number of ways. For example, propane can be used for cooking on gas grills. Natural gas withdrawn from a well may contain liquid hydrocarbons and nonhydrocarbon gases. This is called "wet" natural gas. The natural gas is separated from these components near the site of the well or at a processing plant. The gas is then considered "dry" and is sent through pipelines to a local distribution company, and, ultimately, to the consumer.

Most of the natural gas consumed in the United States is produced in the United States. Some is imported from Canada and shipped to the United States in pipelines. A small amount of natural gas is shipped to the United States as LNG. We can also use machines called "digesters" that turn today's organic material (plants, animal wastes, etc.) into natural gas. This process replaces waiting for millions of years for the gas to form naturally.

4.5.2 Fracking for Gas

Conventional natural gas is found in permeable reservoirs, typically composed of sandstone or limestone, where extraction is relatively straightforward because the gas generally flows freely. Unconventional gas is found in rocks with extremely low permeability, which makes extracting it much more difficult. Such gas is extracted by employing so called "unconventional" techniques such as hydraulic fracturing (fracking), in which water mixed with sand and other chemicals is pumped underground at a high enough pressure to create and maintain small cracks in the rock. The fracturing operation results in a significant increase in the surface area exposed within the formation – from 1,000 to 100,000 times more. This means that it is possible to access natural gas reserves that could not otherwise have been produced. This process has been applied since the late 1940s.
4.6 Fossil Fuels and Greenhouse Gases

Fossil fuels are made up mainly of hydrogen and carbon. When burned, the carbon combines with oxygen to create CO$_2$. The amount of CO$_2$ produced depends on the carbon content of the fuel. For example, for the same amount of energy produced, natural gas produces about half and petroleum produces about three-fourths of the amount of CO$_2$ produced by coal. Energy-related carbon dioxide (CO$_2$) emissions, resulting from the combustion of coal, petroleum, and natural gas, account for about 80% of total U.S. human-caused (anthropogenic) GHG emissions. There are many sources of non-energy CO$_2$ emissions, but those emissions account for a relatively small share of total GHG emissions. See chapter 7 for a discussion of the results of GHG emissions.

Energy use is largely driven by economic growth and by weather patterns that affect heating and cooling needs. The fuels used in electricity generation also have an impact on the amount of GHG emissions. In the United States, most of the electricity generated comes from coal power plants and consequently, majority of the carbon dioxide emission resulting from electricity generation is from coal combustion (Figure 4.11). Although the industrial sector is the largest consumer of energy (including direct fuel use and purchased electricity), the transportation sector emits more carbon dioxide because of its near complete dependence on petroleum fuels. The residential and commercial sectors have lower emission levels (most of which comes from fossil energy combustion to produce electricity) than the transportation and industry sectors.

![Figure 4.11: A) Major fuel/energy sources for U.S. electricity generation, 2013. B) Resulting carbon dioxide emissions from electricity generation by fuel type, 2013. Based on data from U.S. Energy Information Administration](image)

4.7 Nuclear Energy

Nuclear energy is energy in the nucleus (core) of an atom. There is enormous energy in the bonds that hold protons and neutrons in the nucleus together. Energy is released when those
bonds are broken. Nuclear energy can be released from atoms by splitting apart the nucleus of an atom to form smaller atoms, a process known as **nuclear fission**. During nuclear fission, a small atomic particle called a **neutron** hits the uranium atom and splits it, releasing a great amount of energy in the form of heat and radiation. More neutrons are also released when the uranium atom splits. These neutrons go on to bombard other uranium atoms, and the process repeats itself over and over again. This is called a **chain reaction** (Figure 4.12). Nuclear power plants use the energy from nuclear fission to produce electricity.

![Fission chain reaction](image)

**Figure 4.12**: Fission chain reaction – begins when a neutron bombards a U-235 atom, splitting it into two fission fragments, along with more neutrons and energy. The neutrons bombard other uranium atoms releasing more energy and more neutrons and the reaction continues.

### 4.7.1 Nuclear fuel processing

Uranium is a naturally occurring radioactive element that decays into daughter **isotopes**, releasing radiation energy in the process. There are three naturally occurring isotopes of uranium almost all (99.27 %) of which is uranium-238 (U-238); the remainder consists of U-235 (0.72 %) and U-234 (0.006 percent). **U-235** is the preferred nuclear fuel because when its atoms are split (fissioned), they not only emit heat and high energy radiation but also enough neutrons to maintain a chain reaction and provide energy to power a nuclear power plant. Uranium is found in rocks all over the world but is relatively rare and the supply is finite making it a nonrenewable energy source.
Uranium usually occurs in combination with small amounts of other elements and once it is mined, the U-235 must be extracted and processed before it can be used as a fuel in a nuclear power plant to generate electricity. The process begins with exploration for uranium and the development of mines to extract the discovered ore (ore refers to rock that contains minerals of economic importance). Mining is either conventional (underground or open pit) or unconventional, such as in-place (in-situ) solution mining or heap leaching, which use liquid solvents to dissolve and extract the ore. Mined uranium ore (Figure 4.13 A) typically yields one to four pounds of uranium concentrate per ton of uranium ore (0.05% to 0.20%).

![Figure 4.13: A) Uranium ore B) Yellowcake (U₃O₈). Images obtained from United States Geological Survey (A) and United States Department of Energy (B).](image)

Uranium ore from a conventional mine is usually refined into uranium concentrate in a process referred to as milling. The ore is crushed and ground into fine powder that is then reacted with chemicals to separate the uranium from other minerals. The concentrated uranium product is typically a bright yellow or orange powder called yellowcake (U₃O₈) (Figure 4.13 B), and the waste stream from these operations is called mill tailings. Uranium ore in solution is also milled into yellowcake by retrieving the uranium out of the solution and concentrating it.

The yellowcake then undergoes conversion into uranium hexafluoride (UF₆) gas. This step enables the atomic segregation of the three naturally occurring uranium isotopes into individual components. In the UF₆ gas, the original concentrations of uranium isotopes are still unchanged. This gas is then sent to an enrichment plant where the isotope separation takes place and the concentration of U-235 is increased to about a 4% to 5% (compared to 0.72% original concentration). The product, called enriched UF₆, is sealed in canisters and allowed to cool and solidify before it is transported to a fuel assembly plant.

The next step in the production of nuclear fuel takes place at fuel fabrication facilities. Here, the enriched UF₆ gas is reacted to form a black uranium dioxide (UO₂) powder. The powder is then compressed and formed into the shape of small ceramic fuel pellets (Figure 4.14 A). Each ceramic pellet produces roughly the same amount of energy as 150 gallons of oil. The pellets are stacked and sealed into long metal tubes that are about 1 centimeter in diameter to form fuel rods. (Figure 4.14 B) Fuel rods are then bundled together to make up a fuel assembly (Figure 4.14 C). Depending on the reactor type, there are about 179 to 264 fuel rods in each fuel assembly. A typical reactor core holds 121 to 193 fuel assemblies.
Figure 4.14: Fuel fabrication process. A) Uranium dioxide powder compressed into fuel pellets. B) Fuel pellets stacked and sealed in metal tubes forming fuel rods. C) Fuel rods are bundled into a fuel assembly. Images A and B from NRC (public domain); C from RIA Novosti archive, image #132602 / Ruslan Krivobok / CC-BY-SA 3.0

4.7.2 Nuclear Power Plant

After fabrication, fuel assemblies are transported to nuclear power plants where they are used as a source of energy for generating electricity. They are stored onsite until they are needed by the reactor operators. At this stage, the uranium is only mildly radioactive, and essentially all radiation is contained within the metal tubes. When needed, the fuel is loaded into a reactor core (Figure 4.15). Typically, about one third of the reactor core (40 to 90 fuel assemblies) is changed out every 12 to 24 months.

The most common type of reactors are the pressurized water reactors (PWR) (Figure 4.15) in which water is pumped through the reactor core and heated by the fission process. The water is kept under high pressure inside the reactor so it does not boil. The heated water from the reactor passes through tubes inside the steam generator where the heat is transferred to water flowing around the tubes in the steam generator. The water in the steam generator boils and turns to steam. The steam is piped to the turbines. The force of the expanding steam drives the turbines, which spin a magnet in coil of wire – the generator – to produce electricity.

After passing through the turbines, the steam is converted back to water by circulating it around tubes carrying cooling water in the condenser. The condensed steam – now water – is returned to the steam generators to repeat the cycle.
The three water systems (condenser, steam generator, and reactor) are separate from each other and are not permitted to mix. Water in the reactor is radioactive and is contained within the containment structure whereas water in the steam generator and condenser is nonradioactive.

The second most common type of nuclear reactor is the **boiling water reactor** (BWR). The main difference between a BWR and PWR is that in a BWR, the reactor core heats water, which turns to steam and then drives a steam turbine. In a PWR, the water in the reactor core never boils but instead transfers its heat to water in a steam generator.

![A schematic diagram of a pressurized water reactor (PWR), the most common type of nuclear reactor. Diagram from Tennessee Valley Authority (public domain).](www.tva.com)

**Figure 4.15:**

### 4.7.3 Benefits of Nuclear Energy

By using fission, nuclear power plants generate electricity without emitting air pollutants like those emitted by fossil fuel-fired power plants. This means that financial costs related to chronic health problems caused by air pollutants such as particulate material, carbon monoxide, nitrogen oxides and ozone among others are significantly reduced. In addition nuclear reactors do not produce carbon dioxide while operating which means that nuclear energy does not contribute to the global warming problem.

Another benefit of nuclear energy over fossil fuels especially coal is that uranium generates far more power per unit weight or volume. This means that less of it needs to be mined and consequently the damage to the landscapes is less especially when compared to the damage that results from coal mining such as mountaintop removal.

### 4.7.4 The Drawbacks of Nuclear Energy

The main environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes.
These materials can remain radioactive and dangerous to human health for thousands of years. Radioactive wastes are classified as low-level and high-level. By volume, most of the waste related to the nuclear power industry has a relatively low-level of radioactivity. Uranium mill tailings contain the radioactive element radium, which decays to produce radon, a radioactive gas. Most uranium mill tailings are placed near the processing facility or mill where they come from. Uranium mill tailings are covered with a barrier of material such as clay to prevent radon from escaping into the atmosphere, and they are then covered by a layer of soil, rocks, or other materials to prevent erosion of the sealing barrier.

The other types of low-level radioactive waste are the tools, protective clothing, wiping cloths, and other disposable items that get contaminated with small amounts of radioactive dust or particles at nuclear fuel processing facilities and power plants. These materials are subject to special regulations that govern their handling, storage, and disposal so they will not come in contact with the outside environment.

High-level radioactive waste consists of irradiated or spent nuclear reactor fuel (i.e., fuel that is no longer useful for producing electricity). The spent reactor fuel is in a solid form consisting of small fuel pellets in long metal tubes called rods. Spent reactor fuel assemblies are initially stored in specially designed pools of water, where the water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. There is currently no permanent disposal facility in the United States for high-level nuclear waste.

When a nuclear reactor stops operating, it must be decommissioned. This involves safely removing the reactor and all equipment that has become radioactive from service and reducing radioactivity to a level that permits other uses of the property. The U.S. Nuclear Regulatory Commission has strict rules governing nuclear power plant decommissioning that involve cleanup of radioactively contaminated plant systems and structures, and removal of the radioactive fuel.

An uncontrolled nuclear reaction in a nuclear reactor can potentially result in widespread contamination of air and water. Some serious nuclear and radiation accidents have occurred worldwide. The most severe accident was the Chernobyl accident of 1986 the then Soviet Union (now Ukraine) which killed 31 people directly and sickened or caused cancer in thousands more. The Fukushima Daiichi nuclear disaster (2011) in Japan was caused by a 9.0 magnitude earthquake that shut down power supply and a tsunami that flooded the plant’s emergency power supply. This resulted in the release of radioactivity although it did not directly result in any deaths at the time of the disaster. Another nuclear accident was the Three Mile Island accident (1979) in Pennsylvania, USA. This accident resulted in a near disastrous core meltdown that was due to a combination of human error and mechanical failure but did not result in any deaths and no cancers or otherwise have been found in follow up studies of this accident.

The processes for mining and refining uranium ore and making reactor fuel require large amounts of energy. Nuclear power plants have large amounts of metal and concrete, which also require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore or in constructing the nuclear plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.
Sources


Websites

Nuclear Regulatory Commission [www.nrc.gov](http://www.nrc.gov)

Tennessee Valley Authority [www.tva.com](http://www.tva.com)


U.S. Environmental Protection Agency [www.epa.gov](http://www.epa.gov)

Wikimedia Commons [https://commons.wikimedia.org/wiki/](https://commons.wikimedia.org/wiki/) Source of various photos and images
Chapter 5: Alternative energy
Topics: solar, biofuel, wind and geothermal

Learning outcomes, by the end of this chapter students should be able to.

1. Describe arguments for alternative energy
2. Explain the following aspects of solar energy:
   a. Describe how passive solar energy works and provide examples of its use.
   b. Explain how solar panels (photovoltaic cells) work.
   c. Describe the limitations and environmental costs associated with solar energy.
3. Explain the following aspects of biofuels / biomass energy:
   a. Describe what is meant by the term “carbon neutral” and explain how biomass energy can and cannot be carbon neutral.
   b. Describe current achievements in biofuels and potential of this area for growth.
4. Describe wind energy and explain the advantages and disadvantages.
5. Describe geothermal energy and explain the advantages and disadvantages

ALTERNATIVE ENERGY AND THE ENVIRONMENT

Energy sources that are more or less continuously made available in a time framework useful to people are called renewable energy. Renewable energy sources are often considered alternative sources because, in general, most industrialized countries do not rely on them as their main energy source. Instead, they tend to rely on non-renewable sources such as fossil fuels or nuclear power. Because the energy crisis in the United States during the 1970s, dwindling supplies of fossil fuels and hazards associated with nuclear power, usage of renewable energy sources such as solar energy, hydroelectric, wind, biomass, and geothermal has grown. Renewable energy comes from the sun (considered an "unlimited" supply) or other sources that can theoretically be renewed at least as quickly as they are consumed. If used at a sustainable rate, these sources will be available for consumption for thousands of years or longer. Renewable alternatives derive from wind, water, solar or biomass (Figure 5.1). Note that wind, water and biomass energy sources are indirect sources of solar energy. One limitation currently associated with most forms of renewable energy is that the energy is not concentrated and not easily portable.

Energy is an important ingredient in all phases of society. We live in a very interdependent world, and access to adequate and reliable energy resources is crucial for economic growth and for maintaining the quality of our lives. But current levels of energy consumption and production are not sustainable. The principal energy resources used in the world are shown in Figure 5.2. The fuel mix has changed over the years but now is dominated by oil, although natural gas and solar contributions are increasing. About 85% of our energy comes from nonrenewable fossil fuels. The link between global warming and fossil fuel use, with its production of carbon dioxide through combustion, has made, in the eyes of many scientists, a shift to non-fossil fuels of utmost importance—but it will not be easy. About 40% of the world’s energy comes from oil, and much of that goes to transportation uses.
Figure 5.1 A variety of voltage sources (clockwise from top left): the Brazos Wind Farm in Fluvanna, Texas (credit: Leaflet, Wikimedia Commons); the Krasnoyarsk Dam in Russia (credit: Alex Polezhaev); a solar farm (credit: U.S. Department of Energy); and a group of nickel metal hydride batteries (credit: Tiaa Monto). The voltage output of each depends on its construction and load, and equals emf only if there is no load.

Figure 5.2. World energy consumption by source, in billions of kilowatt-hours: 2006. (credit: KVDP)

The World’s Growing Energy Needs

World energy consumption continues to rise, especially in countries like China where economics is improving (Figure 5.3). Global demand for energy has tripled in the past 50 years and might triple again in the next 30 years. While much of this growth will come from the rapidly booming
In the economies of China and India, many of the developed countries, especially those in Europe, are hoping to meet their energy needs by expanding the use of renewable sources. Although presently only a small percentage, renewable energy is growing very fast, especially wind energy. For example, Germany plans to meet 20% of its electricity and 10% of its overall energy needs with renewable resources by the year 2020 (Figure 5.4). Energy is a key constraint in the rapid economic growth of China and India. In 2003, China surpassed Japan as the world’s second largest consumer of oil. However, over 1/3 of this is imported. Unlike most Western countries, coal dominates the commercial energy resources of China, accounting for 2/3 of its energy consumption. In 2009 China surpassed the United States as the largest generator of CO2. In India, the main energy resources are biomass (wood and dung) and coal. Half of India’s oil is imported. About 70% of India’s electricity is generated by highly polluting coal. Yet there are sizeable strides being made in renewable energy. India has a rapidly growing wind energy base, and it has the largest solar cooking program in the world.

**Figure 5.3.** Past and projected world energy use (source: Based on data from U.S. Energy Information Administration, 2011).
While non-renewable sources dominate, some countries get a sizeable percentage of their electricity from renewable resources. For example, about 67% of New Zealand’s electricity demand is met by hydroelectric. Renewable resources, primarily hydroelectric, generate only 10% of the U.S. electricity.

**SOLAR ENERGY**

Solar energy is the ultimate energy source driving life on earth and many human activities (Figure 5.5). Though only one billionth of the energy that leaves the sun (Figure 5.6) actually reaches the earth's surface, this is a more than enough to meet the world’s energy requirement. In fact, all other sources of energy, renewable and non-renewable, are actually stored forms of solar energy. The process of directly converting solar energy to heat or electricity is considered a renewable energy source. Solar energy represents an essentially unlimited supply of energy as the sun will long outlast human civilization on earth. The difficulties lie in harnessing the energy. Solar energy has been used for centuries to heat homes and water, and modern technology (photovoltaic cells) has provided a way to produce electricity from sunlight.

There are two basic forms of radiant solar energy use: passive and active. **Passive solar energy** systems are static (Figure 5.7), and do not require the input of energy in the form of moving parts or pumping fluids to utilize the sun's energy. Instead passive solar energy uses heating and cooling strategies that have been used historically such as natural ventilation, solar heat gain, solar shading and efficient insulation. Figure Passive Solar Design (Figure 5.7) shows some of these elements. In the winter solar radiation is trapped by the greenhouse effect of south facing windows (north in the southern hemisphere) exposed to full sun. Heat is trapped, absorbed and
stored by materials with high thermal mass (usually bricks or concrete) inside the house. It is released at night when needed to warm up the building as it loses heat to the cooler outdoors. Shading provided by trees or shades keep the sun out in the hot months.

Active solar energy systems require the input of some energy to drive mechanical devices (e.g., solar panels, Figures 5.4 and 5.9), which collect the energy and pump fluids used to store and distribute the energy. Active solar energy systems include photovoltaic cells (solar panels) and solar-electric generating systems. Photovoltaics convert sunlight directly into electricity (Figure 5.5).

Solar electric-generating system utilizes a system of solar collectors (curved mirrors, Figure 5.8) to heat a synthetic oil that flows through a heat exchanger that drives steam turbines.

![Figure 5.5. Mars Observer in Mars Orbit showing the solar panel.](http://www.jpl.nasa.gov/images/spacecraft/marsobserver/craft1-browse.jpg, Wikimedia Commons)

Solar power has minimal impact on the environment, depending on where it is placed. In 2009, one percent of the renewable energy generated in the United States was from solar power (1646 MW) out of the eight percent of the total electricity generation that was from renewable sources. The manufacturing of photovoltaic (PV) cells generates some hazardous waste from the chemicals and solvents used in processing. Often solar arrays are placed on roofs of buildings or
over parking lots or integrated into construction in other ways. However, large systems may be placed on land and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Concentrated solar systems may need to be cleaned regularly with water, which is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations.

Figure 5.6 The Sun photographed at 304 angstroms by the Atmospheric Imaging Assembly (AIA 304) of NASA's Solar Dynamics Observatory (SDO). This is a false-color image of the Sun observed in the extreme ultraviolet region of the spectrum.

http://sdo.gsfc.nasa.gov/assets/img/browse/2010/08/19/20100819_003221_4096_0304.jpg, NASA/SDO (AIA)
Figure 5.7. Passive solar building near Crestone, Colorado. (image wiki Commons)

Figure 5.8. Reflective mirror (concentrating) photovoltaic power system. Concrete block mounts are temporary for this test set to allow access below unit, not necessary for production field installations. The units are oriented with the receiver mount to the south side. Image uploaded
Figure 5.9. a Rooftop Solar Installations Rooftop solar installation on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability; b. 90613-N-7436D-001 NAVAL BASE CORONADO, Calif. (June 13, 2009) Photovoltaic systems at Naval Base Coronado generate 4,112 kilowatt-hours of electricity per day, or more than 1.5 million kwh per year. Photovoltaic systems save the Navy $187,000 annually and reduce the total energy the Navy has to purchase. (U.S. Navy photo/Released)

BIOMASS ENERGY

Biomass energy is from the energy recovered in biomass. This can take a number of forms ranging from direct combustion of wood chips to fermentation of alcohol, which can be mixed with gasoline. Some people are concerned about the prospect of fields of corn being used to produce alcohol at the expense of hungry populations.

Biomass energy is the oldest energy source used by humans. Biomass is the organic matter that composes the tissues of plants and animals. Until the Industrial Revolution prompted a shift to fossil fuels in the mid-18th century, it was the world's dominant fuel source. Biomass can be burned for heating and cooking, and even generating electricity. The most common source of biomass energy is from the burning of wood, but energy can also be generated by burning animal manure (dung), herbaceous plant material (non-wood), peat (partially decomposed plant and animal tissues), or converted biomass such as charcoal (wood that has been partially burned to produce a coal-like substance). Biomass can also be converted into a liquid biofuel such as ethanol or methanol. Currently, about 15 percent of the world's energy comes from biomass.

Biomass is a potentially renewable energy source. Unfortunately, trees that are cut for firewood are frequently not replanted. In order to be used sustainably, one tree must be planted for every one cut down. Biomass is most frequently used as a fuel source in developing nations, but with
the decline of fossil fuel availability and the increase in fossil fuel prices, biomass is increasingly being used as a fuel source in developed nations. One example of biomass energy in developed nations is the burning of municipal solid waste. In the United States, several plants have been constructed to burn urban biomass waste and use the energy to generate electricity.

The use of biomass as a fuel source has serious environmental effects. When harvested trees are not replanted, soil erosion can occur. The loss of photosynthetic activity results in increased amounts of carbon dioxide in the atmosphere and can contribute to global warming. The burning of biomass also produces carbon dioxide and deprives the soil of nutrients it normally would have received from the decomposition of the organic matter. Burning releases particulate matter (such as ash) into the air that can cause respiratory health problems.

**Municipal Solid Waste**

Waste to energy processes are gaining renewed interest as they can solve two problems at once _ disposal of waste as landfill capacity decreases and production of energy from a renewable resource. Many of the environmental impacts are similar to those of a coal plant like air pollution, ash generation, etc. Since the fuel source is less standardized than coal and hazardous materials may be present in municipal solid waste (MSW), or garbage, incinerators and waste-to-energy power plants need to clean the stack gases of harmful materials. The U.S. EPA regulates these plants very strictly and requires anti-pollution devices to be installed. Also, while incinerating at high temperature many of the toxic chemicals may break down into less harmful compounds. If not contained, waste is distributed in many ecosystems.

The ash from these plants may contain high concentrations of various metals that were present in the original waste. If ash is clean enough it can be recycled as an MSW landfill cover or to build roads, cement block and artificial reefs.

Biomass is derived from plants. Examples include lumber mill sawdust, paper mill sludge, yard waste, or oat hulls from an oatmeal processing plant. A major challenge of biomass is determining if it is really a more sustainable option. It often takes energy to make energy and biomass is one example where the processing to make it may not be offset by the energy it produces. For example, biomass combustion may increase or decrease emission of air pollutants depending on the type of biomass and the types of fuels or energy sources that it replaces. Biomass reduces the demand for fossil fuels, but when the plants that are the sources of biomass are grown, a nearly equivalent amount of CO2 is captured through photosynthesis, and thus it recycles the carbon. If these materials are grown and harvested in a sustainable way there can be no net increase in CO2 emissions. Each type of biomass must be evaluated for its full life-cycle impact in order to determine if it is really advancing sustainability and reducing environmental impacts.
Woodchips Photograph shows a pile of woodchips, which are a type of biomass. Source: Ulrichulrich.

**Solid Biomass: Burning Wood**

Using wood, and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower CO2 emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter. For home heating, it is most efficient and least polluting when using a modern wood stove or replace insert that are designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels such as in undeveloped countries, the wood may be harvested faster than trees can grow resulting in deforestation.

Biomass is also being used on a larger scale, where there are small power plants. For instance, Central State Hospital, Milledgeville, GA has a woodchip burning plant (Figure 5.10) that was the most advanced system available for its time and operating today. Colgate College had a wood-burning boiler since the mid-1980's and in one year it processed approximately 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions, and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75 percent of the campus's heat and domestic hot water needs. For more information about this, click here

**Gaseous Biomass: Landfill Gas or Biogas**

Landfill gas and biogas is a sort of man-made biogenic gas. Methane and carbon dioxide are formed as a result of biological processes in sewage treatment plants, waste landfills, anaerobic composting, and livestock manure management systems. This gas is captured, and burned to
produce heat or electricity usually for on-site generation. The electricity may replace electricity produced by burning fossil fuels and result in a net reduction in CO2 emissions. The only environmental impacts are from the construction of the plant itself, similar to that of a natural gas plant.

Liquid Biofuels: Ethanol and Biodiesel

Biofuels may be considered to be **carbon-neutral** because the plants that are used to make them (such as corn and sugarcane for ethanol, and soy beans and palm oil trees for biodiesel) absorb CO2 as they grow and may offset the CO2 produced when biofuels are made and burned. Calculating the net energy or CO2 generated or reduced in the process of producing the biofuel is crucial to determining its environmental impact. Even if the environmental impact is net positive, the economic and social effects of growing plants for fuels need to be considered, since the land, fertilizers, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel vs. food can increase the price of food, which has a negative effect on society. It could also decrease the food supply increasing malnutrition and starvation globally. Biofuels may be derived from parts of plants not used for food (cellulosic biomass) thus reducing that impact. Cellulosic ethanol feedstock includes native prairie grasses, fast growing trees, sawdust, and even waste paper. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugar cane for ethanol and soybeans and palm-oil trees to make biodiesel. This is not sustainable land use.

Biofuels typically replace petroleum and are used to power vehicles. Although ethanol has higher octane and ethanol-gasoline mixtures burn cleaner than pure gasoline, they also are more volatile and thus have higher "evaporative emissions" from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful, ground level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

**Biodiesel** can be made from used vegetable oil and has been produced on a very local basis. Compared to petroleum diesel, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but more nitrogen oxide.

**Biomass growing methods: Vertigro**

(http://www.advancedinergies.com/upload/Algae%20Technologies.pdf, a better alternative).

Vertigro grows its algae in long water-filled, strip-like “baggies” suspended from “hangers” so sunlight can reach both sides of the containers and quicken the algae’s growth rate. The entire system is recyclable: wastewater from algae-production is piped through a treatment system and reused, leftover plant matter from the process is used as feedstock for farm animals or as a natural fertilizer, and oxygen is released.

Vertigo’s fuel, like most biofuels can be used in a regular petrol-driven engine. In the U.S. alone, 1.6 billion gallons of jet fuel are used every month resulting in significant greenhouse gas emissions; however algae-fuel can slow and ultimately stop this trend.
Second Generation Biofuels
Second generation biofuels are shown in Figure Second Generation Biofuels (Figure 5.11). In anticipation of the food versus fuel debate, EISA 2007 placed a cap on the production of corn ethanol (at 15 billion gallons/year, close to what is now produced), with the bulk of biofuels to be derived from agricultural residues such as corn stover (the parts of the corn plant left over from the ears of corn - the stalk and leaves) and wheat straw, forest waste (wood trimmings) and energy crops such as switch grass and short rotation poplar trees which can be grown on abandoned or marginal farmland with minimal irrigation and fertilization.

A U.S. Department of Agriculture study commissioned in 2005 called the Billion Ton Study estimated that approximately one billion tons per year of biomass could be sustainably produced in the United States each year; the energy in this biomass equals to the amount of oil we import. If the energy contained in this biomass can be recovered at an efficiency of 50 percent, we can replace half of our imported oil with domestically produced biofuels.

Collectively termed ‘lignocellulose’ this material consists of three main components; cellulose, hemicellulose, and lignin (Figure 5.11). Chemical or biological pretreatments are required to separate the whole biomass into these fractions. Hemicellulose and cellulose, with the appropriate enzymes or inorganic acids, can be deconstructed into simple sugars and the sugars fermented into ethanol, or with some newer strains of microbes, into butanol. Butanol has only 10% less energy density than gasoline. The lignin fraction of biomass is the most resistant to deconstruction by biological or chemical means and is often burned for heat or power recovery.
At the same time attention turned toward cellulosic ethanol, petroleum refining companies set about to improve biodiesel. A petroleum refining process called hydro treating was used to upgrade plant oil. In this process, the oil is reacted with hydrogen in the presence of inorganic catalysts, and the plant oil is converted into a much higher quality, oxygen-free ‘green diesel’ and jet fuel. This type of biofuel is in fact a ‘drop in replacement’ to petroleum-derived diesel and jet fuel and passes all of the stringent regulations demanded by the automobile and defense industries. It has been tested in a number of commercial and military aircraft.

‘Advanced’ Biofuels
Advanced biofuels are, in fact, characterized by their similarity to present day gasoline, diesel, and jet fuels. Advanced biofuels are infrastructure compatible and energy dense. The two disadvantages with even cellulosic ethanol are its low energy density (the energy content of ethanol being independent of whether it comes from corn, cellulose, etc.) and its incompatibility with existing car engines, oil pipelines, storage tanks, refineries, etc. For these two reasons the latest research and development efforts in the United States have been devoted to hydrocarbon biofuels, which have the same gas mileage as the gasoline and diesel fuels now used, and are completely compatible with the existing oil infrastructure.

![Figure 5.12. Routes to Advanced Biofuels](image-url)

The various routes to drop-in replacement hydrocarbon biofuels are shown in Figure Routes to Advanced Biofuels (Figure 5.12). On the left side of the figure, feedstocks are ordered relative to their abundance and cost. The most abundant and, therefore, cheapest feedstock is lignocellulose from sources such as agricultural residue, forest waste, and energy crops such as...
switch grass and short rotation poplar trees. Of lesser abundance and higher expense are the sugars and starches - corn and sugar cane. The least abundant and most expensive biofuels, lipid-based feedstocks from plant oil or animal fat, are shown at the bottom. Efforts are underway to mass produce oil-laden algae. The oils harvested from algae are relatively easy to convert to hydrocarbon biofuels, by using processing similar to hydrotreating. The main set of problems associated with algae lie in its mass production. Algal feedstocks are easy to convert to hydrocarbons but algae itself is difficult to mass produce, whereas lignocellulose is very abundant but more difficult to convert into hydrocarbons.

WIND POWER

Wind is a renewable energy source that is clean and has very few environmental challenges. Wind turbines are becoming a more prominent sight across the United States, even in regions that are considered to have less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions), and they do not require water for cooling. The U.S. wind industry had 40,181 MW of wind power capacity installed at the end of 2010, with 5,116 MW installed in 2010 alone, providing more than 20 percent of installed wind power around the globe. According to the American Wind Energy Association, over 35 percent of all new electrical generating capacity in the United States since 2006 was due to wind, surpassed only by natural gas.

Most windmills generate about 1kW of electricity, which is only practical for decentralized power generation. California has about 17,000 windmills with a capacity of about 1,400 MW. This is about 80% of all windmills in the U.S. In West Europe windmill generators are quite common.

Since a wind turbine (Figure 5.13) has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop, pasture, forest land, or coastal areas. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian Mountains of the United States instead of engaging in mountain top removal for coal mining.
This wind turbine in the Thames Estuary in the UK is an example of induction at work. Wind pushes the blades of the turbine, spinning a shaft attached to magnets. The magnets spin around a conductive coil, inducing an electric current in the coil, and eventually feeding the electrical grid. (credit: phault, Flickr)

Off shore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land. Wind turbines do have a few environmental challenges. There are aesthetic concerns to some people when they see them on the landscape. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Some people do not like the sound that wind turbine blades make.

Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path. This is of particular concern if these are threatened or endangered species. There are ways to mitigate that impact and it is currently being researched.

There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations. However, overall life cycle analysis has found that turbines make much more energy than the amount used to make and install them.

**GEOTHERMAL ENERGY**

Geothermal energy is using heat energy the Earth’s surface or sub-surface. Geothermal energy uses heat from the Earth’s internal geologic processes in order to produce electricity or provide heating. The subsurface temperature of the Earth provides an endless energy resource. The
environmental impact of geothermal energy depends on how it is being used. Direct use and heating applications have almost no negative impact on the environment. One source of geothermal energy is steam. Groundwater percolates down through cracks in the subsurface rocks until it reaches rocks heated by underlying magma, and the heat converts the water to steam. Sometimes this steam makes its way back to the surface in the form of a geyser or hot spring. Wells can be dug to tap the steam reservoir and bring it to the surface, to drive generating turbines and produce electricity (Figure 5.14). Hot water can be circulated to heat buildings. Regions near tectonic plate boundaries have the best potential for geothermal activity.

Figure 5.14. Installing a Geothermal Pipe System Drilling to install geothermal ground source pipe system. Source: Office of Sustainability
A geothermal system requires heat, permeability, and water. The heat from the Earth’s core continuously flows outward. Sometimes the heat, as magma, reaches the surface as lava, but it usually remains below the Earth's crust, heating nearby rock and water — sometimes to levels as hot as 700°F. When water is heated by the earth’s heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. Geothermal energy can be used for electricity production, for commercial, industrial, and residential direct heating purposes, and for efficient home heating and cooling through geothermal heat pumps. To develop electricity from geothermal resources, wells are drilled into a geothermal reservoir. The wells bring the geothermal water to the surface, where its heat energy is converted into electricity at a geothermal power plant. Geothermal power plants do not burn fuel to generate electricity so their emission levels are very low. They release less than one percent of the carbon dioxide emissions of a fossil fuel plant. Geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97 percent less acid rain-causing sulfur compounds than are emitted by fossil fuel plants. After the steam and water from a geothermal reservoir have been used, they are injected back into the earth.

Geothermal ground source systems utilize a heat-exchange system that runs in the subsurface about 20 feet (5 meters) below the surface where the ground is at a constant temperature. The system uses the earth as a heat source (in the winter) or a heat sink (in the summer). This reduces the energy consumption requires to generate heat from gas, steam, hot water, and chiller and conventional electric air-conditioning systems. The western portion of the United States is most conducive for geothermal energy sources, and over half of the electricity used by the city of San Francisco comes from the Geysers, a natural geothermal field in Northern California. California produces about 50 percent of the world's electricity that comes from geothermal sources. Entire cities in Iceland, which is located in a volcanically active region near a mid-ocean ridge, are heated by geothermal energy. The Rift Valley region of East Africa also has geothermal power plants. Geothermal energy may not always be renewable in a particular region if the steam is withdrawn at a rate faster than it can be replenished, or if the heating source cools off. The energy produced by the Geysers region of California is already in decline because the heavy use is causing the underground heat source to cool. Geothermal energy recovery can be less environmentally invasive than engaging in recovery methods for non-renewable energy sources. Although it is relatively environmentally friendly, it is not practical for all situations. Only limited geographic regions are capable of producing geothermal energy that is economically viable. Therefore, it will probably never become a major source of energy.

Geothermal heat pumps are a very attractive, cost efficient sustainable energy source for both small-scale heating and cooling with a minimal carbon print. It is a well-developed technology that can be easily incorporated into both residential and commercial buildings at either the design stage or by retrofitting buildings.

There are two major types of geothermal heat pump systems: in ground and pond systems. In ground geothermal systems can be vertical or horizontal (Figure 5.15). The excavation cost of vertical systems is generally higher and they require more land area for installation, which is generally not an option in urban locations. Other than excavation costs, vertical and horizontal GHPs have similar efficiencies since the ground temperature below the frost line is essentially constant.
Figure 5.15. In Ground Geothermal Systems Examples of horizontal and vertical ground systems. Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy

Pond geothermal systems are generally preferable if there is water available in the vicinity at almost constant temperature year round. These systems are especially suited to industrial units (e.g. oil refineries) with water treatment facilities to treat processed water before it is discharged. The temperature of treated water from these facilities is essentially constant throughout the year and is an ideal location for a pond system. Pond geothermal systems are constructed with either open loops or closed loops (see Figure Pond Geothermal Systems (Figure 5.16)). Open loop systems actually remove water from the pond, while the close loop systems only remove energy in the form of heat from the pond water. Of course, in open pond system this water is again returned to the pond, albeit at a lower temperature when used for heating.
OTHER ALTERNATIVE RENEWABLE ENERGY SOURCES

HYDROGEN

Hydrogen gas may be an important fuel in the future. It is a clean fuel. The byproduct of hydrogen combustion is water. It is a concentrated form of energy that can be transported. It can be produced by passing an electric current through water to decompose the water molecule into oxygen and hydrogen, a process known as electrolysis (Figure 5.17). Hydrogen can also be produced from hydrocarbons, including natural gas. The nation of Iceland is attempting to become the first hydrogen based energy economy using its abundant geothermal energy resources.
Figure 5.17 The National Spherical Torus Experiment (NSTX) has a fusion reactor in which hydrogen isotopes undergo fusion to produce helium. In this process, a relatively small mass of fuel is converted into a large amount of energy. (credit: Princeton Plasma Physics Laboratory)

WATER POWER

Hydroelectric power uses the water stored behind dams. In the U.S., hydroelectric plants account for about 10% of total production.

Figure 5.18. a. Hydroelectric facility (credit: Denis Belevich, Wikimedia Commons); b. Hoover Power Plant View of Hoover Power Plant on the Colorado River as seen from above. Source: U.S. Department of the Interior.
Hydropower (hydro-electric) is considered a clean and renewable source of energy since it does not directly produce emissions of air pollutants and the source of power is regenerated. However, hydropower dams, reservoirs, and the operation of generators can have environmental impacts. Figure Hoover Power Plant (Figure 5.18) shows the Hoover Power Plant located on the Colorado River. Hydropower provides 35 percent of the United States’ renewable energy consumption (see Figure U.S. Energy Consumption by Energy Source, 2009. Water moved massive turbines that transport electrical power (Figure 5.19)). In 2003 capacity was at 96,000 MW and it was estimated that 30,000 MW capacity is undeveloped.

Figure 5.19. Hydroelectric generators at the Hoover dam. (credit: Jon Sullivan)

Energy produced can be calculated and modeled (Figure 5.20)
Figure 5.20. (a) Water gushes from the base of the Studen Kladenetz dam in Bulgaria. (credit: Kiril Kapustin; http://www.ImagesFromBulgaria.com) (b) In the absence of significant resistance, water flows from the reservoir with the same speed it would have if it fell the distance $h$ without friction.
Hydroelectric power has a number of environmental costs. For example, fish migrations are disrupted. Another cost is the loss of scenic rivers. A dam that is used to create a reservoir or to divert water to a run-of-river hydropower plant can obstruct migration of fish to their upstream spawning areas. A reservoir and operation of the dam can affect the natural water habitat due to changes in water temperatures, chemistry, flow characteristics, and silt loads, all of which can lead to significant changes in the ecology and physical characteristics of the river upstream and downstream. Construction of reservoirs may cause natural areas, farms, and archeological sites to be covered and force populations to relocate. Hydro turbines kill and injure some of the fish that pass through the turbine although there are ways to reduce that effect. In areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon, the dams get in the way.

This problem can be partially alleviated by using ‘fish ladders’ that help the salmon get up the dams. Carbon dioxide and methane may also form in reservoirs where water is more stagnant and be emitted to the atmosphere. The exact amount of greenhouse gases produced from hydropower plant reservoirs is uncertain. If the reservoirs are located in tropical and temperate regions, including the United States, those emissions may be equal to or greater than the greenhouse effect of the carbon dioxide emissions from an equivalent amount of electricity generated with fossil fuels (EIA, 2011 (p. 333)).

**FUEL CELLS**

Fuel cells are highly efficient power plants that produce electricity by combining fuel and oxygen in an electrochemical reaction. Energy is synthesized by an exothermic electrochemical reaction that combines hydrogen and oxygen ions through an electrolyte material to generate electricity and heat. Hydrogen is the most common fuel type. The reaction is essentially the opposite that of electrolysis. Experimental fuel cells have been developed that can power automobiles.

**ELECTRIC CARS**

Electric cars are vehicles that solely depend on electricity to work. They have to be charged with fossil fuel source energy (Figure 5.21), but they are very efficient. Although it might seem like science fiction the electric car is already here, and has been here for the last hundred years. The main problem with the electric car is that it cannot go very far before it needs to be recharged, something that takes between three to six hours. Different models have been explored (Figure 5.22), but for now most cars are equipped as a hybrid with a back up reservoir using fossil fuels.
TIDAL POWER

Tidal power can be harnessed in several ways. In areas of extreme tide range, such as the Bay of Fundy, which has a 15 m tide, a dam constructed across the estuary would let water enter on the incoming tide, then release the water through turbines at low tide. The energy potential is great http://www.ialtenergy.com/tidal-power-news.html, and so is the environmental cost. Though proposed, a tidal power plant has not been constructed at Fundy. There is a 240,000 kW tidal plant at La Rance, France.

POLICY AND CONSERVATION

CONSERVING ENERGY

As we finish this chapter on energy and work, it is relevant to draw some distinctions between two sometimes misunderstood terms in the area of energy use. As has been mentioned elsewhere, the “law of the conservation of energy” is a very useful principle in analyzing physical processes. It is a statement that cannot be proven from basic principles, but is a very good bookkeeping device, and no exceptions have ever been found. It states that the total amount of energy in an isolated system will always remain constant. Related to this principle, but remarkably different from it, is the important philosophy of energy conservation. This concept has to do with seeking to decrease the amount of energy used by an individual or group through (1) reduced activities (e.g., turning down thermostats, driving fewer kilometers) and/or (2) increasing conversion efficiencies in the performance of a particular task—such as developing and using more efficient room heaters, cars that have greater miles-per-gallon ratings, energy efficient compact fluorescent lights, etc. Since energy in an isolated system is not destroyed or created or generated, one might wonder why we need to be concerned about our energy resources, since energy is a conserved quantity. The problem is that the final result of most energy transformations is waste heat transfer to the environment and conversion to energy forms no longer useful for doing work. To state it in another way, the potential for energy to produce useful work has been “degraded” in the energy transformation.
A rational energy policy should encourage research by private industry and should provide funding for basic research, ensure fair access to alternative energy sources, encourages the internalization of external cost of fossil fuel energy, and promotes the dissemination of information about the costs and benefits of alternative energy sources.

**Figure 5.22.** 1985 Mercedes-Benz/Alpha Real "Tour de Sol" Solarmobile; built for the 1985 Tour de Sol Centennial Rally, solar car race from Lake Constance to Lake Geneva.

**Questions:**

1. Describe three major environmental challenges for fossil fuels in general or one in particular.
2. Rate the following electricity sources for their contribution to climate change from most to least: biomass, coal, solar, wind, nuclear, natural gas, oil, geothermal, hydroelectric, MSW. Is there any compelling reason not to use any of the carbon neutral (no net carbon emissions) sources?
3. Describe the environmental and social concerns with regard to biofuels.

**In class activities:** Design a sustainable city of the future

**Websites for more information and further discussion**


For a video presentation on the different ways to use geothermal energy, visit [http://geothermal.marin.org/video/vid_pt5.html](http://geothermal.marin.org/video/vid_pt5.html)
Are Electric Vehicles Better for the Environment than Gas-Powered Ones?

http://www.technologyreview.com/view/517146/are-electric-vehicles-better-for-the-environment-than-gas-powered-ones/

See excel file with terminology introduced in this chapter.
Chapter 6: Air pollution

Emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. Image from National Parks Service (Public Domain).

Learning Objectives:
By the end of this chapter, students will be able to
• Describe the composition and structure of the atmosphere.
• Explain the importance of the ozone layer, its depletion, and specific steps taken to address it.
• Distinguish between indoor and outdoor air pollution and how these compare among industrialized and less industrialized countries
• Identify natural and anthropogenic sources of air pollution
• Explain the effects of air pollution on human and ecosystem health
• Explain how the Clean Air Act legislation works and describe its outcomes

Chapter Outline

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6.1 Composition and Structure of the Atmosphere

Atmosphere refers to the layer of gases that surrounds Earth and is held in place by Earth’s gravitational attraction (gravity). The mix of gases in the atmosphere forms a complex system organized into layers that together support life on Earth. Although there are numerous gases, as shown in Table 6.1, the top four gases make up 99.998% of the volume of clean dry air (unpolluted air that does not contain water vapor). Of this dry composition of the atmosphere nitrogen, by far, is the most common (78%). Nitrogen dilutes oxygen and prevents rapid or instantaneous burning at the Earth’s surface, as oxygen gas is a necessary reactant of the combustion process. Nitrogen is also needed and used by living things to make proteins, though as nitrogen gas, N₂, it is unavailable to most living things. Oxygen is used by all living things to make molecules that are essential for life. It is also essential for aerobic respiration as well as combustion or burning. Argon is a non-reactive gas and we use it in light bulbs, in double-pane windows, and to preserve priceless documents such as the original Declaration of Independence and the Constitution. Carbon dioxide is an essential gas used by plants and other organisms to make sugar (food) through photosynthesis. This process is essential for other life as well because during photosynthesis, water molecules are split apart and their oxygen is released back to the atmosphere. Carbon dioxide also acts as a blanket that prevents the escape of heat into outer space (see more on this in Chapter 7). The atmosphere is rarely, if ever, completely dry. Water vapor (water in a ‘gas’ state) is usually present up to about 4% of the total volume depending on location. In the Earth’s desert regions (30° N/S) when dry winds are blowing, the water vapor contribution to the composition of the atmosphere will be near zero.

Table 6.1: Average composition of clean dry air in the lower atmosphere

<table>
<thead>
<tr>
<th>Gas</th>
<th>Symbol</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>78.08%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>20.95%</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.93%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>0.03%</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>18.20 parts per million</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>5.20 parts per million</td>
</tr>
<tr>
<td>Krypton</td>
<td>Kr</td>
<td>1.10 parts per million</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>SO₂</td>
<td>1.00 parts per million</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>2.00 parts per million</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>0.50 parts per million</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O</td>
<td>0.50 parts per million</td>
</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>0.09 parts per million</td>
</tr>
<tr>
<td>Ozone</td>
<td>O₃</td>
<td>0.07 parts per million</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>NO₂</td>
<td>0.02 parts per million</td>
</tr>
<tr>
<td>Iodine</td>
<td>I₂</td>
<td>0.01 parts per million</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>Trace</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>Trace</td>
</tr>
</tbody>
</table>


Earth’s atmosphere is divided into four distinct layers based on thermal characteristics (temperature changes), chemical composition, movement, and density (Figure 6.1). The troposphere is the lowest layer extending from the surface up to roughly 18 km above the surface depending on location (varies from as low
as 6 km to as high as 20 km). There is continuous flow and swirling of air constantly through convection currents redistributing heat and moisture around the globe. This results in the short-lived and local patterns of temperature and moisture that we call **weather**. Because gravity holds most air molecules close to the Earth’s surface, the troposphere is the densest of all layers, containing about 75% of the total mass of the atmosphere. The density of the gases in this layer decrease with height so the air becomes thinner. In response, the temperature in the troposphere also decreases with height. As one climbs higher, the temperature drops from an average around 17°C (62°F) at sea level to about -51°C (-60°F) at the **tropopause**, a sharp boundary at the top of the troposphere that limits mixing between the troposphere and the upper layers.

![Figure 6.1: An average temperature profile through the lower layers of the atmosphere. Height (in miles and kilometers) is indicated along each side. Source: National Weather Service http://www.srh.noaa.gov/jetstream/atmos/atmprofile.htm](http://www.srh.noaa.gov/jetstream/atmos/atmprofile.htm)
The **stratosphere** is the layer that extends from the tropopause up to about 50 km to 53 km above the Earth’s surface depending on location. The proportions of most gases in this layer is similar to that of the troposphere with two main exceptions: 1) there is almost no water vapor in the stratosphere and 2) the stratosphere has nearly 1,000 times more ozone (O\textsubscript{3}) than the troposphere. With only about 19% of the total mass of the atmosphere, the density of the stratosphere is significantly lower than the troposphere. However, temperature in this region increases with height as a result of heat that is produced during the formation of ozone (more on ozone in section 6.2). This heat is responsible for temperature increases from an average -51 °C (-60°F) at tropopause to a maximum of about -15°C (5°F) at the top of the stratosphere. This increase in temperature with height means warmer air is located above cooler air. This prevents "convection" as there is no upward vertical movement of the gases. The consequence of this little to no mixing of gases in the stratosphere makes it relatively calm but also means that once substances such as pollutants enter this zone, they can remain suspended for many years. The top of the stratosphere is bound by a boundary known as the **stratopause**.

Above the stratosphere is the **mesosphere** which extends to about 85 km above the Earth's surface. The mesosphere has no ozone molecules and the other gases such as oxygen and nitrogen continue to become less dense with height. As a result, not much ultraviolet and x-ray radiation from the sun is absorbed by molecules in this layer so temperature decreases with altitude. Both the stratosphere and the mesosphere are considered the middle atmosphere.

Between about 85 km and 600 km lies the **thermosphere**. This layer is known as the upper atmosphere. Unlike the mesosphere, the gases in this layer readily absorb incoming high energy ultraviolet and x-ray radiation from the sun. Because of this absorption, the temperature in the thermosphere increases with height and can reach as high as 2,000°C (3,600°F) near the top depending on solar activity. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin due to the very thin atmosphere. The high temperature indicates the amount of energy absorbed by molecules but with so few in this layer, the total number of molecules is not enough to heat our skin. There’s no sharp boundary that marks the end of the atmosphere. Pressure and density simply continue to decrease with distance until they become indistinguishable from the near-vacuum of outer space.

### 6.2 Ozone

Ozone (O\textsubscript{3}) is a molecule in which three atoms of oxygen are bonded together. The oxygen gas in the air we breathe has two oxygen atoms bonded together (O\textsubscript{2}). Ozone is relatively unstable and releases its third oxygen atom readily so it oxidizes and burns things more readily than oxygen gas. This characteristic makes ozone in the troposphere (ground-level ozone) an air pollutant (see section 6.3) but in the stratosphere, ozone is essential for protecting life on Earth. Ozone in the stratosphere is formed when an oxygen molecule (O\textsubscript{2}) is broken apart into two separate oxygen atoms (O) by high-energy ultraviolet (UV) solar radiation. Each of the resulting oxygen atoms (O) in turn reacts with an oxygen molecule (O\textsubscript{2}) creating ozone (O\textsubscript{3}) (Figure 6.2). Once produced, ozone can absorb UV radiation breaking the molecule to regenerate an oxygen molecule and a single oxygen atom. So, while ozone is continually being replenished, it is also continually being destroyed. If the rate of ozone creation is equal to the rate of destruction, the total amount will remain the same. Because there is so much oxygen in our atmosphere, this “ozone-oxygen cycle” is continuously absorbing UV radiation.
6.2.1 The Ozone Layer

Ozone makes up a very small proportion of the gases in our atmosphere and most of it is concentrated in a portion of the stratosphere roughly 17 – 30 km above the surface. This region, called the ozone layer, acts as a protective shield that protects life on the surface of the Earth by absorbing most of the harmful portions of the high-energy UV radiation coming from the sun. UV is subdivided into three types namely UV-A, UV-B, and UV-C (Figure 6.3). Of these three types, UV-A is the least energetic and least harmful but can cause some damage to living cells, resulting in sunburns and skin damage. UV-A is also not absorbed by ozone in the stratosphere and is therefore transmitted through the atmosphere to the surface of the Earth. UV-C is the most harmful and most energetic of all UV, but is strongly absorbed in both the thermosphere and the stratosphere and does not make it to the Earth’s surface. UV-C is the one responsible for the splitting of oxygen molecules in the stratosphere that leads to the formation of ozone. When ozone absorbs UV it regenerates oxygen atoms and releases heat which warms the upper part of the stratosphere. Since UV-C does not make it to the Earth’s surface, the most harmful form of UV radiation that reaches the surface is UV-B. However, the amount of UV-B that reaches Earth’s surface is significantly reduced because most of it is absorbed by ozone in the stratosphere. Ozone is the only known gas that absorbs UV-B.

Natural conditions in the stratosphere sustain a dynamic balance between the creation and destruction of ozone which helps to ensure the continued existence of the ozone layer. Any disruption of this balance that results in a higher rate of ozone destruction than ozone creation would result in depletion of ozone. Ozone depletion, consequently, leads to significant increase in the amount of harmful UV-B radiation that reaches the Earth’s surface and this what we are talking about when we discuss the ozone problem.
6.2.2 The Ozone Hole

The Ozone Hole is not really a “hole” but rather an area where the thickness of the ozone layer is greatly reduced. This hole is a result of ozone depletion that occurs every year during the Antarctic spring (Figure 6.4) and was first reported to the public by the British Antarctic Survey in 1985. The thickness of the ozone layer above the Antarctic continued to decline while the geographic area covered by the ozone hole continued to increase, reaching its lowest concentration (thickness) in 1994 and largest geographic area in 2000. Recent data shows that ozone concentration globally and in the Arctic and Antarctic is no longer declining.

During the long winter months of darkness over the Antarctic, atmospheric temperatures drop, creating unique conditions for chemical reactions that are not found anywhere else in the atmosphere. During this time, the Antarctic air mass is isolated from the rest of the atmosphere and circulates around the pole in what is known as the polar vortex. This isolation allows temperatures to drop low enough to create ice crystals at high altitudes. Ozone, nitric acid, sulfuric acid and other chlorine containing molecules are absorbed on the surfaces of these ice particles. When the sun rises over the Antarctic in the southern spring (October), light rapidly releases free chlorine atoms into the stratosphere. The chlorine atoms react with ozone breaking it down to molecular oxygen and an oxygen atom. The polar vortex keeps the ozone-depleted air inside the vortex from mixing with the undepleted air outside the vortex, hence the formation of an ozone hole.
6.2.3 Ozone Depletion

Global ozone concentrations change periodically with regular natural cycles such as changing seasons, winds, and long time scale sun variations. Concentrations of ozone in the atmosphere are measured in parts per billion (ppb). Scientists have been measuring ozone since the 1920’s using ground-based instruments that look skyward. Satellite measurements of concentrations of atmospheric ozone began in 1970 and continue today.

Ozone depletion occurs when the rate at which ozone is broken down is greater than the rate of its creation, interfering with the dynamic balance between creation and destruction that maintains the ozone layer. When this happens, the amount of harmful UV-B radiation that reaches the Earth’s surface increases. Ozone depletion was first identified over the Antarctic. Scientists suggested that reactions involving man-made chlorine-containing compounds were responsible for depleting ozone in the stratosphere. This hypothesis was based mostly on the physical and chemical properties of these compounds and knowledge about atmospheric conditions.

Chlorofluorocarbons (CFCs) are man-made compounds made up of chlorine, fluorine and carbon. These compounds were commonly used as propellants in everyday products such as shaving cream, hair spray, deodorants, paints and insecticides and as coolants in refrigerators and air conditioners. CFCs are extremely stable molecules and do not react with other chemicals in the lower atmosphere, part of the reason why they were considered a safe choice. Their stability means that they tend to remain in the atmosphere for a very long time. With the constant movement of air in the lower atmosphere, CFCs eventually make their way into the stratosphere. Exposure to ultraviolet radiation in the stratosphere breaks them apart, releasing chlorine atoms. Free chlorine (Cl) atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide (ClO) and leaving an oxygen molecule (O$_2$) (Figure 6.5). The ClO reacts with other atoms freeing up the Cl making it available to react with another ozone molecule, repeating the cycle over and over resulting in ozone depletion.

**Figure 6.4:** Ozone concentrations over the Antarctic region for four months representing the four seasons. Ozone concentration drops significantly during the Antarctic spring (October). *Source:* www.nasa.gov
Figure 6.5: Ozone destruction. UV radiation frees a chlorine (Cl) atom from a CFC molecule, this atom reacts with ozone and produces an oxygen gas molecule and chlorine monoxide (ClO). ClO reacts with another oxygen atom, it frees up the Cl atom which then proceeds to destroy another ozone molecule. Source: Wiki commons https://commons.wikimedia.org/wiki/Category:Ozone#/media/File:Chlorine_catalysis.GIF

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy another ozone molecule. These two reactions happen over and over again, so that a single atom of chlorine, acting as a catalyst, destroys many molecules (about 100,000) of ozone. The consequence of stratospheric ozone depletion is increased levels of UV-B radiation reaching the Earth’s surface, posing a threat to human health and the environment. Figure 6.6 shows a lower than average amount of stratospheric ozone over North America in 1997 when it was abnormally cold compared to 1984, which was warmer than average, showing that ozone depletion does not exclusively affect just the South Pole (Antarctic).

Figure 6.6: Seasonal ozone depletion over North America was lower in 1984 and greater in 1997. Source: NASA http://earthobservatory.nasa.gov/IOTD/view.php?id=1771
6.2.4 The Montreal Protocol

International policy efforts to restrict production of ozone depleting CFCs culminated in the 1987 treaty known as the Montreal Protocol in which signing nations agreed to cut CFC production in half by 1998. At least five follow-up agreements since then helped to deepen the cuts, advanced timetables for compliance, and addressed additional ozone-depleting substances such as halons, methyl chloroform, carbon tetrachloride, and hydrochlorofluorocarbons (HCFCs). Most countries around the world have phased out production of the substances covered by the agreements and industry has been able to shift to safer alternative chemicals. As a result, there’s evidence that the Antarctic ozone hole has stopped growing worse, although recovery is not expected anytime soon. Phasing out CFCs and HCFCs is also beneficial in protecting the earth’s climate, as these substances are also very damaging greenhouse gases.

As part of the United States' commitment to implementing the Montreal Protocol, the U.S. Congress amended the Clean Air Act (section 6.7), adding provisions for protection of the ozone layer. Most importantly, the amended Act required the gradual end to the production of chemicals that deplete the ozone layer. The Clean Air Act amendments passed by Congress requires the Environmental Protection Agency (EPA) to develop and implement regulations for the responsible management of ozone-depleting substances in the United States. Under the Clean Air Act, EPA has created several regulatory programs to address numerous issues, including:

- ending the production of ozone-depleting substances,
- ensuring that refrigerants and halon fire extinguishing agents are recycled properly,
- identifying safe and effective alternatives to ozone-depleting substances,
- banning the release of ozone-depleting refrigerants during the service, maintenance, and disposal of air conditioners and other refrigeration equipment,
- requiring that manufacturers label products either containing or made with the most harmful ozone depleting substances.

6.3 Outdoor Air Pollution

Air pollution refers to the introduction, into the atmosphere, of substances that have harmful effects on humans, other living organisms, and the environment either as solid particles, liquid droplets or gases. Air pollution can result from natural processes such as dust storms, forest fires, and volcanic eruptions, or from human activities such as biomass burning, vehicular emissions, mining, agriculture, and industrial processes. Improved technology and government policies have helped reduce most types of outdoor air pollution in many industrialized countries including the United States, in recent decades. However, outdoor air quality is still a problem in less industrialized nations, especially in megacities of rapidly industrializing nations such as China and India.

Outdoor pollutants can come from stationary (point) sources or mobile (nonpoint) sources (Figure 6.7). Stationary sources have a fixed location, for example power plant smokestacks, burning, construction sites, farmlands and surface mines among others. Mobile sources of air pollutants move from place to place while emitting pollutants. Examples of mobile sources include vehicles, aircrafts, ships, and trains.
Pollutants are categorized into two major types based on how they originated namely primary and secondary pollutants. **Primary pollutants** are those released directly from the source into the air in a harmful form. The primary pollutants that account for nearly all air pollution problems are carbon monoxide (58%), volatile organic compounds (VOCs, 11%), nitrogen oxides (15%), sulfur dioxides (13%), and particulate material (3%). **Secondary pollutants** are produced through reactions between primary pollutants and normal atmospheric compounds. For example, ground-level ozone forms over urban areas through reactions, powered by sunlight, between primary pollutants (oxides of nitrogen) and other atmospheric gases such as VOCs.

### 6.3.1 Criteria pollutants

Under the Clean Air Act (see section 6.7.1), the Environmental Protection Agency (EPA) establishes air quality standards to protect public health and the environment. EPA has set national air quality standards for six common air pollutants namely: 1) carbon monoxide; 2) ground-level ozone; 3) nitrogen dioxide; 4) sulfur dioxide; 5) lead; and 6) particulate matter (also known as particle pollution). Of the six pollutants, particulate pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called primary standards. Another set of limits intended to prevent environmental and property damage is called secondary standards.

1. **Carbon Monoxide (CO):** is a colorless, odorless gas emitted from combustion processes, specifically, the incomplete combustion of fuel. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
2. **Ground-level ozone** \((O_3)\): is a colorless gas with a slightly sweet odor that is not emitted directly into the air, but is created by the interaction of sunlight, heat, oxides of nitrogen \((NO_x)\) and volatile organic compounds \((VOCs)\). Ozone is likely to reach unhealthy levels on hot sunny days in urban environments. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO\(_x\) and VOCs.

3. **Nitrogen dioxide** \((NO_2)\): is one of a group of highly reactive gases known as "oxides of nitrogen," or "nitrogen oxides \((NO_x)\)." Other nitrogen oxides include nitrous acid and nitric acid. NO\(_2\) is a yellowish-brown to reddish-brown foul-smelling gas that is a major contributor to smog and acid rain. Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Most emissions in the U.S. result from combustion in vehicle engines, electrical utility, and industrial combustion.

4. **Sulfur dioxide** \((SO_2)\): Sulfur dioxide is one of a group of highly reactive gases known as "oxides of sulfur." The largest sources of SO\(_2\) emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO\(_2\) emissions include industrial processes such as extracting metals from their ores, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment.

5. **Lead** \((Pb)\): is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in motor vehicles (such as cars and trucks) and industrial sources. As a result of EPA's regulatory efforts to remove lead from gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent during that time period. The major sources of lead emissions today are ore and metal processing and piston-engine aircraft operating on leaded aviation gasoline. Today, the highest levels of lead in air are usually found near lead smelters.

6. **Particulate material** \((PM)\), sometimes known simply as **particulates** refers to solid particles and liquid droplets suspended in the air we breathe. Particulate pollution is made up of a variety of components, including acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (pollen and mold spores). The size of the particles in directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller generally pass through the throat and nose and enter the lungs. EPA groups these into two types: "inhalable coarse particles," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "fine particles," with diameters that are 2.5 micrometers and smaller. How small is 2.5 micrometers? Think about a single hair from your head. The average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle (Figure 6.8). Our respiratory systems are equipped to filter larger particles out of the air once it is inhaled. However, the lungs are vulnerable to both coarse particles \((PM_{10})\), and fine particles \((PM_{2.5})\). These can slip past the respiratory system's natural defenses and get deep into the lungs and some may even get into the bloodstream. Coarse particles come from road dust while fine particles come from combustion processes.
Figure 6.8: Graphic showing size comparison of particulate material (PM\textsubscript{10} and PM\textsubscript{2.5}) compared to fine beach sand and human hair. Source: US EPA [http://www.epa.gov/air/particlepollution/basic.html](http://www.epa.gov/air/particlepollution/basic.html)

6.3.2 Volatile Organic Compounds

Volatile organic compounds (VOCs) are carbon-containing chemicals emitted as gases from natural and human-made sources. Natural sources of VOCs include plants, the largest source, and bacteria in the guts of termites and ruminant animals. These compounds are generally oxidized to carbon monoxide and carbon dioxide in the atmosphere. VOCs are of great concern because they are precursors for the formation of ozone, a secondary air pollutant.

A large number of synthetic organic chemicals such as benzene, toluene, formaldehyde, vinyl chloride, chloroform, and phenols are widely used as ingredients in countless household products. Paints, paint strippers, varnishes, many cleaning, disinfecting, cosmetic, degreasing, and hobby products all contain VOCs. Fuels are also made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored. The “new car smell” characteristic of new cars is from a complex mix of dozens of VOC. Also, concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. They are often held responsible for sick building syndrome, an illness resulting from indoor pollution in which the specific cause is not identified.

6.3.3 Smog

Smog is a mixture of air pollutants (sulfur dioxide, nitrogen oxides, ozone, and particulates) that often form over urban areas as a result of fossil fuel combustion. The term was coined from the terms “smoke” and “fog” referring to a brownish haze that pollutes the air, greatly reducing visibility and making it difficult for some people to breathe (Figure 6.9 and 6.10). There are two main types of smog: industrial and photochemical smog. **Industrial smog** is produced primarily by the burning of fossil fuels which produces carbon dioxide (from complete combustion), carbon monoxides (from partial
combustion), sulfur, and mercury. The sulfur reacts with other chemicals in the atmosphere producing several sulfur compounds including sulfur dioxide. These compounds along with particulate material make up industrial smog. **Photochemical smog** is formed when sunlight drives chemical reactions between primary pollutants from automobiles and normal atmospheric compounds. The product is a mix of over 100 different chemicals with the most abundant being ground-level ozone.

Figure 6.9: Smog over Almaty city, Kazakhstan. Photo by Igors Jefimovs. **Source**: Wikicommons [https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Smog_over_Almaty.jpg](https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Smog_over_Almaty.jpg)

Figure 6.10: Smog over Santiago in Chile. **Source**: German Wikipedia [https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Santiago30std.jpg](https://commons.wikimedia.org/wiki/Category:Smog#/media/File:Santiago30std.jpg)

### 6.3.4 Toxic pollutants

Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples of toxic air pollutants include benzene, which is found in gasoline; perchloroethylene, which is emitted from some dry cleaning facilities; methylene chloride, which is used as a solvent and paint stripper by a number of industries; and others such as dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as volcanic eruptions and forest fires. Exposure to air toxics is mainly through breathing but some toxic air pollutants such as mercury can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals and are eventually magnified up through the food chain. Like humans, animals may experience health problems if exposed to sufficiently high quantities of air toxics over time.

### 6.4 Indoor Air Pollution

In both developed and developing nations, indoor air pollution poses a greater health risk than outdoor air pollution. According to the World Health Organization (WHO) and other agencies such as the Environmental Protection Agency (EPA), indoor air generally contains higher concentrations of toxic pollutants than outdoor air. Additionally, people generally spend more time indoors than outdoors,
hence, the health effects from indoor air pollution in workplaces, schools, and homes are far greater than outdoor. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home.

Outdoor air enters and leaves a building by infiltration, natural ventilation, and mechanical ventilation. In infiltration, outdoor air flows into the house through openings, joints, and cracks in walls, floors, and ceilings, and around windows and doors. In natural ventilation, air moves through open windows and doors. Air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. Finally, there are a number of mechanical ventilation devices, from outdoor-vented fans that intermittently remove air from a single room, such as bathrooms and kitchen, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the house. The rate at which outdoor air replaces indoor air is described as the air exchange rate. When there is little infiltration, natural ventilation, or mechanical ventilation, the air exchange rate is low and pollutant levels can increase. High temperature and humidity levels can also increase concentrations of some pollutants.

There are many sources of indoor air pollution in any home (Figure 6.11). These include combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; building materials and furnishings as diverse as deteriorated, asbestos-containing insulation, wet or damp carpet, and cabinetry or furniture made of certain pressed wood products; products for household cleaning and maintenance, personal care, or hobbies; central heating and cooling systems and humidification devices. Pollutants causing indoor air pollution can also originate from outside sources such as radon, pesticides, and outdoor air pollution. Radon is a naturally occurring radioactive gas produced from the decay of uranium in rock. If a building/home is constructed in an area with uranium containing rock, the gas can seep through the foundations and accumulate in basements. Exposure to radon can cause lung cancer.

The relative importance of any single source depends on how much of a given pollutant it emits and how hazardous those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more carbon monoxide than one that is properly adjusted. Some sources, such as building materials, furnishings, and household products like air fresheners, release pollutants more or less continuously. Other sources, related to activities carried out in the home, release pollutants intermittently. These include smoking, the use of unvented or malfunctioning stoves, furnaces, or space heaters, the use of solvents in cleaning and hobby activities, the use of paint strippers in redecorating activities, and the use of cleaning products and pesticides in house-keeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

Risks from indoor air pollution differ between less industrialized and industrialized nations. Indoor pollution has a greater impact in less industrialized nations where many people use cheaper sources of fuel such as wood, charcoal, and crop waste among others for cooking and heating, often with little or no ventilation. The most significant indoor pollutant, therefore, is soot and carbon monoxide. In industrialized nations, the primary indoor air health risks are cigarette smoke and radon.
6.5 Effects of Air Pollution on Human Health

The World Health Organization (WHO) and other international agencies recognize air pollution as a major threat to human health. Numerous scientific studies have linked air pollution to a variety of health problems (Table 6.2) including: aggravation of respiratory and cardiovascular diseases; decreased lung function; increased frequency and severity of respiratory symptoms such as difficulty breathing and coughing; increased susceptibility to respiratory infections; effects on the nervous system, including the brain, such as IQ loss and impacts on learning, memory, and behavior; cancer; and premature death. Immediate effects of air pollution may show up after a single exposure or repeated exposures. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure.

Immediate effects of air pollution include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution, if it can be
identified. Symptoms of some diseases, including asthma, hypersensitivity pneumonitis, and humidifier fever, may also show up soon after exposure to some indoor air pollutants.

Table 6.2: Sources and health effects of criteria pollutants

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Sources</th>
<th>Health Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-level Ozone (O₃)</td>
<td>Secondary pollutant typically formed by chemical reaction of volatile organic compounds (VOCs) and NOₓ in the presence of sunlight.</td>
<td>Decreases lung function and causes respiratory symptoms, such as coughing and shortness of breath; aggravates asthma and other lung diseases leading to increased medication use, hospital admissions, emergency department (ED) visits, and premature mortality.</td>
</tr>
<tr>
<td>Particulate Matter (PM)</td>
<td>Emitted or formed through chemical reactions; fuel combustion (e.g., burning coal, wood, diesel); industrial processes; agriculture (plowing, field burning); and unpaved roads.</td>
<td>Short-term exposures can aggravate heart or lung diseases leading to respiratory symptoms, increased medication use, hospital admissions, ED visits, and premature mortality; long-term exposures can lead to the development of heart or lung disease and premature mortality.</td>
</tr>
<tr>
<td>Lead</td>
<td>Smelters (metal refineries) and other metal industries; combustion of leaded gasoline in piston engine aircraft; waste incinerators; and battery manufacturing.</td>
<td>Damages the developing nervous system, resulting in IQ loss and impacts on learning, memory, and behavior in children. Cardiovascular and renal effects in adults and early effects related to anemia.</td>
</tr>
<tr>
<td>Oxides of Nitrogen (NOₓ)</td>
<td>Fuel combustion (e.g., electric utilities, industrial boilers, and vehicles) and wood burning.</td>
<td>Aggravate lung diseases leading to respiratory symptoms, hospital admissions, and ED visits; increased susceptibility to respiratory infection.</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>Fuel combustion (especially vehicles), industrial processes, fires, waste combustion, and residential wood burning.</td>
<td>Reduces the amount of oxygen reaching the body’s organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms leading to hospital admissions and ED visits.</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>Fuel combustion (especially high-sulfur coal); electric utilities and industrial processes; and natural sources such as volcanoes.</td>
<td>Aggravates asthma and increased respiratory symptoms. Contributes to particle formation with associated health effects.</td>
</tr>
</tbody>
</table>

Source: [www.epa.gov](http://www.epa.gov)

The likelihood of immediate reactions to air pollutants depends on several factors. Age and preexisting medical conditions are two important influences. Some sensitive individuals appear to be at greater risk for air pollution-related health effects, for example, those with pre-existing heart and lung diseases (e.g., heart failure/ischemic heart disease, asthma, emphysema, and chronic bronchitis), diabetics, older adults, and children. In other cases, whether a person reacts to a pollutant depends on individual sensitivity, which varies tremendously from person to person. Some people can become sensitized to biological pollutants after repeated exposures, and it appears that some people can become sensitized to chemical pollutants as well.
6.6 Acid Rain

Pure rainfall is slightly acidic, pH 5.6, because water reacts with atmospheric carbon dioxide to produce weak carbonic acid. When higher than normal amounts of nitric and sulfuric acid occur in the atmosphere, the result is precipitation with a pH below 5.6 which is referred to as acid rain. Acid rain includes both wet deposition (rainfall, snow, fog) and dry deposition (particulates). Acid rain formation result from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO\textsubscript{2}) and nitrogen oxides (NO\textsubscript{x}) resulting from fossil fuel combustion. In the United States, roughly $\frac{2}{3}$ of all SO\textsubscript{2} and $\frac{1}{4}$ of all NO\textsubscript{x} come from electric power generation that relies on burning fossil fuels, like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds (Figure 6.12). The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles. Regions of greatest acidification tend to be downwind from heavily industrialized source areas of pollution.

![Figure 6.12: Formation of acid rain from both natural and anthropogenic pollutants](http://www.epa.gov/acidrain/images/origins.gif)

Acid rain is a serious environmental problem that is particularly damaging to lakes, streams, and forests and the plants and animals that live in these ecosystems, as well as to infrastructure. Some of the impacts include:

- Leaching of soil nutrients such as calcium, magnesium, and potassium out of the topsoil, altering soil chemistry and harming plants and soil organisms.
- Acid rain causes the release of substances that are toxic to trees and other plants, such as aluminum, into the soil. Scientists hypothesize that this combination of loss of soil nutrients and increase of
toxic aluminum may be one way that acid rain harms trees (Figure 6.13). Such substances also wash away in the runoff and are carried into streams, rivers, and lakes.

- Damage to automotive paints and other coatings. The reported damage typically occurs on horizontal surfaces and appears as irregularly shaped, permanently etched areas.
- Acidic particles contribute to the corrosion of metals (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones) (Figure 6.14).
- Sulfates and nitrates that form in the atmosphere contribute to visibility impairment, meaning we cannot see as far or as clearly through the air. Sulfate particles account for 50 to 70 percent of the visibility reduction in the eastern part of the U.S., affecting our enjoyment of national parks, such as the Shenandoah and the Great Smoky Mountains.

6.7 Air Pollution Legislation

In 1930, 63 people died and 1000 were sickened in Belgium when a phenomenon referred to as temperature inversion caused pollutants to be trapped near the surface, leading to a sudden spike in atmospheric sulfur levels. In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. The cloud which lingered for five days, killed 20 people and caused sickness in 6,000 of the town’s 14,000 people. In 1952, the infamous London fog in which acid aerosols trapped in the lower atmosphere killed 4000 people. Events like these alerted us to the dangers that air pollution poses to public health.

6.7.1 Clean Air Act

In the United States, several federal and state laws were passed, including the original Clean Air Act of 1963, which established funding for the study and cleanup of air pollution. But there was no comprehensive federal response to address air pollution until Congress passed a much stronger Clean Air Act in 1970. That same year Congress created the Environmental Protection Agency (EPA) and
gave it the primary role in carrying out the law. Since 1970, EPA has been responsible for a variety of Clean Air Act programs to reduce air pollution nationwide. The Clean Air Act is a federal law covering the entire country. However, states, tribes and local governments do a lot of the work to meet the Act’s requirements. For example, representatives from these agencies work with companies to reduce air pollution. They also review and approve permit applications for industries or chemical processes.

6.7.2 EPA’s Role

EPA's mission is basic health and environmental protection from air pollution for all Americans. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that focus on:

- reducing outdoor, or ambient, concentrations of air pollutants that cause smog, haze, acid rain, and other problems;
- reducing emissions of toxic air pollutants that are known to, or are suspected of, causing cancer or other serious health effects; and
- phasing out production and use of chemicals that destroy stratospheric ozone.

Under the Clean Air Act, EPA sets limits on certain air pollutants, including setting limits on how much can be in the air anywhere in the United States. The Clean Air Act also gives EPA the authority to limit emissions of air pollutants coming from sources like chemical plants, utilities, and steel mills. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits than those set by EPA. EPA must approve state, tribal, and local agency plans for reducing air pollution. If a plan does not meet the necessary requirements, EPA can issue sanctions against the state and, if necessary, take over enforcing the Clean Air Act in that area. EPA assists state, tribal, and local agencies by providing research, expert studies, engineering designs, and funding to support clean air progress. Since 1970, Congress and the EPA have provided several billion dollars to the states, local agencies, and tribal nations to accomplish this.

6.7.3 State and Local Governments' Role

It makes sense for state and local air pollution agencies to take the lead in carrying out the Clean Air Act. They are able to develop solutions for pollution problems that require special understanding of local industries, geography, housing, and travel patterns, as well as other factors. State, local, and tribal governments also monitor air quality, inspect facilities under their jurisdictions and enforce Clean Air Act regulations. States have to develop State Implementation Plans (SIPs) that outline how each state will control air pollution under the Clean Air Act. A SIP is a collection of the regulations, programs and policies that a state will use to clean up polluted areas. The states must involve the public and industries through hearings and opportunities to comment on the development of each state plan.

6.7.4 Outcomes of the Clean Air Act

For more than forty years, the Clean Air Act has cut pollution as the U.S. economy has grown. The combined emissions of the six criteria pollutants has continued to decrease while population, gross domestic product, energy consumption, and vehicle miles travelled have all continued to increase (Figure 6.14). The following is a summary of some of the accomplishments of the Clean Air Act:

- Clean Air Act programs have lowered levels of the six criteria pollutants - particulates, ozone, lead, carbon monoxide, nitrogen dioxide and sulfur dioxide - as well as numerous toxic pollutants.
Figure 6.14: Showing a decrease in the combined emissions for the six criterial pollutants in the past two decades. Meanwhile, population, energy consumption, vehicle miles travelled, and gross domestic product have all increased. **Source:** US EPA

- From 1970 to 2012, aggregate national emissions of the six common pollutants alone dropped an average of 72 percent while gross domestic product grew by 219 percent (Figure 6.14). This progress reflects efforts by state, local and tribal governments; EPA; private sector companies; environmental groups and others.
- The emissions reductions have led to dramatic improvements in the quality of the air that we breathe.
- These air quality improvements have enabled many areas of the country to meet national air quality standards set to protect public health and the environment. For example, all of the 41 areas that had unhealthy levels of carbon monoxide in 1991 now have levels that meet the health-based national air quality standard. A key reason is that the motor vehicle fleet is much cleaner because of Clean Air Act emissions standards for new motor vehicles.
- Airborne lead pollution, a widespread health concern before EPA phased out lead in motor vehicle gasoline under Clean Air Act authority, now meets national air quality standards in most areas of the country.
Sources


Websites
Wikimedia Commons https://commons.wikimedia.org/wiki/ Source of various photos and images
Environmental Protection Agency http://www.epa.gov/
National Aeronautics and Space Administration (NASA) http://www.nasa.gov/
National Weather Service http://www.srh.noaa.gov/jetstream/atmos/layers.htm
The Carbon Cycle

**Carbon**, just like all other elements, cycles through the environment and is constantly in the process of changing forms and locations. In this section, as in many other pieces of scientific literature, we will periodically refer to carbon by its chemical symbol, C. There is no new carbon in the world, rather, all carbon is continuously recycled from one form to another. All plants, animals (including humans!), fungi, bacteria, and archaea are made of mostly carbon-based molecules such as lipids, carbohydrates, proteins, and nucleic acids. Carbon is also prevalent in soils, rocks and sediments, water bodies (dissolved), and the atmosphere. These locations where carbon resides are known as pools or **reservoirs**, and the processes that move carbon from one location to another are called **fluxes**. Figure 7.1 shows a simplified version of the global carbon cycle.

![Figure 7.1](image-url)

**Figure 7.1**: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.
Some reservoirs hold on to carbon for only a short time. Aerobic (oxygen-using) organisms convert carbohydrates created by other organisms into carbon dioxide (CO₂) almost instantaneously, which they exhale into the atmosphere. When considering the flux of respiration, living organisms are the source of carbon, and the atmosphere is the sink. The carbon stays in the reservoir of living organisms for a relatively short time, depending on their life span, from hours and days to years and decades. In contrast, the residence time of carbon in the fossil pool is dramatically different. Fossil fuels form over a course of 300-400 million years, forming from ancient plants and animals that decomposed slowly under very specific, anaerobic (without oxygen) conditions in wetland environments. Their bodies were gradually transformed by the heat and pressure of the Earth’s crust into the fossil fuels that we mine today to provide petroleum oil, natural gas, and coal (see more on this in chapter 4).

Reservoirs and fluxes of importance
The two largest reservoirs of carbon on Earth are the oceans, which cover the majority of Earth’s surface, and the lithosphere (the mineral fraction of Earth: soils, rocks, and sediments). Each of these reservoirs holds more carbon than all of the other reservoirs combined. Much of the carbon stored in these reservoirs, especially deep in the lithosphere or in deep ocean environments, has an extremely long residence time, and does not actively participate in rapid fluxes. The notable exceptions here, of course, are fossil fuels, which are mined by humans and converted into gaseous forms of carbon through combustion.

Biomass, which is biological material derived from living, or recently living organisms, is a much smaller reservoir of carbon. The amount of carbon stored in all of the terrestrial vegetation (550 Gt C) (Gt = gigatonne = 10⁹ metric tons = 10¹⁵ g) is just a fraction of that stored in the oceans (38,000 Gt C) and lithosphere (18,000 Gt C). All of the carbon that is currently stored in all of the vegetation on Earth got there through the process of photosynthesis. Plants and other photosynthetic organisms are called primary producers, because they “fix” atmospheric CO₂ into organic carbon, such as sugar, a form that is usable by animals and other organisms that need to consume their carbon molecules.

Photosynthetic organisms, such as plants, algae, and cyanobacteria, bring in CO₂ from the atmosphere and, using energy from the sun, convert CO₂ and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (Equation 7.1). These glucose molecules are simple sugars that autotrophs (“self-feeders”) can “burn” for energy, or transform into other usable carbon molecules through the process of cellular respiration (described in the next paragraph), or to build plant biomass. Photosynthesis takes place in organelles called chloroplasts, shown in Figure 7.2. Photosynthesis accounts for 123 Gt of C per year that is removed from the atmosphere and stored in plant biomass. Such a massive amount of
photosynthesis occurs on Earth that no other single flux moves as much carbon in the same timeframe.

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} \ + \text{solar energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]  \hspace{1cm} \text{Eq. 7.1}

**Figure 7.2:** Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll \(a\) they contain, and are the site of photosynthesis. Chlorophyll \(a\) is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) *Closterium moniliferum* Ralfs, (Chlorophyta) green coccoid algae; b) *Botryococcus braunii* Kützing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

Biomass in the carbon cycle, including plants and animals, is the reservoir of carbon that we are most likely most familiar with, and also the reservoir that is most readily available to us. We all participate in the flux of consumption of carbon when we eat food. All of our food is simply plant and/or animal biomass. Our body takes the carbon molecules contained in this biomass, and uses them, along with the oxygen we breathe in, for cellular respiration to create the adenosine triphosphate (ATP) we need for energy. The products of cellular respiration include the CO\(_2\) we exhale, water, and energy that is stored in ATP (Equation 7.2). Our bodies also builds additional biomass out of the carbon molecules in this food, allowing us to create new cells for growth or replenishment. This is the only way we, and all other heterotrophs (“other-eaters”), can bring in the carbon we need to build and maintain our bodies. Remember, you are what you eat!

\[ \text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{energy} \]  \hspace{1cm} \text{Eq. 7.2}
Cellular respiration is an important flux in the carbon cycle, and one that contributes carbon to the atmosphere. Remember that animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through their food. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO$_2$ through photosynthesis. Any carbon molecules that are left over after the organism has acquired sufficient energy through cellular respiration make up the biomass of the plant. As plants and animals die and decompose, their bodies are consumed by decomposer organisms such as fungi and bacteria. Through the flux of decomposition, some decaying biomass is converted into atmospheric carbon by the decomposers, while most of the biomass is buried into the soil, contributing to soil carbon. In oxygen-rich environments, decomposers rapidly consume dead and decaying biomass using the same process of aerobic cellular respiration described above. In oxygen-deficient environments, decomposers complete other metabolic pathways, and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include methane (CH$_4$), nitrous oxide (N$_2$O), and the foul-smelling hydrogen sulfide (H$_2$S).

The biomass reservoir of the carbon cycle is also important to us as a source of energy. Through the flux of combustion, we convert the potential energy held in biomass into heat energy that we can use, and release carbon dioxide in the process. If you have ever burned logs on a campfire, or even burned food on the stove, you have completed this flux of biomass combustion. Of course, this happens naturally as well, the best example being natural forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration. The difference is that in cellular respiration, energy is released in a controlled fashion, and captured in ATP molecules. In combustion, all of this energy is released rapidly in the form of light and heat.

As all of the fluxes we’ve discussed so far involve the atmosphere, we have not yet discussed the flux that connects the atmosphere to the oceans. Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae (also called phytoplankton in Figure 7.1), and second through the chemical reaction of ocean-atmosphere exchange. The ocean, as with all surface water bodies, always contains some dissolved CO$_2$. This CO$_2$ is in equilibrium with the CO$_2$ in the air. Some atmospheric CO$_2$ is constantly dissolving into the ocean, while some dissolved CO$_2$ is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in Figure 7.1, however, this is no longer the case. In the section Human impacts on the carbon cycle, we will discuss why this is the case.

Activity: Better understanding the carbon cycle
To further review the carbon cycle, and better understand the human impacts on it, use this interactive graphic from Woods Hole laboratories: http://www.whoi.edu/feature/carboncycle/. As you will see, the information described in this text is only a small portion of the total carbon cycle on Earth. Finally, complete Table 7.1 as a way to review the sink/source relationship
within this cycle. See if you can correctly identify the source and sink of carbon for each of these important fluxes in the carbon cycle.

Table 7.1. Practice understanding the sink/source relationship with cycles

<table>
<thead>
<tr>
<th>Carbon flux</th>
<th>Carbon source</th>
<th>Carbon sink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular respiration</td>
<td>Carbohydrates in living organisms</td>
<td>CO₂ in the atmosphere</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decomposition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean/atmosphere exchange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel formation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Human impacts on the carbon cycle
Humans, just like all other living organisms, have impacted the global carbon cycle since the dawn of our species. However, the magnitude of our impacts has changed dramatically throughout history. The **Industrial Revolution**, which occurred around the turn of the 19th century, began to make major changes in the use of resources around the world. Beginning in Britain, industrialization eventually affected the whole world. The development of coal-fueled steam power, and later transportation following the discovery of large oil deposits, had enormous influence on the economic and social structure of the world. As the world accelerated in the production and transportation of manufactured goods, the production and consumption of fossil fuels grew. As economic growth continued to increase, so did the production of carbon dioxide.
through fossil fuel combustion. See Figure 7.4 later in this text.

Some of the human impacts on the carbon cycle have been quantified for you in Figure 7.1. Changes to fluxes in the carbon cycle that humans are responsible for include: increased contribution of CO\(_2\) and other greenhouse gases to the atmosphere through the combustion of fossil fuels and biomass; increased contribution of CO\(_2\) to the atmosphere due to land-use changes; increased CO\(_2\) dissolving into the ocean through ocean-atmosphere exchange; and increased terrestrial photosynthesis. The first two impacts, both contributing excess CO\(_2\) to the atmosphere at a rate of 4 Gt of carbon per year have, by far, the largest impact on our planet. For this reason, this is the change that we will most often focus on throughout this section. The excess CO\(_2\) in the atmosphere is responsible for the increased CO\(_2\) dissolving into the ocean, which we will discuss later in this section. This is also, in part, responsible for the increased terrestrial photosynthesis that can be observed, as additional CO\(_2\) is available to plants for photosynthesis. However, intensive agricultural and forestry practices also contribute to the change in this flux.

One characteristic example of a human impact on the carbon cycle is illustrated in Figure 7.3. Throughout most of our recent human history, people have been physically altering the landscape around them in order to have more control over their surroundings and increase their odds of survival. One way that people have done this is through agriculture. In order for most forms of agriculture to be successful, native vegetation is eliminated or minimized. Resources from this native vegetation, such as wood, may be used for combustion to provide heat, sanitation, or fuel for cooking. Combustion may also be used as an efficient way to clear the land and make way for crops or grazing lands for livestock. Often, settlements are formed around these newly fashioned agricultural fields, and the land is used in a similar fashion for many years in the future.

Let’s identify the ways in which humans are impacting the carbon cycle in this scenario of agricultural establishment. You should be able to identify from the above paragraph that the flux of combustion will release CO\(_2\) previously held in vegetation into the atmosphere. In addition, remember that the land that used to house native vegetation is now home to agricultural lands. In most controlled agricultural environments, there is less total vegetative biomass than there would be under natural conditions. This decreased biomass leads to lower total photosynthesis rates, thereby decreasing the amount of CO\(_2\) that is removed from the atmosphere and turned into plant biomass. Also, open soil on the fields between crops, during the winter months, or as a result of overgrazing allows for the air to penetrate deep into the soil structure. This provides the environment necessary for enhanced aerobic respiration by soil microorganisms. This decreases soil carbon, which can lead to erosion and soil degradation, and also releases additional CO\(_2\) to the atmosphere.
As you learned in Chapter 5, biomass is an important form of energy to human civilization. Prior to the Industrial Revolution, this was essentially the only form of fuel to which most people on Earth had access. In many less-industrialized countries, combustion of biomass such as wood or animal dung is still the primary energy source that many citizens, particularly in rural areas, depend on for domestic use (heating, sanitation, and cooking) as it is inexpensive, relatively efficient, and readily available. Figure 7.3c shows the global distribution of biomass fires in the world. While the burning of biomass for domestic use contributes to some of these fires, it is the so-called slash-and-burn agriculture that makes up a larger contribution. Take a minute to compare the areas highlighted in Figure 7.3c to the countries of the world that are currently experiencing rapid population growth (Chapter 3). If you need a refresher, use the CIA World Factbook website to view current global population growth values by country: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2002rank.html.

While biomass burning still has a significant impact on the global carbon cycle, human impacts on fluxes such as fossil fuel extraction and combustion continue to grow. For a review of the impacts of non-renewable energy sources such as fossil fuels, see Chapter 4. Burning of any fossil fuel (coal, natural gas, crude oil) moves carbon from a previously-sequestered state deep within the Earth’s crust into carbon dioxide in the atmosphere. As countries become more industrialized, their reliance on and combustion of fossil fuels tends to increase. Look at the graph in Figure 7.4, which compares CO₂ emissions from fossil fuels of regions across the globe.

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How has the use and distribution of fossil fuels changed throughout the past 250 years?

**Figure 7.4.** Total annual CO$_2$ emissions from fossil fuel combustion 1850-2011 by global region. Data from the Carbon Dioxide Information Analysis Center (CDIAC) [http://cdiac.esd.ornl.gov/](http://cdiac.esd.ornl.gov/)

The data shown in Figure 7.4 reveals much about the regions of the world it depicts. The effects of historic events such as the Great Depression of 1929-1939, World Wars, the fall of the Soviet Union in 1991, and the Kuwait oil fires of 1991 can be seen. Furthermore, between 1850 and 2011, different regions have gone in and out of the lead position as top producer of CO$_2$ from fossil fuel emissions. Population is one reason why fossil fuel use has changed throughout time. This is particularly apparent when comparing the data for Western Europe to that of India and Southeast Asia.
As countries industrialize, their relationship with agriculture also changes. **More-industrialized countries** rely very little on slash-and-burn agriculture. Their agricultural practices, however, are no less impactful on the environment. The growing population (Chapter 3) in many countries has required agriculture to become industrialized in order to meet demand. As a person living in the United States, **industrialized agriculture** probably produces the vast majority of the food you eat, including grains, fruits and vegetables, dairy and eggs, meats, and even fish. Industrialized agriculture can refer to a variety of practices, but has several main components: the use of motorized machinery; the use of chemicals such as fertilizers, pesticides, hormones, and/or antibiotics; and the intense and efficient production of one product across a large area of land.

One example of the impacts of industrialized agriculture is the production of methane (CH$_4$), a potent greenhouse gas. You will learn more about methane later in this section. As you saw earlier, methane is a common product of anaerobic metabolisms. The gut of **ruminant animals** (such as sheep, cattle, and goats) has evolved to allow the animals to digest the very tough carbon molecules, such as cellulose, in grass. They do this through symbiosis, or cooperation, with anaerobic bacteria who live in the gut tract. These anaerobic bacteria produce methane and other gases as a result of their metabolism when they break down molecules like cellulose. This is sometimes called enteric fermentation. The methane gas is excreted from the animal, and this contributes significantly to total methane emissions (Figure 7.5). A similar type of bacteria live in the fecal matter, or manure, of livestock. As the manure is handled or stored for future use, methane is also released to the environment.

The methane excretions of one cow or a few sheep would be miniscule and insignificant. If you were a small farmer with only enough livestock to feed your family, your contribution to total methane emissions would be close to zero. However, the demand for animal protein from meat, dairy, and eggs is very large in the United States. As of January 2015, the United States had a

![Figure 7.5. US methane emissions by source. 36% of the US methane production comes from agriculture: enteric fermentation (production of methane by anaerobic bacteria within the ruminant gut) and manure management. All emissions estimates from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2013. US EPA.](image)
total cattle inventory of 89.9 million animals, and in 2014, 25.5 billion pounds of beef was consumed in the United States (statistics: National Cattlemen’s Beef Association). The impacts of enteric fermentation and manure management for almost 90 million animals are very significant, as seen in Figure 7.5. In both cases, carbon that was previously stored in biomass (cattle feed) is moved into the atmosphere, this time in the form of CH$_4$. This is another example of how humans have impacted the carbon cycle.

Previously in this chapter, you identified other ways the carbon cycle is impacted by human agriculture. Through industrialized agriculture, we must also account for the fossil fuels that are used. In order to deliver agricultural products to consumers, fossil fuels are used numerous times: deliveries of fertilizer, feed, and/or seed to farms; farm machinery; delivery of products to processors; food processing; delivery of foods to super markets; etc.

As animal products, especially meat, are expensive, the demand is typically greater in more-industrialized countries than it is in less-industrialized countries. This makes industrialized agriculture, and especially industrialized animal agriculture, one of the major contributors to greenhouse gas emissions in more-industrialized countries.

Knowledge check – answer these questions on your own to further explore the impacts of biomass and fossil fuel burning on the global carbon cycle.

1. Why is there a correlation between population growth rate and global distribution of biomass fires?
2. Do you think this correlation is more likely due to personal biomass fires for activities such as cooking, or due to slash-and-burn agriculture? Why?
3. Given any other knowledge you might have about the areas highlighted in in Figure 7.3c, what other environmental impacts may be occurring here besides carbon cycle alterations?
4. Compare the production of CO$_2$ emissions from fossil fuel combustion across world regions in 1900, 1950, and 2011 in Figure 7.4. What has accounted for these differences?
5. Has the total worldwide production of CO$_2$ from fossil fuels increased evenly relative to human population growth during the time period displayed in Figure 7.4? Why or why not?
6. What are the differences in contributions of greenhouse gas emissions from more-industrialized countries and less-industrialized countries? What are the similarities?

Resources
Carbon Dioxide Information Analysis Center http://cdiac.esd.ornl.gov/
NOAA Earth System Research Laboratory: Carbon Cycle Science http://www.esrl.noaa.gov/research/themes/carbon/
Sass, Ronald. *Q2: What are the Causes of Global Climate Change?* OpenStax CNX. Sep 22, 2009 [http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3](http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3)

USDA Climate Change and Agriculture in the United States: Effects and Adaptation

US EPA Overview of Greenhouse Gases: Methane

Woods Hole Oceanographic Institution: Carbon Around the Earth

**Terms list**

Aerobic | Less-industrialized country
Anaerobic | Lithosphere
Autotroph | Methane
Biomass | More-industrialized country
Carbon | Nitrous oxide
Carbon dioxide
Cellular respiration | Ocean-atmosphere exchange
Chloroplast | Photosynthesis
Combustion | Potential energy
Consumption | Primary producer
Decomposition | Reservoir
Equilibrium | Residence time
Flux | Ruminant animal
Greenhouse gas | Sink
Heterotroph | Slash-and-burn agriculture
Industrial Revolution | Source
Industrialized agriculture
The Science of Climate Change

What is causing global climate change?

Scientists have identified the source of our current global climate change as being the increased human-caused emissions of greenhouse gases such as carbon dioxide (CO\textsubscript{2}), methane (CH\textsubscript{4}), and nitrous oxide (N\textsubscript{2}O), since the industrial revolution. Greenhouse gases are defined as large (at least three atoms) gas molecules that participate in the greenhouse effect. While you already know about the “big three” greenhouse gases (CO\textsubscript{2}, CH\textsubscript{4}, and N\textsubscript{2}O), it’s important to realize that water vapor (H\textsubscript{2}O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, is it still an essential component of the natural greenhouse effect that occurs in our atmosphere.

The Earth receives energy from the sun and in turn radiates energy back into space. When these two energies are equal, a stable temperature of the Earth is achieved. This temperature can be calculated from basic physics and is equal to about -18°C (0°F). This thermal equilibrium temperature is obviously much colder than that of the surface of the Earth. The actual average value of the Earth’s surface temperature is about 15°C (59°F). The difference between these temperatures is due primarily to the natural greenhouse gas concentrations in the atmosphere, causing the greenhouse effect. If the Earth had no naturally occurring atmospheric greenhouse gases, the temperature at the surface of the Earth would equal the thermal equilibrium temperature. The influence of these greenhouse gases, mainly water and some CO\textsubscript{2}, moderates the Earth’s climate and makes life possible (Figure 7.6).

As solar radiation reaches the Earth’s atmosphere, there are a variety of possibilities for its fate. Some solar radiation is reflected by the Earth and its atmosphere, and does not contribute to warming. Some passes through the atmosphere and reaches the surface of the Earth. When this solar radiation is absorbed by objects on Earth’s surface, it is re-emitted as infrared radiation (heat) that escapes to space. However, some of this heat is intercepted in the atmosphere by greenhouse gases. These gases absorb and re-emit the radiation in all directions. This creates a warming impact on the Earth’s surface Radiation can be bounced around from one greenhouse gas molecule to another, becoming trapped, and increasing its warming potential. For this reason, an increased greenhouse gas concentration causes an increase in the overall warming potential of the Earth’s atmosphere.

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Figure 7.6. This diagram shows the Earth's greenhouse effect. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, certain gases in the atmosphere, called greenhouse gases, absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth’s surface warmer than it otherwise would be. While this greenhouse effect occurs naturally, making life as we know it possible, human activities in the past century have substantially increased the amount of greenhouse gases in the atmosphere, causing the atmosphere to trap more heat and leading to changes in the Earth’s temperature. Credit: US EPA
On a geological time scale, the climate has changed many times in the past, even before the presence of humans. These changes occurred naturally because man had not yet evolved. A well-known example of past climate change is the occurrence of ice ages. Ice ages have occurred repeatedly throughout Earth’s history, the most severe ice age of which scientists have reliable data occurred around 650,000 years ago. During this time, solid, glacial ice covered much of Canada, the northern United States, and northern Europe; the level of the ocean decreased 120 m, and the global average temperature decreased by 5°C.

A geologic history of ice events is preserved in the ice sheets covering Antarctica and Greenland. This history has been uncovered over the past decades by scientists who have cored deeply into the ice and deciphered the temperature and atmospheric composition records stored in the ice. This process of obtaining ice cores is shown in Figure 7.7. The temperature at which the ice originally formed can be obtained from an interpretation of the measured ratio of the stable isotopes (see Chapter 1 for a description of isotopes) of oxygen in the molecules of water forming the ice. The atmospheric gas composition is taken from air bubbles trapped in the ice at the time of formation. From these data, scientists have gathered a set of reliable data that track atmospheric temperature and gas concentrations that dates back 800,000 years. These data helped scientists come to the conclusion that the Earth’s temperature and greenhouse gas concentrations are directly correlated to one another (Figure 7.8). During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO₂ concentrations below 200 parts per million (ppm). We can also see from these data, that CO₂ concentrations can be naturally elevated to as high as 300 ppm, correlating with increased temperatures.

Figure 7.7. On Dec. 8, 2010, Michelle Koutnik, of the University of Copenhagen's Center for Ice and Climate, prepared a core of Antarctic ice to be wrapped and put into core tubes for transport back to labs at Brigham Young University in Utah. But first, Koutnik measured the core's length, diameter and weight. The traverse was the first of two field campaigns to study snow accumulation on the West Antarctic Ice Sheet and tie the information back to larger-scale data collected from satellites. Credit: NASA/Lora Koenig.

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Figure 7.8. Estimates of the Earth’s changing CO$_2$ concentration (top) and Antarctic temperature (bottom), based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO$_2$ concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO$_2$ concentrations. NOTE: The past century’s temperature changes and rapid CO$_2$ rise (to 400 ppm in 2015) are not shown here. Source: Based on data appearing in NRC (2010).

The 100,000 year major cycle of the ice ages and some variations within the cycles agree very well with predicted periodic relationships between the Earth’s orbit around the sun, generally referred to as the Milankovitch cycles. Milankovitch cycles describe the very slight “wobbles” that occur in the Earth’s tilt and path as it moves around the sun. The Earth is always slightly tilted on its axis with respect to the sun. The angle of this tilt, however, changes periodically, varying from about 22° to about 25°. A less severe tilt will cause milder summers and winters close to the poles, preventing full summer ice melt in the northern- and southernmost regions, and allowing for a buildup of ice from year to year.
The path through which the Earth travels on its journey around the sun also changes from a more circular to a more elongated shape. Again, a round orbit will cause milder summers and winters close to the poles. These are very long term changes, and the results of the Milankovitch cycles can be observed in the changes in temperature and atmospheric CO₂ concentration shown in Figure 7.8. The climate change event that scientists are currently documenting is occurring much more rapidly than could be explained by Milankovitch cycles. Therefore, scientists agree that the cause of our currently changing climate is due to human impacts and not natural forces.

**Greenhouse gases**

We will be covering the four major categories of greenhouse gases that have been impacted by humans the most. See Table 7.2 for a numeric comparison of these greenhouse gases.

- Carbon dioxide, CO₂
- Methane, CH₄
- Nitrous oxide, N₂O
- Synthetic **fluorinated gases**, including **hydrofluorocarbons** (HFCs), **perfluorocarbons** (PFCs), and **sulfur hexafluoride** (SF₆)

Carbon dioxide (CO₂) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we’ll discuss here. Remember that CO₂ is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO₂ is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry (Chapter 4). To get an idea of how CO₂ concentration has changed over time, watch this video compiled by the National Oceanic and Atmospheric Administration (NOAA): [http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html](http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html). This video contains atmospheric CO₂ concentrations measured directly, dating back to 1958, as well as atmospheric CO₂ concentrations measured indirectly from ice core data, dating back to 800,000 BCE. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases leads to an increase in the surface temperature of the Earth.

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While CO$_2$ is produced by aerobic cellular respiration, gases such as CH$_4$ and N$_2$O are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH$_4$ emissions, as you saw in section 7.1. In addition to anaerobic bacteria, methane is also a significant component of natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. For a review of how fossil fuels are mined, see Chapter 4. Finally, landfills contribute significantly to CH$_4$ emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH$_4$ include swamps and wetlands, and volcanoes.

The vast majority of N$_2$O production by humans comes from agricultural land management. While some N$_2$O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N$_2$O emissions. Some N$_2$O is also emitted from transportation and industry.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO$_2$, CH$_4$, and N$_2$O, are responsible for most of the human-caused global climate change over the past century. Figure 7.9 shows the increases in all three gases following the industrial revolution. Ice core data (Figure 7.8) shows us that the atmospheric CO$_2$ concentration never exceeded 300 ppm before the industrial revolution. As of early 2015, the current atmospheric CO$_2$ concentration is 400 ppm. Comparing Figure 7.9 to Figure 7.8, above, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels?

![Figure 7.9](image_url). Increase in greenhouse gas concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the
One class of greenhouse gas chemicals that has no natural sources is the fluorinated gases. These include HFCs, PFCs, and SF₆, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in Table 7.2. Some of these chemicals, as well as the older chlorofluorocarbons (CFCs), have been phased out by international environmental legislation under the Montreal Protocol (see Chapter 6). Due to their long lifespan, many of these now-banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the global warming potential, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO₂ is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO₂ always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in Table 7.2. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH₄ and N₂O compared to CO₂. How does this impact the comparison of the environmental effects of agricultural practices in less-industrialized and more-industrialized countries that we completed in section 7.1?

Table 7.2. Comparison of common greenhouse gases in the atmosphere. Data from US EPA. For more information: http://epa.gov/climatechange/ghgemissions/gases.html

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Chemical formula or abbreviation</th>
<th>Lifetime in atmosphere</th>
<th>Global warming potential (100-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>Variable</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>12 years</td>
<td>28-36</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O</td>
<td>114 years</td>
<td>298</td>
</tr>
<tr>
<td>Hydrofluorocarbons</td>
<td>Abbreviation: HFCs</td>
<td>1-270 years</td>
<td>12-14,800</td>
</tr>
<tr>
<td>Perfluorocarbons</td>
<td>Abbreviation: PFCs</td>
<td>2,600-50,000 years</td>
<td>7,390</td>
</tr>
<tr>
<td>Sulfur hexafluoride</td>
<td>SF₆</td>
<td>3,200 years</td>
<td>22,800</td>
</tr>
</tbody>
</table>
Other climate influencers

In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the surface temperature. This primarily occurs due to a decrease in the albedo of light-colored surfaces by the darker-colored carbon black, soot, dust, or particulate matter. As you know, it is more comfortable to wear a white shirt on a hot summer day than a black shirt. Why is this? Because the lighter-colored material bounces more solar radiation back toward space than the darker-colored material does, allowing it to stay cooler. The darker-colored material absorbs more solar radiation, increasing its temperature. Just as the white shirt has a higher albedo than the black shirt, light-colored objects in nature (such as snow) have a higher albedo than dark-colored objects (such as soot or dust). As humans increase the amount of carbon black, soot, dust, and particulates in the atmosphere, we decrease the albedo of light-colored surfaces, causing them to absorb more solar radiation and become warmer than they would without human influence. An example of this can be seen in the snow on Figure 7.10.

![Figure 7.10. A photograph of the extreme dust deposition from the deserts of the Colorado Plateau onto the Colorado Rockies snowpack in 2009. Taken from the high point of the Senator Beck Basin in the San Juan Mountains, it captures the extent of the impact of darkening in which the snow albedo dropped to about 30%, more than doubling the absorption of sunlight. Credit: S. McKenzie Skiles, Snow Optics Laboratory, NASA/JPL](image)

This section is modified from OpenStax material. Download for free at http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619beca33@3
Tools scientists use to study climate change

Scientists must gather together all data that is available to them in order to make meaningful conclusions and predictions regarding climate change. When they bring these data together, the prediction they make is in the form of a scientific model. A model is a projection of what might happen in the future based on knowledge of current and past events. The models that are published to predict climate change must pass a rigorous scientific peer-review process, and often require the combination of findings of hundreds of experiments. These large-scale models are typically beyond the capacity of a standard desktop computer, and must be run by large super-computers housed at research universities or government laboratories. For more information on how scientists build and test models, follow the link below and click on the slideshow animation, paying special attention to the sections “Model Overview” and “Testing Models.” [http://www.epa.gov/climatechange/science/future.html](http://www.epa.gov/climatechange/science/future.html)

![Figure 7.11](image.png)

**Figure 7.11.** Observed and projected changes in global average temperature under three no-policy emissions scenarios. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. A wider range of model types shows outcomes from 2 to 11.5°F. Changes are relative to the 1960-1979 average. Source: USGCRP 2009
Figure 7.11 is one example of a scientific model of the impacts of climate change. Within this figure, we see the directly-measured observations of global average temperature (black line). We also see models of four different scenarios: 1900 to 2000 simulation using actual greenhouse emissions (green line), and 2000 to 2100 simulation using very high (purple line), high (red line), and low (blue line) greenhouse gas emissions scenarios.

Why did scientists make a model of the data from 1900 to 2000 in Figure 7.11 when they could just look up the data in published literature? This is an important component of model testing. In order to ensure accuracy of the model, you should not only be able to predict future events, but past events as well. Scientists use this as a way to “calibrate” their model. Since this model reliably predicts past events, chances are good that it will reliably predict future events as well.

Another example of a climate model is shown in Figure 7.12, this time comparing climate projections with and without the influences of humans on greenhouse gas emissions. This large model is a combination of the work of many different models, in order to achieve the most accurate outcome.

![Figure 7.12](image-url)

**Figure 7.12.** Comparison between observed average global temperatures and corresponding modeled temperatures with and without anthropogenic climate forces (IPCC, Working group 1, 2007).

This section is modified from OpenStax material. Download for free at [http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3](http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3)
In Figure 7.12, the decadal averages of observations are shown for the period 1906 to 2005 (black line). All temperatures are plotted relative to zero being defined as the corresponding average for the period from 1901 to 1950. The blue shaded band shows the 5% to 95% confidence interval for 19 simulations from 5 climate models using only the natural forcing effects due to solar activity and volcanoes. The red shaded band shows the 5% to 95% confidence interval for 58 different simulations from 14 climate models using both natural and anthropogenic forces. These different simulations and the different models are used by different scientific groups and represent different treatments of the Earth’s systems. It is thus quite encouraging that model calculations are in major agreement with the assumption that global temperature change from 1900 to 2000 is due to both natural and anthropogenic effects, with anthropogenic effects being the major causes in its recent dramatic increase.

You will see more examples of climate models as you make your way into the final section of the climate change chapter: consequences of climate change.

This section is modified from OpenStax material. Download for free at http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3

Resources

NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/


Sass, Ronald. Q2: What are the Causes of Global Climate Change? OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3

University of San Diego Virtual Museum: Climate Change http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml


Terms list
Albedo
Chlorofluorocarbon
Confidence interval
Fluorinated gases
Global warming potential
Greenhouse effect
Hydrofluorocarbon
Ice age
Ice core
Landfill
Milankovitch cycles
Model
Parts per million
Perfluorocarbon
Solar radiation
Stable isotopes
Sulfur hexafluoride
Thermal equilibrium temperature
Water vapor
Consequences of Climate Change

As part of your assigned reading for this section, read the article “The Coming Storm” by Don Belt published in *National Geographic:*

http://ngm.nationalgeographic.com/print/2011/05/bangladesh/belt-text

In this section, we will discuss the effects of climate change, both those that have already been observed, as well as future predictions based on scientific climate models (see section 7.2 for a discussion of scientific models). Here, the differences between the terms **global warming** and **climate change** become apparent. Global warming refers to the increase in the average temperature of the Earth’s atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. We have already observed this increase occurring, as you saw in Figure 7.12 from section 7.2. We have also seen, and expect to continue to see, other changes occurring in the climate of the Earth. Furthermore, changes have been observed, and we expect to continue to observe, changes in other chemical, physical, and biological aspects of the Earth’s environment. We will only discuss some of the consequences of climate change in this section, including changes in temperature, precipitation, ocean level, and ocean acidity. There are many more changes that have been seen, and are projected to continue in the future. These include: changes in the amount and distribution of ice and snow, changes in seasonality, ecosystem shift, and habitat changes of plant and animal populations, in addition to others. For more information about these consequence of climate change, visit this site:

http://www.epa.gov/climatechange/science/indicators/index.html

**Temperature and precipitation**

Temperature and **precipitation** are the two most direct impacts on the Earth’s climate due to climate change. By now, you should already understand why an increase in greenhouse gas levels in the atmosphere causes an increase in temperature. But why does it also impact precipitation patterns? As you already know, water vapor is an important component of the Earth’s atmosphere (see Chapter 6). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. Here in Georgia, we have very hot and humid summers. The high summer humidity in this region is possible due to the increased capability warm air has to hold water vapor. Simply put, warmer air can hold more water than cooler air. As air cools, its ability to hold water vapor decreases, and any excess water will leave the air as liquid water. A great example of this is the formation of dew on surfaces overnight. During the day, the temperature is warmer than it is at night, and the air has a relatively high holding capacity for water vapor. When the sun sets, the air cools, decreasing its capacity to hold water vapor. That extra water must go somewhere, and it does that by accumulating on surfaces. Similarly, when warm and cool air fronts collide, the chances for rain and thunderstorms increase. Furthermore, an increase in temperature enhances evaporation occurring at the Earth’s
surface. This increased evaporation leads to greater concentrations of water vapor in the atmosphere which can lead to increased precipitation.

The change in temperature that we have already seen in the Earth’s average atmospheric temperature is relatively small (about 0.6 °C, according to Figure 7.12 from section 7.2). However, as with many of the aspects of climate change, the potential for greater changes increases dramatically as time progresses in the future. This can be seen in Figure 7.13, which displays a model of the predicted temperature increase. Notice that these changes occur relatively rapidly, and are not uniform across the globe. What might be some of the reasons for this?

![Figure 7.13](image)

**Figure 7.13.** Projected changes in global average temperatures under three emissions scenarios (rows) for three different time periods (columns). Changes in temperatures are relative to 1961-1990 averages. The scenarios come from the IPCC Special Report on Emissions Scenarios: B1 is a low emissions scenario, A1B is a medium-high emissions scenario, and A2 is a high emissions scenario. Source: IPCC Working Group I: The Physical Science Basis, 2007.

Changes in precipitation occur due to a variety of factors, including changes in atmospheric water vapor content due to changing temperature, as discussed above. Also at play is the heightened *evaporation* rate of water on Earth’s surface under warmer temperatures. More evaporation leads to more precipitation. Finally, shifts in wind patterns impact the distribution of precipitation events. As you can see in Figure 7.14, there are some areas of the globe that are expected to have an increase in precipitation, while others are expected to have a dramatic
decrease. Some major population centers projected to have a moderate to severe precipitation increase include (population estimates of the metropolitan area given in parentheses): New York, United States (20.1 million); Bogotá, Colombia (12.1 m.); and Manila, Philippines (11.9 m.). What sort of challenges might these cities face in the future as they deal with this change in their climate?

Figure 7.14. Change in annual average precipitation projected by the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) by the GFDL CM2.1 model for the 21st century based on the A1B emissions scenario (see Figure 7.13). The plotted precipitation differences were computed as the difference between the 2081 to 2100 20-year averages minus the 1951 to 2000 50-year average. Blue areas project increases in precipitation; brown areas project decreases.

In contrast, many more major metropolitan areas are projected to have a moderate to severe precipitation decrease (droughts) by the end of the 21st century. These include Delhi, India (21.8 m.); Lagos, Nigeria (21 m.); São Paulo, Brazil (20.9 m.); Kolkata, India (14.6 m.); Istanbul, Turkey (14.4 m.); Los Angeles, United States (13.3 m.); Rio de Janeiro, Brazil (12 m.); Paris, France (12 m.); and Lahore, Pakistan (11.3 m.). The largest challenge that these areas are likely to face is a dwindling water supply for drinking and agriculture. See Chapter 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations and farms.

Additional challenges may be felt by all areas of the world with regard to changes in the seasonality or timing of precipitation, as well the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All of these factors affect the availability of soil water for plants,
the flow of rivers and streams, and the overall accessibility of water worldwide. Furthermore, scientists predict an increase in the number and severity of storms as climate change progresses. For a full discussion of the potential impacts of this, see the assigned article.

**Sea level rise**
While we know that water continuously cycles around the world (see Chapter 8 for information on the water cycle), and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as **glaciers**) are decreasing. This contributes to an increase in sea level worldwide (Figure 7.15).

![Global Average Absolute Sea Level Change, 1880-2014](image)

**Figure 7.15.** This graph shows average absolute cumulative changes in sea level for the world’s oceans since 1880, based on a combination of tide gauge measurements and recent satellite measurements. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

From the data in Figure 7.15, we see that sea level has increased at an average of 0.06 inches (0.15 cm) per year over the time period shown above. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches
There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting land ice (such as the glacier shown in figure 7.16) contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through runoff. We also observe sea ice melting (see http://www.epa.gov/climatechange/science/indicators/index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the water stays in the same locations, and the overall sea level does not change.

The second factor that influences sea level rise is a phenomenon called thermal expansion. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance (see Chapter 1 supplemental material). This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. Figure 7.17 depicts the measured land area lost due to increasing sea level since 1996. Note that the Southeast (defined here as the
Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.

Figure 7.17. This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.

While the ecological effects of sea level rise remain in the United States, we don’t project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less-industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

Ocean acidification
Dissolved CO₂ is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of aragonite, a mineral form of the molecule calcium carbonate,
CaCO₃. These organisms rely on the formation of carbonate ions (see Chapter 1 supplemental material for information on ions), CO₃²⁻, from dissolved CO₂, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where bicarbonate (HCO₃⁻) is formed as an intermediate, and hydrogen ions (H⁺) are generated (equations 7.3 and 7.4).

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{HCO}_3^- \\
\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}
\]

To have a better visualization of this process, follow along with the interactive graphic at: http://www.whoi.edu/home/oceanus_images/ries/calcification.html.

As you can see, both equations 7.3 and 7.4 each produce one H⁺. This is significant to water chemistry because an increase in H⁺ concentration means a decrease in the pH of the water. You can see in Figure 7.18 that a lower pH means that the liquid is more acidic. As shown in the interactive graphic, an increase in CO₂ in the atmosphere causes additional CO₂ to be dissolved in the ocean. This means that more CO₂ in the atmosphere leads to more acidic ocean environments.

Unfortunately for shell-building animals, the buildup of H⁺ in the more acidic ocean environment blocks the absorption of calcium and CO₃²⁻, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world’s oceans, as shown in Figure 7.19.

The increasing acidity of the world’s oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO₂ levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through coral bleaching, caused by the effects of climate change including ocean acidification and increased temperature. For Figure 7.18. The pH scale and relative acidity. Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.
more information, visit the NOAA Coral Reef Conservation Program website: http://coralreef.noaa.gov/threats/climate/.

Figure 7.19. This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

Looking Forward: Climate Solutions
While the situation surrounding global climate change is in serious need of our attention, it is important to realize that many scientists, leaders, and concerned citizens are making solutions to climate change part of their life’s work. The two solutions to the problems caused by climate change are mitigation and adaptation, and we will likely need a combination of both in order to prosper in the future.

Adaptation strategies
We know that climate change is already occurring, as we can see and feel the effects of it. For this reason, it is essential to also adapt to our changing environment. This means that we must
change our behaviors in response to the changing environment around us. Some adaptation strategies are discussed in the required article reading.

Adaption strategies will vary greatly by region, depending on the largest specific impacts in that area. For example, in the city of Delhi, India, a dramatic decrease in rainfall is projected over the next century (Figure 7.14). This city will likely need to implement policies and practices relating to conservation of water, for example: rainwater harvesting, water re-use, and increased irrigation efficiency. Rain-limited cities near oceans, such as Los Angeles, California may choose to use desalination to provide drinking water to their citizens. Desalination involves taking the salt out of seawater to make it potable (Chapter 8).

Cities with low elevations near oceans may need to implement adaptation strategies to rising sea levels, from seawalls and levees to relocation of citizens. One adaptations strategy gaining use is the creation or conservation of wetlands, which provide natural protection against storm surges and flooding.

Mitigation strategies

In general, a strategy to mitigate climate change is one that reduces the amount of greenhouse gases in the atmosphere or prevents additional emissions. Mitigations strategies attempt to “fix” the problems caused by climate change. Governmental regulations regarding fuel efficiency of vehicles is one example of an institutionalized mitigation strategy already in place in the United States and in many other countries around the world. Unlike some other countries, there are no carbon taxes or charges on burning fossil fuels in the United States. This is another governmental mitigation strategy that has been shown to be effective in many countries including India, Japan, France, Costa Rica, Canada, and the United Kingdom.

In addition to government measures and incentives, technology can also be harnessed to mitigate climate change. One strategy for this is the use of carbon capture and sequestration (CCS). Through CCS, 80-90% of the CO₂ that would have been emitted to the atmosphere from sources such as a coal-fired power plant is instead captured and then stored deep beneath the Earth’s surface. The CO₂ is often injected and sequestered hundreds of miles underground into porous rock formations sealed below an impermeable layer, where it is stored permanently (Figure 7.20).
Scientists are also looking into the use of soils and vegetation for carbon storage potential. Proper management of soil and forest ecosystems has been shown to create additional carbon sinks for atmospheric carbon, reducing the overall atmospheric CO$_2$ burden. Increasing soil carbon further benefits communities by providing better-quality soil for agriculture and cultivation.

Technologies related to alternative energy sources (Chapter 5) mitigate climate change by providing people with energy not derived from the combustion of fossil fuels. Finally, simple activities such as energy conservation, choosing to walk or bike instead of driving, and disposing of waste properly are activities that, when done by large numbers of people, actively mitigate climate change by preventing carbon emissions.

Take a moment to identify ways that you personally can be involved in the mitigation of or adaptation to climate change. What changes can you make in your own life to prevent excess carbon emissions? Similar to your ecological footprint, which you should have already calculated in lab, you can also calculate your **carbon footprint**. Use the EPA’s carbon footprint
calculator to do so, and investigate the Reduce Your Emissions section to find ways to decrease your carbon footprint.

**Resources**


**Terms list**

<table>
<thead>
<tr>
<th>Acidity</th>
<th>Climate</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptation</td>
<td>Climate change</td>
<td>Precipitation</td>
</tr>
<tr>
<td>Aragonite</td>
<td>Coral bleaching</td>
<td>Runoff</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>Desalination</td>
<td>Sea ice</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>Evaporation</td>
<td>Thermal expansion</td>
</tr>
<tr>
<td>Carbon capture and sequestration</td>
<td>Glacier</td>
<td>Wetland</td>
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<td>Carbon footprint</td>
<td>Global warming</td>
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<td>Carbon tax</td>
<td>Hydrogen ions</td>
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<td>Carbonate</td>
<td>Land ice</td>
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<td>Mitigation</td>
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</table>
CHAPTER 8: WATER

Learning Objectives

As a result of this unit:

• Students will be able to draw multiple interacting water molecules and identify the bonds and atoms
• Students will explain how the molecular structure of the water molecule contributes to the unique properties of water.
• Students will demonstrate an understanding of how much water is available on Earth and how it is distributed
• Students will be able to compare regional and national responses to water issues.
• Students will be able to explain water-related problems (for example water scarcity, water-borne diseases, water pollution, flooding) from different regions of the world
• Students will be able to explain how human modifications of natural water systems can be both beneficial and destructive
• Students will be able to describe solutions to water-related problems
• Students will be able to read and interpret graphs and charts about water
• Students will demonstrate knowledge of some of the major regulations related to water in the USA
• Students will gain a rudimentary understanding of groundwater flow, management and protection
CHAPTER 8: WATER

This chapter has been adapted from OpenStax (Biology and Concepts in Biology texts), USGS Water Resources, the EPA and The Encyclopedia of Earth

“Whiskey is for drinking. Water is for fighting”

Introduction

Why do scientists spend time looking for water on other planets? Why is water so important? It is because water is essential to life as we know it. Water is one of the more abundant molecules and the one most critical to life on Earth. Approximately 60–70 percent of the human body is made up of water. Without it, life as we know it simply would not exist. The quotation above, which has been attributed to Mark Twain, suggests realism that water is extremely important. In recent years we have seen a rise in conflicts and dispute about water. Fortunately, most of the conflicts have ended up in the courts instead of the battlefields. This chapter is devoted to this precious resource that sustains our planet and its living things.

Chapter outline:

1. Properties of water
   a. hydrogen bonding
   b. Physical state of water
   c. Heat capacity
   d. Heat of Vaporization
   e. Universal Solvent
   f. Cohesion and Adhesion

2. Global Water Distribution and Use

3. The Hydrologic Cycle

4. Components of the Hydrologic Cycle
   a. Atmosphere and precipitation
   b. Rivers and Streams
   c. Lakes, Ponds and reservoirs
   d. Wetlands
   e. Oceans
   f. Groundwater

5. Water Scarcity and Shortage

6. Water Pollution and Quality
   a. Types of water pollution
   b. Sources of water pollution

7. Water Management
   a. Water pollution control
   b. Watershed Management
   c. Regulations

Water

Water is an important commodity for life on Earth and is something we all need in our daily activities. It has in human history been referred to as the “essence of life”, “blue gold” and “more precious than oil”. What makes water so important is its unique and special properties. These special properties of water include water’s high heat capacity and heat of vaporization, its ability
to dissolve polar molecules, its cohesive and adhesive properties, and its dissociation into ions that leads to the generation of pH. Understanding these characteristics helps to elucidate its importance in maintaining life on Earth. Before we discuss these properties we will review the molecular structure of water which gives rise to these special properties.

**Properties of Water**

A water molecule is composed of one oxygen and two hydrogen atoms that are joined together by polar covalent bonds. Covalent mean that the atoms share electrons, instead of completely giving up electrons to one another. Polar means that the electrons are not shared equally, the oxygen atom holds onto the electrons more strongly than the hydrogen atoms. These polar covalent bonds (figure 8.1), along with the molecular shape, cause a water molecule to be polar molecule, meaning that there is an uneven distribution of the charges. While there is no net charge to a water molecule, the polarity of water creates a slightly positive charge on hydrogen and a slightly negative charge on oxygen, contributing to water’s properties of attraction. Water’s charges are generated because oxygen is more electronegative than hydrogen, making it more likely that a shared electron would be found near the oxygen nucleus than the hydrogen nucleus, thus generating the partial negative charge near the oxygen.

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<th>Molecular shape</th>
<th>Molecular type</th>
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<td></td>
<td>Polar covalent</td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>δ⁻ C — H δ⁺</td>
<td>Nonpolar</td>
</tr>
<tr>
<td></td>
<td>Nonpolar covalent</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>δ⁻ O = C δ⁻</td>
<td>Nonpolar</td>
</tr>
<tr>
<td></td>
<td>Polar covalent</td>
<td></td>
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</tbody>
</table>

**Figure 8.1**: Whether a molecule is polar or nonpolar depends on both bond type and molecular shape. Both water and carbon dioxide have polar covalent bonds, but carbon dioxide is linear, so the partial charges on the molecule cancel each other out. Methane is also a nonpolar molecule (From OpenStax Concepts of Biology text)

**Hydrogen Bonds**

As a result of water’s polarity, each water molecule attracts other water molecules because of the opposite charges between water molecules. Because the hydrogen atom is slightly positive, it will be attracted to neighboring negative charges. When this happens, a weak interaction occurs between the positive hydrogen from one molecule and the negative charge on
the more electronegative atoms of another molecule, usually oxygen or nitrogen. This interaction is called a **hydrogen bond**. This type of bond is common and occurs regularly between water molecules. Individual hydrogen bonds are weak and easily broken; however, they occur in very large numbers in water and in organic polymers, creating a major force in combination. These hydrogen bonds contribute to the following water’s unique properties.

1. Water is the universal solvent
2. Exists in nature as a solid, liquid, and gas
3. The density of ice is less than liquid water
4. Water has a high surface tension
5. Water has a high heat capacity
6. Water exists as a liquid at room temperature

### Physical State of Water on Earth

Water on Earth can naturally exist as solid, liquid or gas. The unique location in the Solar System, the tilt, rotation and revolution of our planet combine to make water present on all three states of matter. This has an important implication for life on Earth. The formation of hydrogen bonds is an important quality of liquid water that is crucial to life as we know it. As water molecules make hydrogen bonds with each other, it takes on some unique chemical characteristics compared to other liquids and, since living things have a high water content, understanding these chemical features is key to understanding life. In liquid water, hydrogen bonds are constantly formed and broken as the water molecules slide past each other. The breaking of these bonds is caused by the motion (kinetic energy) of water molecules due to the heat contained in the system. When the heat is raised as water is boiled, the higher kinetic energy of the water molecules causes the hydrogen bonds to break completely and allows water molecules to escape into the air as gas (steam or water vapor). On the other hand, when the temperature of water is reduced and water freezes, the water molecules form a crystalline structure maintained by hydrogen bonding (there is not enough energy to break the hydrogen bonds). The open structure of ice (Figure 8.2) makes ice less dense than liquid water, a phenomenon not seen in the solidification of other liquids.

Water’s lower density in its solid form is due to the way hydrogen bonds are oriented as it freezes: the water molecules are pushed farther apart compared to liquid water. With most other liquids, solidification when the temperature drops includes the lowering of kinetic energy between molecules, allowing them to pack even more tightly than in liquid form and giving the solid a greater density than the liquid.

The lower density of ice, illustrated in Figure 8.2, an anomaly, causes it to float at the surface of liquid water, such as in an iceberg or the ice cubes in a glass of ice water. In lakes and ponds, ice will form on the surface of the water creating an insulating barrier that protects the animals and plant life in the pond from freezing. Without this layer of insulating ice, plants and animals living in the pond would freeze in the solid block of ice and could not survive. The ice crystals that form upon freezing rupture the delicate membranes essential for the function of living cells, irreversibly damaging them.
Figure 8.2: Hydrogen bonding makes ice less dense than liquid water. (A) The lattice structure of water is more condensed than that of ice (B & C). The lattice structure of ice makes it less dense than the freely flowing molecules of liquid water, enabling it to float on water. (Credit a: modification of work by Jane Whitney, image created using Visual Molecular Dynamics (VMD) software)

High Heat Capacity

Water has the highest specific heat capacity of any liquid. Water’s high heat capacity is a property caused by hydrogen bonding among the water molecules. Specific heat is defined as the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius. For water, this amount is one calorie. It takes water a long time to heat up and a long time to cool. In fact, the specific heat capacity of water is about five times more than that of sand. This explains why land cools faster than the sea. Due to its high heat capacity, water is used by warm blooded animals to more evenly disperse heat and maintain temperature in their bodies: it acts in a similar manner to a car’s cooling system, transporting heat from warm places to cool places, causing the body to maintain a more even temperature.

Heat of Vaporization

Water also has a high heat of vaporization, the amount of energy required to change one gram of a liquid substance to a gas. A considerable amount of heat energy (586 cal) is required to accomplish this change in water. This process occurs on the surface of water. As liquid water heats up, hydrogen bonding makes it difficult to separate the liquid water molecules from each other, which is required for it to enter the gaseous phase (steam). As a result, water acts as a heat sink or heat reservoir and requires much more heat to boil than does a liquid such as ethanol (grain alcohol), whose hydrogen bonding is weaker than water’s hydrogen bonding. Eventually, as water reaches its boiling point of 100° Celsius (212° Fahrenheit), the heat is able to break the hydrogen bonds between the water molecules, and the kinetic energy (motion) between the water molecules allows them to escape from the liquid as a gas. Even when below its boiling point, water’s individual molecules acquire enough energy from other water molecules such that some surface water molecules can escape and vaporize: this process is known as evaporation.

Since hydrogen bonds need to be broken for water to evaporate means that a substantial amount of energy is used in the evaporation process. As the water evaporates, energy is taken up by the process, cooling the environment where the evaporation is taking place. In many living
organisms, including in humans, the evaporation of sweat, which is 90 percent water, allows the organism to cool so that homeostasis of body temperature can be maintained.

**Water as a Solvent**

Since water is a polar molecule with slightly positive and slightly negative charges, ions and polar molecules can readily dissolve in it. Water is, therefore, referred to as a *solvent*, a substance capable of dissolving other polar molecules and ionic compounds. The charges associated with these molecules will form hydrogen bonds with water, surrounding the particle with water molecules. This is referred to as a **sphere of hydration**, or a hydration shell, as illustrated in Figure 8.3 and serves to keep the particles separated or dispersed in the water. When ionic compounds are added to water, the individual ions react with the polar regions of the water molecules and their ionic bonds are disrupted in the process of **dissociation**. Dissociation occurs when atoms or groups of atoms break off from molecules and form ions. Consider table salt (NaCl, or sodium chloride): when NaCl crystals are added to water, the molecules of NaCl dissociate into Na\(^+\) and Cl\(^-\) ions, and spheres of hydration form around the ions, illustrated in Figure 8.3.

![Figure 8.3](image)

**Figure 8.3** When table salt (NaCl) is mixed in water, spheres of hydration are formed around the ions. (After OpenStax Concepts of Biology text book)

When salt is mixed with water, the salt dissolves because the covalent bonds of water are stronger than the ionic bonds in the salt molecules. The positively-charged sides of the water molecules are attracted to the negatively-charged chloride ions and the negatively-charged sides of the water molecules are attracted to the positively-charged sodium ions. Essentially, a tug-of-war ensues with the water molecules winning the match. Water molecules pull the sodium and chloride ions apart, breaking the ionic bond that held them together. After the salt compounds are pulled apart, the sodium and chloride atoms are surrounded by water molecules, as this diagram shows. Once this happens, the salt is dissolved, resulting in a homogeneous solution.

**Water's Cohesive and Adhesive Properties**

Have you ever filled a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass (Figure 8.4)
Figure 8.4. Water in a glass form a dome shape above the glass due to cohesive forces of attraction among water molecules. Photo Credit: Sam Mutiti

. This water can stay above the glass because of the property of **cohesion**. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-gas (water-air) interface, although there is no more room in the glass. Cohesion allows for the development of **surface tension**, the capacity of a substance to withstand being ruptured when placed under tension or stress. This is also why water forms droplets when placed on a dry surface rather than being flattened out by gravity (Fig 8.5)

Figure 8.5. Beading up of water due strong cohesive forces between water molecules (Water USGS, right hand photo credit: J Schmidt; National Park Service).

When a small scrap of paper is placed onto the droplet of water, the paper floats on top of the water droplet even though paper is denser (heavier) than the water. Cohesion and surface tension keep the hydrogen bonds of water molecules intact and support the item floating on the top. It’s even possible to “float” a needle or an insect on top of a glass of water if it is placed gently without breaking the surface tension, as shown in Figure 8.6.
Figure 8.6 The weights of the needle and water strider are pulling the surface downward; at the same time, the surface tension is pulling it up, suspending them on the surface of the water and keeping them from sinking. (Credit: Cory Zanker (left) and Tim Vickers (right))

Another important property of water is adhesion, or the attraction between water molecules and other molecules. This attraction is sometimes stronger than water’s cohesive forces, especially when water is exposed to charged surfaces such as on the inside of thin glass tubes known as capillary tubes. Adhesion is observed when water “climbs” up the tube placed in a glass of water: notice that the water appears to be higher on the sides of the tube than in the middle. This is because the water molecules are attracted to the charged glass walls of the capillary tube more than they are to each other and, therefore, adhere to it. This type of adhesion is called capillary action, and is illustrated in Figure 8.7.

Figure 8.7: Capillary action in a glass tube is caused by the adhesive forces exerted by the internal surface of the glass exceeding the cohesive forces between the water molecules themselves. (Credit: modification of work by Pearson-Scott Foresman, donated to the Wikimedia Foundation)
Global Water Distribution and Use

Most of the water on the planet is in oceans and unavailable for human consumption due to its high salinity (Figure 8.8).

![Distribution of Earth’s Water](http://water.usgs.gov/edu/earthwherewater.html)

**Figure 8.8:** Graphical representation of available water:
http://water.usgs.gov/edu/earthwherewater.html

Of all the water in the world, only about 0.64% is fresh water that is available for consumption (the other fresh water is locked up in ice). Of this available fresh water, 98.4% is found as groundwater below the surface of the Earth and only 1.4% is surface water in rivers and lakes. You can see in Table 8.1 and Figure 8.8 that groundwater is the largest available fresh water resource on Earth and, therefore, it is important to fully understand and protect this resource.

**Table 8.1:** Over a third of Earth’s fresh water is locked up in icecaps and glaciers leaving under a third available for human use.

<table>
<thead>
<tr>
<th>Sizes of Major Reservoirs</th>
<th>Out of 35,000,000 km³ fresh water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>% of Total</td>
</tr>
<tr>
<td>Icecaps and Glaciers</td>
<td>69.6</td>
</tr>
<tr>
<td>Fresh groundwater</td>
<td>30.0</td>
</tr>
<tr>
<td>Fresh surface water</td>
<td>0.299</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>0.0368</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sizes of Major Reservoirs</th>
<th>Out of 1,386,000,000 km³ all water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>% of Total</td>
</tr>
<tr>
<td>Oceans and other saline</td>
<td>97.5</td>
</tr>
<tr>
<td>Icecaps and Glaciers</td>
<td>1.76</td>
</tr>
<tr>
<td>Fresh groundwater</td>
<td>0.756</td>
</tr>
<tr>
<td>Fresh surface water</td>
<td>0.104</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>0.0129</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sizes of Major Reservoirs</th>
<th>Out of 10,600,000 km³ unfrozen fresh water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>% of Total</td>
</tr>
<tr>
<td>Fresh groundwater</td>
<td>98.7</td>
</tr>
<tr>
<td>Fresh surface water</td>
<td>0.984</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>0.121</td>
</tr>
</tbody>
</table>

Most of the water used by humans is surface water because of the ease of access and cheaper extraction (Figure 8.9). In the United States, about 40% of all public supplies and domestic water used is from groundwater. In some communities 100% of the domestic water is from groundwater. Public supply is water withdrawn by public and private water suppliers to
supply water for at least 25 people or have a minimum of 15 connections. **Domestic** water supplies is defined by the USGS as water that is used for indoor and outdoor uses at residences, and includes uses such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, watering lawns and gardens, and maintaining pools. As more pressure is placed on surface water by the ever increasing population and pollution from human activities, groundwater is becoming more and more important as a source of drinking water in the US (Figure 8.9 and 8.10) and the rest of the world.

Most of the water withdrawn from both surface and groundwater sources is mainly used for industrial cooling, irrigation and public water supply.

![Figure 8.9](http://water.usgs.gov/edu/wusw.html)  
**Fig. 8.9:** Amount of water withdrawn from surface water sources compared to groundwater. Most of the water withdrawn is from surface water sources.

![Figure 8.10](http://water.usgs.gov/edu/wusw.html)  
**Figure 8.10:** Water withdrawals by usage. Most of the water withdrawn for thermoelectric power is surface water while most of the water withdrawn for domestic and mining use is groundwater. [http://water.usgs.gov/edu/wusw.html](http://water.usgs.gov/edu/wusw.html)

Water usage can also be categorized as either **consumptive** or **non-consumptive** use. **Consumptive** use is that part of water withdrawn that is either evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate aquatic environment and not returned back. **Non-consumptive** use is the water that is withdrawn and returned back to the immediate environment with minimum loss. The largest percentage of water withdrawn goes to thermoelectric cooling, which is a non-consumptive use as it is returned to the same source (Figure 8.11). However, irrigation, water
that is applied by a water system to sustain plant growth, accounts for the most consumptive use of all water withdrawn. In some countries, such as Egypt, irrigation accounts for over 70% of water withdrawn. Irrigation is water that is applied by a water system to sustain plant growth. Irrigation also includes water that is used for frost protection, application of chemicals, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching salts from the root zone.

![Figure 8.11](http://water.usgs.gov/watuse/images/category-pages/2010/total-category-pie-2010.png)

**Figure 8.11:** Estimated 2010 water withdrawals. Irrigation and thermoelectric power usages account for most water withdrawals. http://water.usgs.gov/watuse/images/category-pages/2010/total-category-pie-2010.png

More water use terminology can be found at: [http://water.usgs.gov/watuse/wuglossary.html](http://water.usgs.gov/watuse/wuglossary.html)

In the US there is a difference in how states withdraw and use water (Figure 8.12). California and Texas account for over 20% of all water withdrawn. In fact, California consumes more water than is available within the state and is therefore forced to get water from the other states. Despite this deficiency almost everyone in California has access to clean and safe drinking water. Contrast this to Lusaka, the capital city of Zambia, which has more water available than is withdrawn but more than a third of its population has no access to safe drinking water. Can you think of a reason why not everyone in Lusaka has access to clean and safe drinking water?
**Figure 8.12:** A comparison of water usage by state, California and Texas use the most water in the United States. Data expressed as a percentage of the total water use in the US. (Source USGS)

**The Hydrologic Cycle**

The hydrologic cycle (water cycle) represents a continuous global cycling of water from one reservoir to another. This cycle can be viewed or represented at both the local (watershed) and global scales, Figures 8.13 and 8.14 respectively.

**Figures 8.13:** The water cycle representing how water moves on earth. The hydrologic cycle at the watershed scales, ocean reservoir not included.

The major water reservoirs on Earth are oceans, glaciers, groundwater, rivers and lakes. Water spends different amounts of time in the various reservoirs. The main factors that control residence time in a reservoir are size (volume of reservoir) and flux (rate of movement of water in and out of the reservoir).
To gain a deeper appreciation of the water cycle, let us follow a water molecule through the water cycle. Starting in the ocean (an arbitrary starting point) the water molecule can become part of the water that is converted into vapor and enter the atmosphere. Heat energy from the sun, which drives the water cycle, heats water in the oceans and cause evaporation. Evaporation is the process by which water changes from a liquid to a gas or vapor. Evaporation is the primary pathway that water moves from the liquid state back into the water cycle as atmospheric water vapor. Nearly 90% of moisture in the atmosphere comes from evaporation, with the remaining 10% is from plant transpiration. Transpiration is the process by which moisture is carried through plants from roots to small pores on the underside of leaves, where it changes to vapor and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves. Rising air currents take the vapor up into the atmosphere, along with water from evapotranspiration, which is a combination of water transpired from plants and that evaporated from the soil. The vapor rises into the air where cooler temperatures cause it to condense into clouds. Condensation is the process by which water vapor is converted from gaseous state back into liquid state. Clouds might eventually grow bigger and moist enough to release the water molecule in the form of precipitation. Precipitation is water falling from the clouds in the atmosphere in form of ice (snow, sleet, hail) or liquid (e.g. rain, drizzle). Precipitation that falls as snow can accumulate as ice caps and glaciers. Did you know that the largest glacier on Earth is the Severny Island ice cap in the Russian Arctic? These can melt and flow on land as overland flow. Precipitation that falls as liquid usually ends up as surface runoff in the form of overland flow and stream flow. Surface runoff is precipitation which travels over the soil surface to the
nearest stream channel. **Stream flow** is the movement of water in a natural channel, such as a river. A majority of the precipitation falls directly onto the ocean and returns the water molecule back to restart the journey. This is also true for surface runoff, most of the water eventually returns to the ocean via stream flow. This also returns the water molecule back the ocean to start the journey again.

A portion of the water that falls as precipitation can enter lakes where it can evaporate back into the atmosphere, condense and fall back as precipitation again. Water in the lake can also be taken up by plants and transpired back into the atmosphere. Some of the water that falls as precipitation can infiltrate into the ground and become part of groundwater. **Infiltration** is the process by which water enters the subsurface by gravitation pull. Some of the water infiltrates into the ground and replenishes **aquifers** (saturated subsurface rock), which store huge amounts of freshwater for long periods of time. Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as **groundwater discharge**, and some groundwater finds openings in the land surface and emerges as freshwater **springs**. Yet more groundwater is absorbed by plant roots to end up as evapotranspiration from the leaves. Over time, though, all of this water keeps moving and most of it ends up in the ocean.

**Components of the Hydrologic Cycle**

**Atmosphere and Precipitation**

Most precipitation falls in the form of rain. There are three main kinds of rain; **frontal**, **convective** and **orographic** (Figure 8.15). **Frontal** rainfall is precipitation formed when two air masses of different temperatures and moisture content converge. **Convective** rainfall is formed when intense localized heating causes hot moist air to raise, condense and form rain clouds. Intense rain would then fall as the clouds get supersaturated. **Orographic** rainfall is rain that forms over mountains. When a moist air mass encounters a mountain, it rises and cools. As it cools water vapor condenses to form a rain cloud that produces rain on the windward side of the mountain (Figure 8.15). Most of the rain ends up as surface water runoff.

Surface water is a major component of the hydrological cycle and one that we interact with very regularly. It includes lakes, wetlands, stormwater runoff (overland flow), water in ponds, potholes, rivers and streams.

**Streams and Rivers**

A river forms from water moving from a higher altitude to lower altitude, under the force of gravity. When rain falls on the land, it either evaporates, seeps into the ground or becomes runoff (water running on the surface). When water runs on the land surface it usually converges as it moves towards lower elevation. The converging runoff can concentrate into single channels of conveyance called creeks, stream or rivers. Usually these start as small rill and rivulets that would join up downhill into larger streams and creeks which can also join up downstream to form even bigger rivers. The streams and rivers that join up to form a larger river are called **tributaries**, Figure 8.16. The land area drained by a river and all its tributaries is called a **watershed** or catchment or river basin.
The area adjacent to a river that floods frequently is called a floodplain. **Floodplains** are areas that rivers use to temporarily store excess water during storm events and frequently contain very fertile soils. This has historically encouraged humans to move into floodplains and use them for agriculture, resulting in a reduction in the capacity of the floodplain to act as temporally storage for excess water during storm events, causing increased damaging flooding downstream. Properly functioning floodplains reduce the negative impacts of floods (by reducing severity of flood), and they assist in filtering stormwater and protecting the water quality of rivers. They also act as areas of recharge for groundwater.
The US has numerous rivers that run throughout the nation’s landscape. It is estimated that the US has over 200,000 rivers with the Mississippi River being the largest by volume despite it only being the second longest. The Missouri River is the longest river in US. Most states have at least one important river. In Georgia the main rivers are the Flint, Ochlockonee, Suwannee, Saint Marys, Satilla, Ogeechee, Altamaha, Oconee, Savannah, Chattahoochee, Tallapoosa, Coosa, Ocmulgee and the Tennessee rivers (Figure 8.17).
These rivers are very important for supplying water to the cities and population of the states. The rivers also contain important biological communities and provide opportunities for recreation such as swimming, fishing and white water rafting. Rivers are so important in that, to a large extent, control settlement patterns all over the world. Major cities, communities, factories, industries and power stations are located along rivers. It is therefore very important to protect the quality and integrity of rivers all over the world.

Unfortunately, most of the rivers in the world are too polluted to support certain human activities, especially swimming, fishing and drinking. Close to half of the rivers in the US have been deemed too polluted to support swimming and fishing. A lot of the rivers have also been channelized, dredged or impounded by dams which have ruined their ability to support a lot of human and biological activities. It is estimated that over 600,000 river miles have been dammed in the US. Benefits of dams to humans include providing a source of water (reservoirs and farms ponds), recreation waters and reducing local flooding. On the flip side, dams can also have
negative impacts on people and the environment. They can lead to increased severe flooding downstream of the dam, especially during high rain events. The impoundments can trap stream sediments resulting in reduced sediment supply downstream as well as increased deposition behind the dam. This shift in sediments flow can disrupt and damage aquatic habitats and can increase downstream stream erosion due to lack of sediment supply. The impoundments can also prevent certain aquatic organisms from migrating either upstream or downstream, therefore reducing their range and abilities to survive environmental changes as well cutting them off from spawning areas. Construction of dams can also result in displacement of the local people and loss of traditional lands and cultural history. Reservoirs and ponds usually form behind these impoundments.

**Lakes, Reservoirs and ponds:** If water flows to a place that is surrounded by higher land on all sides, a lake will form (**Figure 8.18**). A lake, pond or reservoir is a body of standing water on the land surface. When people build dams to stop rivers from flowing, the lakes that form are called reservoirs. It is estimated that over 300 million water bodies in the world are lakes, reservoirs and ponds. Most of the Earth’s lakes (about 60%) are found in Canada. Even though lakes and rivers contain less than 1% of the Earth’s water, the US gets over two thirds (70%) of its water (for drinking, industry, irrigation and hydroelectric power generation) from lakes and reservoirs. Lakes are also the cornerstone of the US’s freshwater fishing industry and are the backbone of the nation’s state tourism industries and inland water recreational activities. ([http://water.epa.gov/type/lakes/](http://water.epa.gov/type/lakes/))

**Figure 8.18:** Lake Sinclair in Baldwin and Putnam counties (Photo Credits: GCSU Hydrology Research lab)

**Wetland:** A **wetland** is an area which is home to standing water for notable parts of the year, has saturated soils for a large part of the year and has plants that require large amounts of water to survive. Wetlands include swamps, marshes, and bogs. Wetlands are identified using three characteristics: soils (water-saturated soils are present), hydrology (shallow water table) and vegetation (wetland plants that are adapted to areas that are saturated with water for long periods of time). Wetlands are very important areas of biological diversity and productivity. These are also important areas where geochemical and biological cycles/ processes are consistently taking place. For instance wetlands are considered as areas of significant carbon sequestration (storage), which impacts global climate change. They also act as filters for storm-water runoff before it enters rivers and lakes.
Oceans

As you have probably already guessed, oceans are an important component of the hydrologic cycle because they store majority of all water on Earth (about 95%). Most of the major rivers drain into them. The five oceans covering the surface of the Earth are the Atlantic, Indian, Pacific, Arctic and the Southern Ocean (Figure 8.19).

![Figure 8.19](http://theworldsoceans.com/)

**Figure 8.19**: The five oceans found on planet Earth. The Pacific Ocean is the largest. Source: http://theworldsoceans.com/

Approximately 90% of the water that is evaporated into the hydrologic cycle comes from the ocean. Oceans are an important and large part of the hydrologic cycle, with lots biological diversity and many landforms. Did you know that the average depth of the oceans is about 3.6 km with a maximum depth that can exceed 10 kilometers in areas known as ocean trenches? Ocean water is not available as freshwater because it is saline (saltwater). Saline water contains a high concentration of dissolved salts (about 35 ppt) compared to fresh water (less than 0.5 ppt). The temperature of the oceans varies mostly as a function of latitude (distance from the equator) and depth. Ocean water is warmer near the equator and less dense than water near the poles. The salinity of the ocean water is also not the same everywhere. This difference in salinity and temperature, together with atmospheric air circulation causes ocean water to move as currents. These global ocean currents have both vertical and horizontal movement and are responsible for climate regulation. An ocean current is defined as a horizontal movement of seawater in the ocean. Ocean currents are driven by the circulation of wind above surface waters interacting with evaporation, sinking of water at high latitudes, and the Coriolis force generated by the earth's rotation. Large surface ocean currents are a response of the atmosphere and ocean to the flow of energy from the tropics to Polar Regions. In some cases, currents are transient features and affect only a small area. Other ocean currents are essentially permanent and extend over large horizontal distances.
One major pattern of ocean currents the so-called Global Conveyor Belt, or Thermohaline circulation has a great impact on global Climate (Fig. 8.20). These ocean current, especially the permanent ones, have a great deal of influence on the water cycle. The Kuroshio Current, off the shores of Japan, is the largest current. It can travel between 40 and 121 kilometers/day, and extends to about 1,000 meters deep. The Gulf Stream is a well known stream of warm water in the Atlantic Ocean, moving water from the Gulf of Mexico across the Atlantic Ocean towards Great Britain. The flow continues across the Atlantic Ocean toward Great Britain, a current called the North Atlantic drift. Coming from warm climates, the Gulf Stream moves warmer water to the North Atlantic. These warm currents contribute to the higher average temperatures of the East Coast of the United States, Europe, and Scandinavia, which are about 5°C warmer than other land masses at the same latitude. Cornwall, at the southwest corner of Great Britain, is sometimes referred to as the "Cornish Riviera" because of the milder climate attributable to the Gulf Stream.
Figure 8.20. The ocean conveyor belt (thermohaline circulation) showing the major currents
http://www.eoearth.org/view/article/51cbef2a7896bb431f69cd56/?topic=51cbfc78f702fc2ba812
9e73

The ocean is also home to many forms of life uniquely adapted to survive in this habitat. Unfortunately, humans have degraded the oceans and their life through pollution, overfishing, carbon dioxide acidification and resource exploitation. Figure 8.21 shows a couple of examples of human impacts on the ocean environment.

Figure 8.21: Trash washed up on the beach (A) and seal tangles up and being struggled by plastic trash in the ocean (B).

Watch the video from the Habitable Planet: Oceans Video vhttp://www.learner.org/courses/envsci/unit/text.php?unit=3&secNum=1

Groundwater

Storage and Flow

Almost 99% of the available fresh water is found below the surface as groundwater. Groundwater is not created by some mysterious processes below ground, but is part of the recycled water in the hydrologic cycle. When precipitation falls, some of the water runs off on the surface while some infiltrates into the ground. Groundwater is replenished when water moves from the surface, through unsaturated rocks or sediment (unsaturated or vadose zone), all the way down the saturated parts (saturated zone or phreatic zone) in a process called infiltration and becomes groundwater (Figure 8.22). The top of the saturated portion is called the water table, which is the boundary between saturated and unsaturated zone.

Groundwater is found in aquifers, which are bodies of rock or sediment that store (and yield) large amounts of usable water in their pores. Aquifer productivity is controlled by porosity and permeability. Porosity is the percentage of open space in a rock or sediment body. Permeability is the ability of subsurface material to transmit fluids. Groundwater is found in the saturated zone of a rock body where all pores are completely filled with water. An important concept is that surface water always moves from higher elevation to lower elevation while groundwater always moves from higher energy (hydraulic head) to lower energy. Hydraulic head is the elevation of water in the subsurface and is a measure of the total energy of the water.
Under most circumstances, ground water at a high elevation has high potential energy than water at lower elevation and, therefore, moves in that direction. So, water in an aquifer will often (but not always) flow from areas of higher elevation to lower elevation.

**Figure 8.22:** Model of groundwater system showing the different components of an unconfined groundwater system: http://water.usgs.gov/edu/earthgwaquifer.html

There are two kinds of aquifers, **unconfined** and **confined aquifers**. An unconfined aquifer is one where the aquifer is open to the surface (has no confining layer above) and water can infiltrate directly into it from any place on the surface above (Figure 8.22 and 8.23).
A confined aquifer is one where the saturated material is confined between two impermeable layers above and below, and only has one point of recharge, called a recharge zone (Figure 8.24). Because of having only one area of recharge, confined aquifers are more protected from surface pollution than unconfined aquifers. The confining layer acts as a barrier that keeps contaminants out of the aquifer. Unconfined aquifers do not have this protective barrier and, therefore, any contaminants above the aquifer can get into the aquifer.

Groundwater will continue to flow until it emerges as a spring, or discharges into surface water bodies on the land or in the ocean. To utilize groundwater, we drill holes (wells) into the ground and pump the water out. Sometimes we drill wells called monitoring wells or piezometers to observe and study groundwater. These monitoring wells are usually just open pipes (perforated/slotted at the one end) that are pushed into the ground to allow groundwater to rise up in them (Figure 8.25). When a well is drilled into an unconfined aquifer, the groundwater will rise up to the water table. In a confined aquifer the water rises up above the confining unit to a height equal to the hydraulic head in the aquifer at the well opening.
Figure 8.25 piezometers for groundwater sampling and monitoring (Photo Credit: Sam Mutiti)

Water Scarcity and Shortage

Water has been identified as one of the major environmental crisis facing the world today. More than one billion people in the world lack access to clean drinking water. The demand for water has grown at a very fast pace in response to the rate of global population growth. Figures 8.26, 8.27, and 8.28 illustrate this change in water use over time. It is predicted that over the next two decades, the average supply of water per person will drop by a third.
Figure 8.26: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends:
http://water.usgs.gov/edu/wugw.html
Figure 8.27: Both groundwater and surface water withdrawals have increased over time until 1980 when the withdrawals peaked and stabilized.

Figure 8.28: Trends in water withdrawals by water use (US data).
Water Scarcity and Availability

There is enough fresh water on Earth to supply every human being with enough drinking water. The main problem we face with regards to water is that it is unevenly distributed, polluted, mismanaged and wasted. Tony Allan, the author of Virtual Water, asserts that water follows money. This refers to the fact that rich countries and societies with money and affluence have more access to safe drinking water even when they live in regions without much water. It also means that areas with large supplies of water can still have water scarcity if they lack the financial resources to build the infrastructure to supply people with safe clean drinking water. Water scarcity is caused by the demand for water being greater than the supply. Scarcity can be defined as either physical scarcity or economic scarcity.

Physical water scarcity is a situation where there is an actual shortage of water, regardless of quality or infrastructure. It is estimated that about 1.2 million people around the world are experiencing physical water scarcity. Economic scarcity is a condition where countries lack the financial resources and/or infrastructure to supply their citizens with reliable safe drinking water. About 1.6 billion people are experiencing economic water shortage; most of them live in less industrialized countries. For a lot of places in the world, scarcity is a transient condition that can be reduced or eliminated by installing the right infrastructure. The major problem in less industrialized countries is the lack of political, financial and physical structures to provide water to everyone. A few rich people in these countries get the clean water while the majority of the people who cannot afford to pay for it are left out. Examples of such communities include many villages in Africa, Asia, and South America. Figure 8.29 shows communities in south east Kenya that are experiencing severe water shortages primarily due to lack of infrastructure. In these communities women have to walk long distances to get untreated and contaminated water for drinking and other household needs.
Figure 8.29: Communities in southeast Kenya without ready access to safe drinking water. (A) Groundwater in the area is too salty for consumption. B) Maasai women in Amboseli National Park collecting water from a wetland. C) Women in Magwede village in SE Kenya walking long distances to get water from a Kiosk. D) Children collecting water in Bungule Village from a water kiosk that is only open for about an hour every day. *Photo credit: Jonathan Levy, Sam Mutiti and Christine Mutiti*

**Water Quality (pollution)**

Water pollution is a major problem facing many of our surface water and groundwater sources. Contamination can both be natural due to geologic or meteorological events and anthropogenic (human causes). Human sources of contamination can be categorized as either point source or nonpoint source. **Point-source pollution** is water pollution coming from a single point, such as a sewage-outflow pipe. **Non-point source (NPS) pollution** is pollution discharged over a wide land area such as agricultural runoff and urban stormwater runoff, not from one specific location. Non-point source pollution contamination occurs when rainwater, snowmelt, or irrigation washes off plowed fields, city streets, or suburban backyards. As this runoff moves across the land surface, it picks up soil particles and pollutants, such as nutrients and pesticides.

**Types of Water Pollution**

Contamination of water resources comes in the form of chemical, biological, and physical pollution. **Chemical pollution** include things such as toxic metals, organic compounds, acidic waters from mining activities and industry, pharmaceuticals and many other chemical compounds from industries and wastewater treatment plants. Another form of chemical pollution is radioactive waste which has a significant potential to cause harm to living things. Most of the radioactive pollution comes from agricultural practices such as tobacco farming, where radioactive phosphate fertilizer is used. **Physical pollution** includes sediment pollution, trash thrown in the water bodies, thermal and other suspended load. Temperature typically affects the metabolism of aquatic fauna in a negative way and can encourage eutrophication. **Biological pollution** usually refers to pathogenic bacteria, viruses and parasitic protozoa such as *Giardia*.
*lamblia* and *Cryptosporidium parvum*. Common pathogenic microbes introduced into natural water bodies are pathogens from untreated sewage or surface runoff from intensive livestock grazing. Biological pollution is a common cause of illness and death in less industrialized countries where population density, water scarcity and inadequate sewage treatment combine to cause widespread parasitic and bacterial diseases.

**Sources of water pollution**

Most of the common inorganic chemical water pollutants are produced by non-point sources, mainly intensive agriculture and high-density urban areas. Specific inorganic chemicals and their major sources are: ammonium nitrate and a host of related phosphate and nitrogen compounds used in agricultural fertilizers; heavy metals (present in urban runoff and mine tailings area runoff). However, some inorganics such as chlorine and related derivatives are produced from point sources, ironically employed in water treatment facilities. Moreover, some of the large dischargers of heavy metals to aquatic environments are fixed point industrial plants.

High concentrations of nitrogen (N) and phosphorus (P) in water can cause eutrophication. You are seeing this whenever you notice the greenish tint to the water in our local streams and rivers during low-flow times, or if you have ever seen a green farm pond. These nutrients are primarily coming from treated wastewater (laden with P and N) being dumped into the river from sewage plants, from agricultural areas where farmers allow livestock direct access to the stream, from agricultural areas where there is intense fertilizer application, and from landscapes (homes, gardens, golf courses) with fertilizer runoff. The N and P act as fertilizers in the water and promote algae blooms. As the algae dies, it is decomposed by aerobic bacteria in the water. These bacteria use up the oxygen in the water and the low dissolved oxygen (DO) levels can result in fish kill where large numbers of fish, and other aquatic life, die because of suffocation. The dead zone in the Gulf of Mexico is a huge area of low DO that has a large negative impact on the fishing industry along the Gulf Coast near the mouth of the Mississippi River. The dead zone occurs annually when fertilizers, from farm fields in the Midwest, wash down the Mississippi river.

Improper storage and use of automotive fluids produce common organic chemicals causing water pollution. These chemicals include methanol and ethanol (present in wiper fluid); gasoline and oil compounds such as octane, nonane (overfilling of gasoline tanks); most of these are considered non-point sources since their pathway to watercourses is mainly overland flow. However, leaking underground and above ground storage tanks can be considered point sources for some of these chemicals, and even more toxic organic compounds such as perchloroethylene. Grease and fats (such as lubrication and restaurant effluent) can be either point or non-point sources depending upon whether the restaurant releases grease into the wastewater collection system (point source) or disposes of such organics on the exterior ground surface or transports to large landfills.

The most significant physical pollutant is excess sediment in runoff from agricultural plots, clearcut forests, improperly graded slopes, urban streets and other poorly managed lands, especially when steep slopes or lands near streams are involved. Other physical pollutants include a variety of plastic refuse products such as packaging materials; the most pernicious of these items are ring shaped objects that can trap or strangle fish and other aquatic fauna (Figure 8.21). Other common physical objects are timber slash debris, waste paper and cardboard. Finally power plants and other industrial facilities that use natural water bodies for cooling are the main sources of thermal pollution.
Common pathogenic microbes, in addition to *G. lamblia*, are: species of the genus *Salmonella* (which variously cause typhoid fever and food-borne illnesses); species in the genus *Cryptosporidium*, which are fecal-oral route parasites often transmitted as water pollutants and are associated with inadequate sanitation; parasitic worms that live inside faunal digestive systems for part of their life cycle (this widespread syndrome is spread partially as water pollutants, with an estimated three billion people currently affected). Hepatitis A is a viral disease, one of whose pathways of transmission is water-borne.

Groundwater can also become contaminated from both natural and anthropogenic sources of pollution. Naturally occurring contaminants are present in the rocks and sediments. As groundwater flows through sediments, metals such as iron and manganese are dissolved and may later be found in high concentrations in the water. Industrial discharges, urban activities, agriculture, groundwater withdrawal, and disposal of waste all can affect groundwater quality. Contaminants from leaking fuel tanks or fuel or toxic chemical spills may enter the groundwater and contaminate the aquifer. Pesticides and fertilizers applied to lawns and crops can accumulate and migrate to the water table.

Leakage from septic tanks and/or waste-disposal sites also can contaminate ground water. A septic tank can introduce bacteria to the water, and pesticides and fertilizers that seep into farmed soil can eventually end up in water drawn from a well. Or, a well might have been placed in land that was once used as a garbage or chemical dump site.

**Water Management**

**Water pollution control**

Pollution control begins with testing and monitoring of water quality. Water quality is usually monitored using easy to measure indicators such as pH, specific conductance (commonly referred to as conductivity), temperature, fecal and total coliform bacteria, dissolved oxygen, macroinvertebrates, and algae. Polluted sites typically have reduced DO levels, lower pH (more acidic), higher nutrient levels, more bacteria, and higher temperatures compared to less impacted or pristine sites.

Non-point source control relates mostly to land management practices in the fields of agriculture, mining and urban design and sanitation. Agricultural practices leading to the greatest improvement of sediment control include: contour grading, avoidance of bare soils in rainy and windy conditions, polyculture farming resulting in greater vegetative cover, and increasing fallow periods. Minimization of fertilizer, pesticide and herbicide runoff is best accomplished by reducing the quantities of these materials, as well as applying fertilizers during periods of low precipitation. Other techniques include avoiding of highly water soluble pesticides and herbicides, and use of materials that have the most rapid decay times to benign substances.

The main water pollutants associated with mines and quarries are aqueous slurries of minute rock particles, which result from rainfall scouring exposed soils and haul roads and also from rock washing and grading activities. Runoff from metal mines and ore recovery plants is typically contaminated by the minerals present in the native rock formations. Control of this runoff is chiefly achieved by controlling rapid runoff and designing mining operations to avoid tailings either on steep slopes or near streams.

In the case of urban stormwater control, good urban planning and design can minimize stormwater runoff. By reducing impermeable surfaces (pavement that doesn’t allow water through), then cities can reduce the amount of surface water runoff the carries pollutants into
surface water and causes flooding. Additionally, the use of native plant and xeriscape techniques reduces water use and water runoff and also minimizes the need for pesticides and nutrients. In regard to street maintenance, a periodic use of street sweeping can reduce the sediment, chemical and rubbish load into the storm sewer system.

The two common approaches to water management fall under either voluntary programs or the regulatory program. The regulatory approach has been very successful in controlling and reducing point source pollution, which was the main focus of regulations when they were first introduced. Voluntary programs, together with new amendments to regulations, have had great success in increasing conservation and also reducing diffuse nonpoint source pollution. One of the most widely used voluntary programs is Watershed Management while the regulatory approach is centered on the Clean Water Act (CWA).

Watershed Management

The watershed management approach recognizes that water contamination problems are complex and not localized to a section of a river. Water pollution problems are caused by multiple activities within the watershed and, therefore, require holistic approaches in the entire watershed. A watershed (drainage basin or catchment) is an area of land that drains to a single outlet and is separated from other watersheds by a drainage divide. Rainfall that falls in a watershed will generate runoff (if not trapped or infiltrated into groundwater) to that watershed’s outlet. Topographic elevation is used to define a watershed boundary. A focal point of water management plans is the Best Management Practices (BMPs) section. BMPs are designed to consider all of the various uses of water, maximize conservation and minimize pollution.

The regulatory approach

Water management through policy and laws seeks to clean up polluted water, prevent further pollution and apply punitive measures for polluters. In the US water-related regulations go as far back as 1899 with the Rivers and Harbors Act, also known as the Refuse Act that prohibited the dumping of solid waste and obstruction of waterways. This regulation, however, did not include waste flowing from streets and sewers. In 1948 another regulation, the Federal Water Pollution Act (which is the basis of the Clean Water Act) was enacted. This regulation covered contamination from sewage outfalls. It was created to reduce contamination of both interstate groundwater and surface waters. Through this regulation funding was made available to states and local governments for water quality management.

One of the major water-related regulations in the US is the Clean Water Act (CWA) of 1972. The regulation was very comprehensive with lots of programs and empowered the Environmental Protection Agency (EPA) to create goals, and objective laws for its implementation. The legislation has programs for both point and nonpoint source pollution. One other major piece of regulation governing water was the 1974 Safe Drinking Water Act (SDWA).

In 1974, amended in 1986, the SDWA was enacted to establish standards for many chemical constituents for public water supplied by public water agencies. In the regulations, maximum contaminant level goals (MCLG), which are non-enforceable and maximum contaminant levels (MCLs) that are enforceable where created. MCLG are what would be ideal and desirable while MCL are what should be attained in any drinking water supplied by a public municipal agency. For any carcinogen the MCLG is 0 even though many contaminants have MCLs and detection limits in the parts per billion (ppb) range. Some of them (e.g. dioxin) have
MCLs in the parts per trillion (ppt). To give you a sense of how small this ppt is, it is the same as 0.4 mm divided by the distance to the moon.

A Closer Look at the Clean Water Act

The 1972 Clean Water Acts was an overhaul of the 1948 Federal Pollution Control Act. The current regulation includes numerous programs for water quality improvement and protection. The EPA works with its federal, state and tribal regulatory partners to monitor and ensure compliance with clean water laws and regulations in order to protect human health and the environment. The Clean Water Act is the primary federal law governing water pollution. One of the objectives of the CWA was to restore and maintain the integrity of the nation’s physical, chemical and biological waters quality. The ultimate goals of the act are to establish zero pollutant discharge, as well as fishable & swimmable waters in the country. One main component of the CWA is regulations on industrial and municipal discharges into navigable US waters. The act is designed to be a partnership between states and the federal government. The federal government sets the agenda and standards while the state carries out the implementation of the law. States also have the power to set standards that are more stringent than the federal standards if needed. Under the CWA, discharge into US waters is only legal if authorized by a permit. Perpetrators of the law can be punished using administrative, civil or criminal charges. The second component of the act is providing funding for constructing municipal waste water treatment plants and other projects to improve water quality (Title II and Title VI).

The act covers both point sources (discharge from sources such as pipes) and nonpoint sources (pollution from diffuse sources such as stormwater runoff). Point sources are explicitly covered under section 402, National Pollutant Discharge Elimination System (NPDES). This section requires industries and municipalities to get permits from the EPA before discharging into US waters. The permits require the use of control technology to reduce and prevent pollution.

Water in Crisis (case studies)

- You instructor will assign you a specific case study for the course.
Bibliography


