With the utilization of irrigation systems for wastewater treatment and disposal, engineers should be aware of common contaminants, methods of on-farm wastewater treatment, and methods of risk evaluation. The primary concerns with wastewater treatment and reuse are prevention of disease and prevention of nutrient contamination and eutrophication of surface and subsurface water resources. Regulations and treatment processes have been set up as a barrier between contaminants and people. In addition, best management practices have been established for optimal and safe utilization of waste. Epidemiological studies and quantitative risk assessment methods can help to establish the risk to human health of wastewater treatment, containment, and reuse practices. Based on risk assessment, regulators establish rules for wastewater treatment and disposal. The last wall of defense against disease and death is the immune system.

Pathogens

Disease causing organisms are called pathogens. Pathogens include nonliving viruses and organisms from four of the kingdoms of life.

Prokaryotes – do not have nucleus or organelles in cells.

- Monera (bacteria). All pathogens labeled as bacteria are part of the monera kingdom. The monera kingdom also includes organisms that are important components of wastewater treatment: They degrade waste, convert ammonia to nitrate and ultimately nitrogen gas, and kill harmful pathogens in wastewater

Eukaryotes – include a nucleus and organelles

- Protista. All of the eukaryotes that don't fit in the animal, plant, or fungi kingdoms. This kingdom includes the protozoa, some of which consume bacteria in latter

phases of wastewater treatment, and others cause waterborne diseases.
- Fungi. Responsible for primary decomposition of organic waste. Fungi grow roots into organic matter, including human internal organs, and suck out the nutrients. Some waterborne diseases are caused by fungi.
- Animalia – helminth worms live in wastewater and cause disease.

Some pathogens are spread through wastewater by the fecal-oral route. The process begins when pathogens multiply in the intestinal systems of humans and animals and are then excreted. If left untreated, sewage can enter water systems and contaminate drinking water or food.

Of the pathogens transmitted through water: the most notorious are cholera and typhoid fever. There are an estimated 16 million cases of typhoid fever and 600,000 deaths per year in the world. In addition to typhoid fever, 10 million deaths per year are blamed on waterborne diseases, and between 30 % and 40 % of worldwide illnesses are transmitted by ingestion of contaminated drinking water. Lack of treatment infrastructure and regulations in many developing nations leads to a direct connection when sewage and drinking water.

Pathogens vary in size. Viruses are between 10 and 100 nm in diameter. Mycoplasma and bacteria are between 100 nm and 10 μm. Protozoa are between 1 and 100 μm. Helminth worms are the largest. The size of pathogens determines the level of filtration needed to physically remove them from water.

Viruses

Viruses are not living organisms and only function as obligate parasites: they replicate inside other cells by removing the membrane around the DNA and causing the DNA to produce mRNA that is coded to produce new viruses. Some

cause the host human cell to blow up and scatter the new viruses to infect new cells. Others cause the host cell to continually produce new viruses. Viruses are small (10–100 nm) and difficult to remove by filtration. Toxic viruses transmitted from human to human in wastewater include poliovirus, coxsackie virus, echovirus, hepatitis A, hepatitis E, caliciviruses, rotaviruses, and reoviruses.

The viruses in the gastrointestinal tract are transmitted by the fecal-oral route and are thus of concern in wastewater. One of the deadliest fecal-oral viruses is the coxsackie virus. It replicates in the intestinal lining (epithelial cells), and then it enters the bloodstream. Once it enters the bloodstream, it may cause myocarditis in the heart, meningitis or paralysis in the central nervous system, or encephalitis in the brain. The Norwalk virus (a calicivirus) causes an estimated 23 million cases of diarrhea per year in the United States. Of those cases, food and recreational water activities each cause approximately 7 million cases per year and 3.5 million cases per year are caused by consumption of drinking water.

Bacteria

Bacterial pathogens feed on organic and chemical nutrients. Most fecal-oral toxic bacteria are anaerobic heterotrophs (consume other organisms or organic matter) that grow in the intestine. They generally cause diarrhea, and some emit toxins that may puncture the intestinal lining. Some of the most harmful gastrointestinal bacteria are salmonella, campylobacter, shigella, E. coli O157:H7, and vibrio cholera

Salmonella typhi are bacteria that are spread in water and cause typhoid fever. *They* colonize on organ surfaces. Their favorite location is the gall bladder. Typhoid fever can causes fever, rashes, headache, joint pain, and even death, and has one of the highest fatality rates of waterborne diseases. Because *Salmonella typhi* are in the intestinal tract, the disease is spread through the feces and urine of infected people. Thus, if sewage water is not treated before entering the potable water system in a city, then the disease spreads rapidly. Open sewage systems are also a hazard because flies can land on the sewage and then land on food.

Infected food preparation workers can spread typhoid fever through the fecal-oral route. As they wipe their bottoms, the bacteria stick to their hands, and then they spread the bacteria during food preparation. The most famous case was Typhoid Mary in New York: Mary Mallon was a cook for rich families. One of the families, which contracted typhoid fever, hired a private investigator to determine the cause of a typhoid outbreak in their family. The private investigator found that 22 people contracted typhoid fever at 7 different jobs where Mary worked from 1900 to 1906. Mary refused to believe that she was the source of typhoid fever. In fact, when officials asked to take urine and stool samples, Mary attacked them with a carving knife. Eventually, public health authorities confined her to Brother Island. She was released after 2 years with the understanding that she would give up cooking. However, an outbreak of typhoid fever (25 people) occurred 5 years later at a location where a Mrs. Brown was the cook. Mrs. Brown turned out to be Mary Mallon. New York authorities then confined her to Brother Island for the last 23 years of her life.

Protozoa

Protozoan pathogens feed off the human gut. Some of the most harmful protozoan pathogens are giardia lambia, cryptosporidium, cyclospora, microsporidia, and toxoplasma gondii. Cryptosporidium, which can originate in runoff into streams from feedlots and dairies, is especially resistant to chlorination during the oocyst phase (Fig. 23.1).

Animal and Human Waste

Diseases associated with animal waste include salmonella, anthrax, tuberculosis, tetanus, hog cholera, and foot and mouth disease. Diseases are introduced into water bodies through runoff from fields or cattle confinement facilities. In order to prevent animal borne pathogens from entering surface water bodies, regulations often specify vegetated riparian zones next to water bodies in order to intercept pathogens before storm water runoff enters streams or ponds.

Rather than test for specific pathogens in wastewater, it is much cheaper to test for the presence of indicator organisms or surrogates that are produced in large quantities by humans or animals. It is assumed that if an indicator organism such as fecal coliform is absent, then other pathogens are absent. The ratio of different coliforms can indicate the source of water pollution (animal or human) because the ratio of fecal coliform to fecal streptococcus varies between animals and humans. Animals have a low fecal coliform to fecal streptococcus ratio (<0.6) while humans have a high ratio (4.4). Because fecal coliform is an indicator organism, maximum fecal coliform limits are established for water bodies. Public water supplies before water treatment should be less than 2,000 fecal coliforms/100 ml (MPN/100 ml). Swimming locations should have less than 200 fecal coliforms/100 ml.

Removal of Pathogens by Biological Treatment and Oxidation

Wastewater treatment removes most pathogens from water. The goal is to lower the pathogen count to an acceptable level of risk. The concentration of pathogens in the incoming
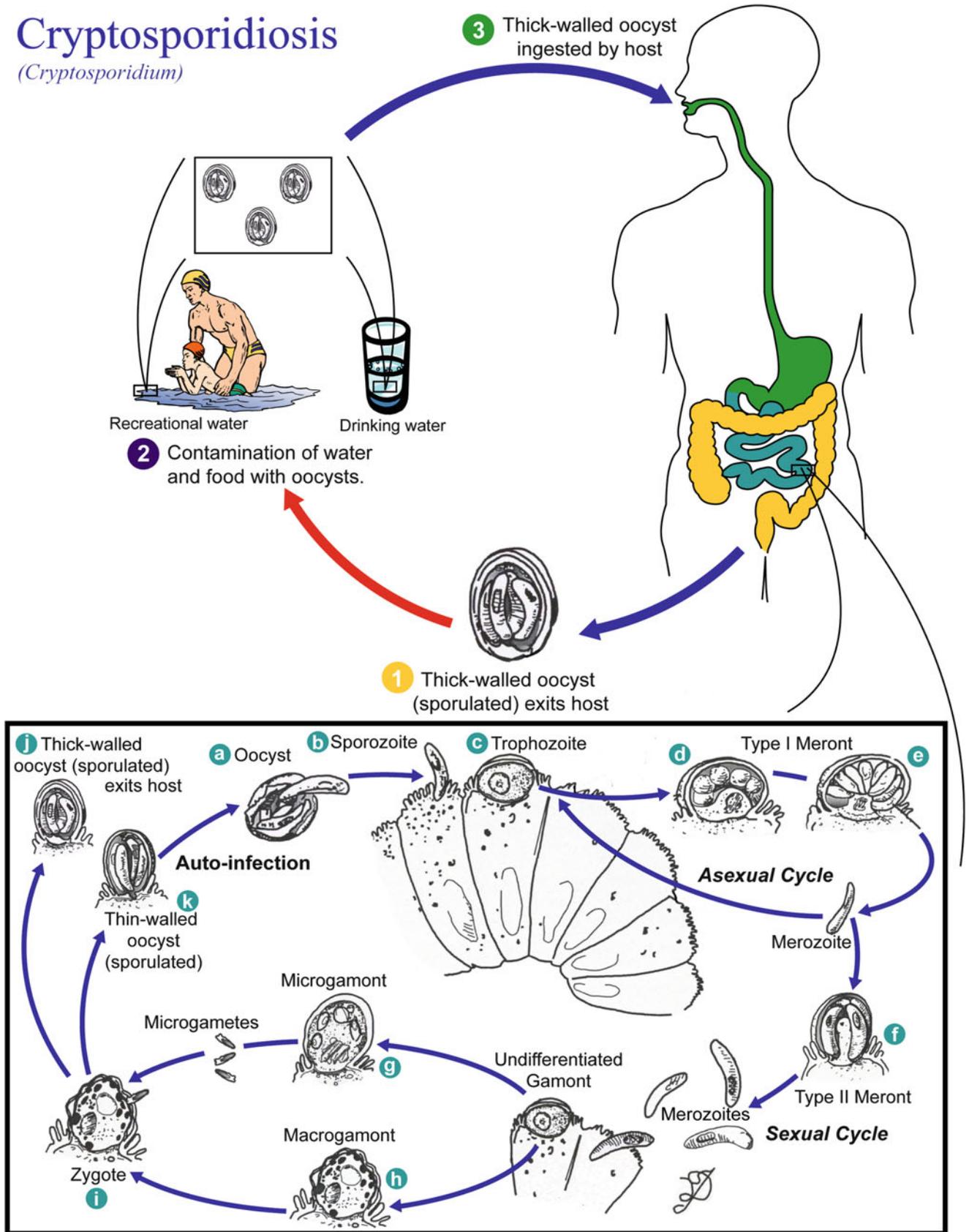
Fig. 23.1 Cryptosporidium life cycle (Credit CDC/Alexander J. da Silva)

Table 23.1 Typical concentrations of organisms in raw and treated (prior to chlorination) wastewater (organisms/100 ml) (Source: Charles Gerba, University of Arizona)

Organisms	Raw sewage	Treated
Enteroviruses	10–100	1–10
Salmonella	100–10,000	10–10,000
Coliforms	10^7–10^9	10^6–10^8
F-RNA coliphages	10^6–10^7	10^5–10^6
Somatic coliphages	10^6–10^7	10^5–10^6
Bacteroides phages	10^4–10^5	10^3–10^4

wastewater stream is one factor that determines the effluent pathogen concentration. In general, developing countries have much higher pathogen counts in raw wastewater because there is a higher incidence of disease. Other factors that influence pathogen concentrations in wastewater are socioeconomic status, per capita water use, and time of year. Typical concentrations of pathogens in raw and treated wastewater are shown in Table 23.1. In general wastewater treatment decreases the concentrations of many microorganisms by approximately 10 times or "1 log removal."

The ability of pathogens to survive in the environment determines the required treatment time. Survival time is influenced by environment, type of organism, and life phase. For example, the cyst and oocysts phases in giardia and cryptosporidium, respectively, are much more resistant than the latter phases of life. Environmental factors that decrease pathogen survival time are high temperature, low water content in soils, antagonistic microflora, and extreme pH (<3 or >9). Soil or organic matter that adsorb organisms increases survival time but also decreases transport, which may decrease the hazard to the environment since organisms are not leached to transported to groundwater or surface water.

Disinfection, the process of killing pathogens by oxidation, is a final step in wastewater treatment. Disinfection methods include chlorine, UV light, ozone, chlorine dioxide and chloramines; the latter three are generally used for disinfection of drinking water. Chlorine and other oxidants kill harmful bacteria by entering into the bacterial cell wall and oxidizing the cell wall, or entering within the cell and disrupting biochemical processes such as protein formation. The goal of the disinfection step is generally to kill 99–99.9 % of microorganisms that survived biological wastewater treatment. The effectiveness of disinfectants is a function of the contact time and the concentration of the disinfectant in water (C* t) where C is in mg/L and t is in minutes. For example, if contact time is 30 minutes, and chlorine concentration is 1 mg/L, then Ct = 30. Typical Ct values for chlorine disinfection are 7,200 for helminth worms, 0.1–1.0 for viruses, and 0.001–0.01 for E. coli. Viruses, protozoa, and helminth worms are the most resistant to disinfection.

Historically, waterborne diseases were common until the introduction of chlorine as a disinfectant for public water systems; the incidence of typhoid fever in the United States dropped from an average of 25 incidences per 100,000 people per year to approximately 400–500 cases per year in the entire nation (less than 0.2 incidences per 100,000 people). Thus, the per capita disease frequency dropped by 100 times due to the introduction of chlorine into public water supplies (Fig. 23.8).

As chlorine gas is dissolved in water, it reacts with water to form hypochlorous acid (HOCl), hydrogen (H^+) and chloride ions (Cl^-):

$$Cl_2 + H_2O \Leftrightarrow HOCl + H^+ + Cl^-.$$

Chlorine exists in two forms within water, hypochlorous acid (HOCl) and hypochlorite (OCl^-). The hypochlorous acid and hypochlorite, OCl^-, equilibrium in water is

$$HOCl \Leftrightarrow H^+ + OCl^-.$$

Hypochlorous acid (free chlorine) is 80 times more effective at killing bacteria than hypochlorite because the hypochlorite has a charge and is repelled from the cell. Hypochlorous acid is the primary form of chlorine in acidic waters, pH < 6.5. Thus, if the initial pH is high, acid must often be added in concert with chlorine in order to drop the pH to 6.5.

Ozone is a strong oxidizer and can be used in place of chlorine; it is not used with chlorine because it oxidizes the chlorine. The problem with ozone disinfection is that ozone quickly degrades, and there is no residual ozone in downstream pipe systems. However, it is a stronger oxidizer than chlorine (more lethal to some organisms).

The effectiveness of oxidants against trace organics is oxidant and contaminant specific. For example, ozone and chlorine deactivate estrogens and antimicrobials; however, ozone is much better than chlorine at removing psychosomatic and similar drugs. Concentration also is a factor. The Southern Nevada Water Authority tried different levels of ozone between 3 and 8 mg/L. At 8 mg/L, all of the compounds were deactivated. They found that degradation is most closely correlated with the concentration of the free residual, rather than the total mass dose. The free residual is what is left over after initial oxidation of organic compounds. One problem with oxidizing trace organics is that the byproducts of oxidation (deactivated organics) may be just as harmful as the original chemicals.

The Immune System

There is a last line of defense if wastewater treatment fails and pathogens enter the body, the human immune system. The immune system produces antibodies that are tailored to

fight specific pathogens that invade the body. The key factor in the fight against pathogens is the relative time required to produce antibodies or other defensive functions in comparison to the reproductive rate of the pathogen. The concentration of pathogens that are ingested and their rate of multiplication, as well as the health of the immune system, determine the resistance to disease.

The immune system is constantly looking for foreign cells in the body by looking for foreign markers on the surfaces of cells, called epitopes. When an invading cell is recognized, stem cells are triggered to become two types of immune cells, lymphoid cells and myeloid cells. B cells are a lymphocyte (lymphoid cell) that is produced after the body recognizes an antigen. The B cells produce plasma cells that produce antibodies that will fight one specific type of pathogen. The antibodies attach themselves to a pathogen and trigger a series of biochemical reactions that destroy the pathogen. Macrophages are myeloid cells that consume pathogens and break them down into peptide chains that are then displayed on the surface of the macrophage. Another lymphocyte, helper T cells, records the shape of the peptide chain and then signals B cells to start producing plasma cells.

Cytotoxic T cells (also known as killer T cells) attach to pathogens and kill them with granules filled with chemicals. Phagocytes are white cells that consume pathogens. Unlike antibodies, these cells do not recognize specific pathogens; they just consume any foreign cell. Other complex systems are designed to kill specific types of pathogens and operate in specific parts of the body such as the mucus membranes.

The body builds up immunity to disease because some of the T cells and B cells used in the initial defense remain after the battle as memory cells. The next time that the pathogen is encountered, the immune system is ready to respond. Vaccines are inactive pathogens that trigger an immune response without the danger of disease. Thus, T cells and B cells remain and will respond quickly to the real pathogens when they are encountered.

Normally, the body is able to manufacture immune cells and antibodies quickly enough to stop the multiplication of pathogens within the body. However, some pathogens can overcome the immune system. For example, when *Salmonella typhi* bacteria are ingested into the digestive tract, they are consumed by monocytes in the bloodstream. However, rather than the monocytes killing the *Salmonella typhi*, the bacteria multiply within the monocyte for a period of 1–2 weeks. Then the bacteria spill out into the bloodstream and can overwhelm the immune system. The large numbers of bacteria in the bloodstream cause the body to develop a high fever. Eventually, the *Salmonella typhi* enter the digestive tract and other organs. Once in the intestines and other organs, the bacteria give off a toxin that causes inflammation and can even puncture the lining of the intestines or cause bursting or leakage in other organs. Victims of typhoid fever are often sick for several months and may die. However, if people have been inoculated against typhoid fever, then the process is aborted before it has a chance to begin.

The rate of infection depends on the organism and the host human. For example, only half of normal healthy adults exposed to enteric (intestinal) viruses (polio and Coxsackie) become infected while 100 % of people exposed to measles become infected. Healthy adults are less likely to become infected than small children, the elderly, and those with compromised immune systems. In addition, the level of infection can vary between persons. Some infected people do not show any sign of disease while others may have a mild illness, severe disease, or death.

Risk Assessment

No human activity is absolutely safe; however, the goal is to make the activity as safe as possible. The 10 most dangerous activities in America, in order, according to a survey of experts, are smoking, drinking alcoholic beverages, driving a car, handguns, surgery, motorcycles, x-rays, electric power, and swimming. Drinking water is not even listed among the top 30 most dangerous activities. Water systems are designed with the criterion that no more than one out of 10,000 people each year become infected with a waterborne pathogen (USEPA Surface Treatment Rule). In comparison, one out of every 2 people in America become sick each year from a food borne pathogen (food poisoning).

Epidemiological studies look at past outbreaks of disease and associate the outbreaks with given practices. In quantitative risk assessment, the possibility of each of the steps in disease transmission is multiplied in order to arrive at the total probability of disease transmission. The process of risk analysis includes three steps: risk assessment – determining the probability that an adverse event will occur and its magnitude, risk management – considers various regulatory options to minimize the risk, and risk communication – transfer of risk information to experts and non-experts.

Quantitative risk assessment has four steps:

1. Hazard Identification – identifying the contaminant (i.e. Salmonella)
2. Dose–response Assessment – relationship between the number of organisms ingested and the probability of becoming infected (i.e. how many does it take to make you sick)
3. Exposure Assessment – Determining the concentration of a pathogen in the water and estimating amount of contact and possibly ingestion.
4. Risk Characterization – Estimating the potential impact (infection, disease) of a pathogen based on the severity of its effects.

Hazard identification is the process of identifying the disease carrying organism, finding the transmission pathway, determining the population exposed to the disease, and quantifying the health effects of the disease.

The dose–response relationship is a function of the type of pathogen and the human immune system. The risk of infection increases as the ingested quantity of pathogen increases. In theory, a single microorganism can multiply and cause disease, but for some pathogens, a minimum quantity of pathogens is required to overwhelm the immune system. The response in a dose–response study is also called an endpoint. Endpoints in a study could be visible symptoms, disease, or death.

The infection rate is the percent of people exposed to the disease who become infected.

Exposure assessment is the product of the assumed concentration of the pathogen, the amount ingested per unit of time, the amount of time of exposure.

In the following example, the risk of disease transmission is calculated for a landscape irrigated with reclaimed wastewater by making the following calculations:

1. Concentration of pathogens in irrigation water
2. Concentration in soil after irrigation
3. Duration of human exposure to soil
4. Rate of ingestion of soil
5. Dose–response

Example 23.1 Partially treated wastewater from an overloaded wastewater lagoon is used for landscape irrigation in a water-stressed city. Calculate the risk of exposure to *Salmonella typhi* bacteria for 50 children who play for 8 hours in the landscaped area. Water content in the soil is 15 % by volume. Soil bulk density is 1.15 mg/ml. The concentration of Salmonella in the lagoon is 10^3 MPN/100 ml. MPN refers to the most probable number. It is found by counting bacterial colonies on plates or gels in the lab. Salmonella can survive in soil for an extended period, so assume that the concentration of salmonella in the soil water is the same as concentration in the irrigation water. Assume that the salmonella are not preferentially absorbed in the upper range of soil by organic matter or clay particles. Children playing in a soil normally ingest approximately 500 mg (size of a peanut) of soil per 8 hours of playtime.

The concentration of salmonella in soil is calculated as follows:

1,000 MPN/100 ml water * 15 ml water/100 ml soil
= 150 MPN/100 ml of soil.

The volume of soil ingested is the mass of the soil divided by the bulk density. Assume that the.

500 mg soil ingested/1.15 mg/ml soil = 435 ml soil

435 ml soil*150 MPN/100 ml soil = 650 Salmonella bacteria
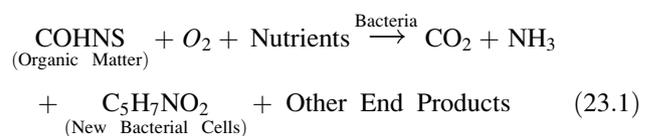
If this were a real study, statistical methods would be used to determine the distribution of ingestion rates; however, in this case, assume that 10 children ingest a greater amount than the average: between 1,000 and 10,000 salmonella bacteria. Thus, 40 children ingest between 0 and 1,000 bacteria. Studies have shown that 1,000 of bacteria must be swallowed at one time in order to cause infection by salmonella. Thus, assume that the children that ingest less than 1,000 salmonella bacteria will probably not become infected. Based on a salmonella dose–response curve, approximately 20 % of children (2 out of the 10) exposed to between 1,000 and 10,000 Salmonella bacteria will become infected. Thus, approximately 2 children out of the total of 50 (4 %) will become infected.
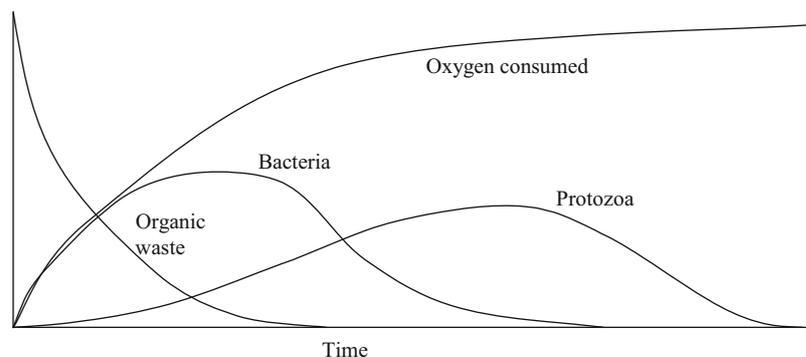
Biochemical Oxygen Demand (BOD)

In addition to causing disease, wastewater can have other detrimental effects. Waste is a food source for microorganisms. In order to consume the waste (respiration), microbes require oxygen. Thus, releasing wastewater into streams can deplete oxygen in the stream and kill wildlife. If wastewater with a heavy organic load is added to surface waters, the dissolved oxygen concentration can decrease from the normal 5–7 mg/L to 2 mg/L or less, a level at which fish die. In order to prevent oxygen depletion, regulations restrict the oxygen demand of wastewater released into streams.

Biochemical Oxygen Demand (BOD) is defined as the amount of oxygen required for the bacterial decomposition (oxidation) of organic matter under aerobic conditions at a standard temperature and incubation time. The amount of oxygen required varies with concentration of organic matter, concentration of bacteria, nature of organic matter, and type of bacteria. Organic matter undergoes two primary transformations in the process of BOD exertion: oxidation and synthesis and endogenous respiration
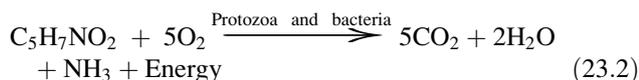
Oxidation and Synthesis

$$\underset{(Organic\ Matter)}{COHNS} + O_2 + Nutrients \overset{Bacteria}{\longrightarrow} CO_2 + NH_3$$
$$+ \underset{(New\ Bacterial\ Cells)}{C_5H_7NO_2} + Other\ End\ Products \qquad (23.1)$$

Fig. 23.2 Oxygen demand and uptake of organic waste and microorganims

Endogenous Respiration

$$C_5H_7NO_2 + 5O_2 \xrightarrow{\text{Protozoa and bacteria}} 5CO_2 + 2H_2O$$
$$+ NH_3 + \text{Energy} \qquad (23.2)$$

When organic matter (CHONS) is oxidized (Eq. 23.1), the resulting bacterial cells have the formula: $C_5H_7NO_2$. Dead bacterial cells are then consumed by protozoa in a process called endogenous respiration. The result of endogenous respiration is stable, nontoxic byproducts.

The test for BOD is a well-established procedure. The BOD of a sample is measured by adding a sample aliquot to a bottle and filling the bottle with dilution water, which is distilled water supplemented with buffering agents, nutrients, and trace metals and aerated to raise the concentration of dissolved oxygen to saturation. The initial dissolved oxygen concentration (DO_i) of the sample is measured, and it is then incubated in the dark at a constant temperature, usually 20°C. At the end of the test, the dissolved oxygen concentration (DO_f) is measured.

$$BOD = (DO_i - DO_f)\frac{V_b}{V_s} = \Delta DO \ (DF) \qquad (23.3)$$

where

DO_i = initial dissolved oxygen concentration, mg/L,
DO_f = final dissolved oxygen concentration, mg/L,
DF = dilution factor: volume of the bottle divided by volume of the sample,
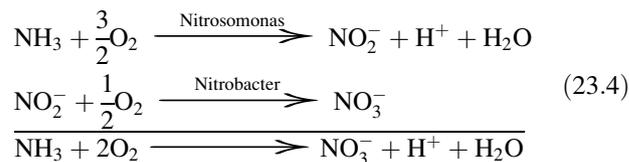V_b = volume of the bottle, ml,
V_s = volume of sample added to the bottle, ml,

The traditional BOD test, developed in England, is 5 days long: it took 5 days for water in the Thames River to travel from London (source of sewage) to the ocean. The 5-day test is called BOD_5, and typical wastewater plant effluent standards are 30 mg/L BOD_5. In the early stages of oxidation of organic matter, oxygen uptake is approximately equal to decrease in BOD (Fig. 23.2). This process generates new bacteria cells. In the initial phase, the protozoans contribute to organic removal but are not as efficient as the bacteria in competing for substrate (organic matter). As food supplies

for microorganisms become scarce, bacteria begin to die off or predate on other living and dead bacteria. Eventually, the number of protozoans increases as they consume bacteria. During these processes, the organic matter is recycled through a number of organisms, with oxygen being consumed as the organic matter is metabolized for each biomass.

The BOD_5 value for raw domestic sewage is 200–300 mg/L while that for animal waste effluent ranges from 6,000 (dairy and beef) to 13,000 (swine) mg/L. Anaerobic lagoon or anaerobic digestion systems can reduce animal waste BOD to a range between 200 mg/L to 4,000 mg/L, depending on the source and the detention time. Wetlands can further decompose the waste; however, animal waste effluent from anaerobic lagoons must be diluted in order to reduce the toxic ammonia concentration that would kill the wetlands plants.

The primary products of the initial breakdown of organic matter are CO_2, H_2O, and NH_3 (ammonia). Oxidation of ammonia to nitrate (nitrification) constitutes a second stage BOD, known as nitrogenous BOD (NBOD) whereas the first stage is often called carbonaceous BOD (CBOD). NBOD occurs simultaneously with the latter stages of CBOD. Nitrification (nitrogenous oxidation) stoichiometry is as follows:

$$NH_3 + \frac{3}{2}O_2 \xrightarrow{\text{Nitrosomonas}} NO_2^- + H^+ + H_2O$$
$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{\text{Nitrobacter}} NO_3^- \qquad (23.4)$$
$$\overline{NH_3 + 2O_2 \xrightarrow{\hspace{2cm}} NO_3^- + H^+ + H_2O}$$

The oxidation of ammonia begins after 7 or 8 days of wastewater treatment have passed. Thus, the BOD_5 primarily measures the CBOD and does not include the NBOD.

Nutrients and Waste in Soils and Wetlands

Although nutrients are needed for crop growth, they are pollutants when discharged into the environment from agriculture or wetlands. The major nutrients of concern in wastewater are nitrogen and phosphorous. Excess concentrations of these nutrients cause algal blooms in streams (eutrophication), and nitrate in water can cause blue baby disease – methemoglobimia:
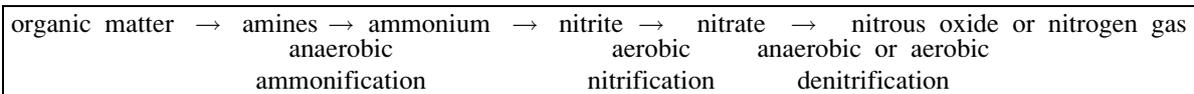
the nitrate replaces oxygen in the blood stream and the baby turns blue. Thus, nitrate discharge concentration in surface water and ground water is limited to 10 mg/L NO_3-N. This is the same as 42 mg/L NO_3^-, as it is specified in Europe. Wastewater effluent standards may include nitrate, ammonia, and/or total nitrogen and are generally in the range of 10 mg/L. Often, design requirements for nitrogen are lower in summer than in winter for natural wastewater systems because bacteria are more active at higher temperature.

Nitrogen exists in many forms in water: organic nitrogen, amines, ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_{23-}), nitrate (NO_3^-). Total nitrogen, TN, includes all nitrogen forms. Total ammonia includes ammonia and ammonium ion. Nitrogen also exists as nitrogen gas (N_2), and nitrous oxide gas (NO_2) in the atmosphere. The goal in wastewater treatment of nitrogen is to convert the total nitrogen in water to nitrogen gas or to remove the nitrogen by plant uptake.

Bacteria sequentially transform nitrogen from one form to another in soils and wetlands. The nitrogen cycle includes anaerobic (no oxygen) bacteria, aerobic (oxygen) bacteria and facultative (anaerobic or aerobic) bacteria.

The steps from conversion of organic N to NO_3^- (nitrate) are called mineralization, which includes ammonification and nitrification.

organic matter → amines → ammonium → nitrite → nitrate → nitrous oxide or nitrogen gas
anaerobic   aerobic   anaerobic or aerobic
ammonification   nitrification   denitrification

In soils, nitrate is a much greater groundwater pollution hazard than ammonium. The reason for this is that clay particles in soil have a negative surface charge; thus, they tend to absorb positively charged ammonium. In contrast, nitrate is not absorbed, and is washed directly through the soil to the groundwater when water leaches through the soil.

In some cases, farming practices release nitrate at inopportune times. For example, in the Midwestern United States, nitrogen in plant matter that is disked into the soil during fall mineralizes in winter (becomes nitrate). Then, spring rains wash the nitrate through the soil and into the groundwater, drains, and streams. In irrigated areas, excess irrigation or storms after a heavy fertilization can leach large quantities of fertilizer through the soil. Thus, this is a problem that has little relation to fertilization but primarily to drainage and farming practices.

Application of manure, biosolids, and other waste products is a common method of fertilization and waste disposal. The timing of waste application is important. For example, nitrogen in fresh manure is approximately 60–80 % in the organic form (NRCS AWMFH). Anaerobic lagoon effluent has an organic fraction of approximately 20–30 %. Organic N is not available to crops and is immobile in soil. When organic N is applied to soils, it takes 4–5 months for 40–90 % of the organic N to be converted to ammonia and then to nitrate in cold climates. However, in warmer climates, total mineralization may take place in 2 months (NRCS AWMFH).

Ammonia (NH_3) is the unionized form and ammonium ion (NH_4^+) is the ionized form. Ammonia is not available to plants, but ammonium ion is available. Ammonia and ammonium ion are in equilibrium in water, with the percent of unionized ammonia dependent on temperature and pH. Although generally not a concern in soils, ammonia is a concern in wetlands and water bodies because it kills plants and fish. Ammonia is so toxic to fish that the EPA's maximum recommended limit for unionized ammonia in surface waters is 0.02 mg/L.

The nitrogen cycle is complex in wetlands, with many sources, sinks, and processes (Fig. 23.3). There are three sources of ammonia in wetlands: hydrolysis of urea, bacterial decomposition of fecal matter, and oxidation of cells (Fig. 23.3). In addition, denitrification and degradation of wetlands plants can result in formation of ammonia. Ammonia is lost by volatilization to the atmosphere if the total ammonia (unionized) concentration in a wetland is greater than 20 mg/L. If ammonia concentration is low, then the primary ammonia removal mechanism in wetlands is absorption to soil and organic particles or nitrification. Nitrification of ammonia in wetlands is limited by the rate that wetlands plants add oxygen to the water.

In wetlands, negatively charged nitrate does not absorb to soil particles and must be removed by plant uptake or bacterial denitrification. Denitrification takes place in anaerobic conditions so anaerobic zones are often added to wetlands in order to complete the nitrogen cycle. As with nitrification, denitrification is a two-step process that involves the creation and destruction of nitrite (NO_2^-). Nitrate is also taken up by plants so nitrate removal by the wetland can be increased if plants are periodically harvested.

Herbaceous aquatic plants pump oxygen into the water (Fig. 23.4) and facilitate nitrification and denitrification by

Fig. 23.3 The nitrogen cycle in wetlands (Credit NRCS, NEH 637–03)

Fig. 23.4 Oxygen flow into wetlands induced by herbaceous aquatic plants

Fig. 23.5 Microenvironments with high oxygen near plant roots (Credit NRCS, NEH 637–03)
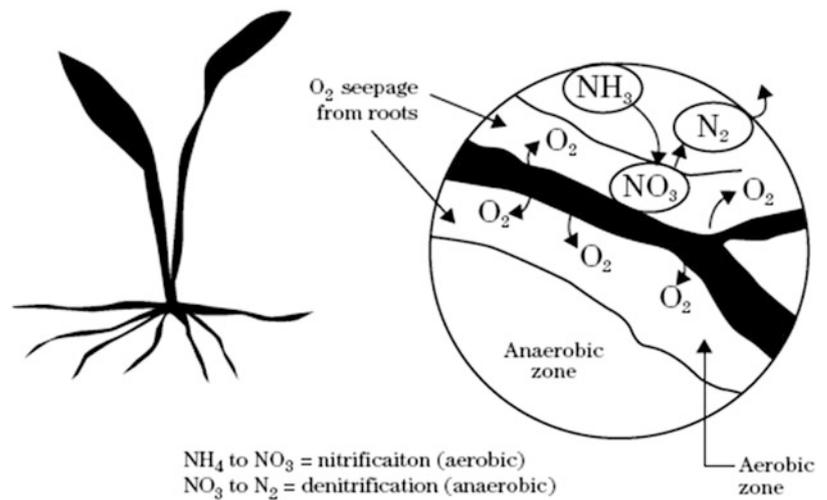
creating microenvironments with high oxygen near the roots (Fig. 23.5).

The soil in wetlands is an important part of the treatment process. Plants suck wastewater into soil as they draw in water for evapotranspiration. As the wastewater moves through the soil, it is filtered and treated by microorganisms. Organic nitrogen associated with suspended solids can be removed via sedimentation and incorporated into the soil matrix.

Dead plant litter within the water is an important substrate for microbial growth. Plant litter, along with nondegradable solids, and dead microorganisms settle on the soil surface and form a peat layer. This layer absorbs metals and phosphorous. In fact, 90 % of wetlands treatment takes place on microbes that are attached to plant litter (Kadlec and Knight 1996).

In addition to nitrogen, the other primary nutrient of concern is phosphorous. Phosphorous exists in three forms – organic, soluble, and attached – with 70 % of phosphorous in fresh animal waste in the organic form. Soluble phosphorous is used by plants. Attached phosphorous is bound to positively charged cations such as calcium. For example, gypsum, calcium phosphate ($CaPO_4$) is attached phosphorous. Phosphorous transformations in soils are as shown in Fig. 23.6.

If not overloaded, agricultural soil is an effective nutrient and contaminant filter (Fig. 23.7). Plant uptake and microorganisms remove most of the nutrients from effluent. However, if soils are overloaded with effluent, then contaminants can leach to the ground water. The upper soil region is the location with the most microorganisms and the most rapid waste treatment. Once waste reaches the groundwater, little waste treatment takes place.

The NRCS lists the following animal waste practices (Fig. 23.8) that can lead to environmental contamination.

1. Contaminated well: Well water contaminated by bacteria and nitrates because of leaching through soil.
2. Waste storage structure: Poisonous and explosive gases in structure.
3. Animals in poorly ventilated building: Ammonia and other gases create respiratory and eye problems in animals and corrosion of metals in building.
4. Waste applied at high rates: Nitrate toxicity and other N-related diseases in cattle grazing cool-season grasses; leaching of NO3 and microorganisms through soil, fractured rock, and sinkholes.
5. Discharging lagoon, runoff from open feedlot, and cattle in creek: (a) Organic matter creates low dissolved oxygen levels in stream; (b) Ammonia concentration reaches toxic limits for fish; and (c) Stream is enriched with nutrients, creating eutrophic conditions in downstream lake.
6. Runoff from fields where livestock waste is spread and no conservation practices on land: P and NH4 attached to eroded soil particles and soluble nutrients reach stream, creating eutrophic conditions in downstream lake.
7. Eutrophic conditions: Excess algae and aquatic weeds created by contributions from items 5 and 6; nitrite poisoning (brown-blood disease) in fish because of high N levels in bottom muds when spring overturn occurs.
8. Leaching of nutrients and bacteria from poorly sealed lagoon: May contaminate ground water or enter stream as interflow.
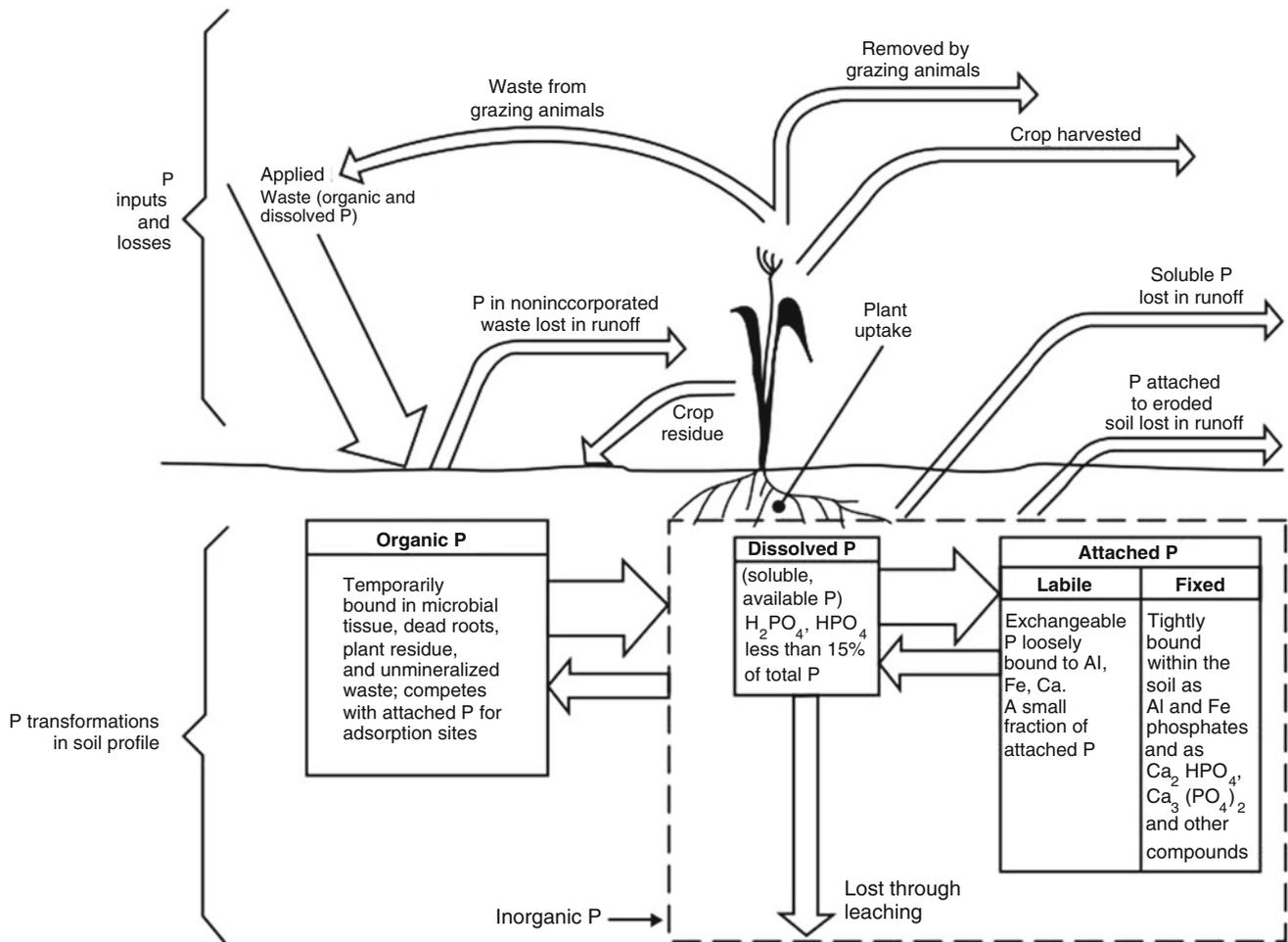
Fig. 23.6 Phosphorus inputs and losses at a waste application site and phosphorus transformation within the soil profile (abbreviated phosphorus cycle) (Credit NRCS AWMFH)

In addition to ground water pollution, surface water run-off from agriculture impacts streams and other water bodies. Approximately 20,000 miles of streams and rivers in the US are negatively impacted by animal waste effluent BOD and nutrients.

Trace Chemicals

Pesticides and other agricultural chemicals are facing increasing scrutiny and regulation. Pesticides such as atrazine, diuron, and hexachlorocyclohexane have been found in drinking water. Animal feeding operation chemicals, such as growth stimulants, are a major concern. Other trace chemicals that may be in soil include selenium and other metals. Soils and wetlands have been found to remove many of the trace chemicals that originate in cities.

Monitoring trace contaminants is a major challenge. Many of the tests are extremely expensive. Even if it was possible to monitor all of the chemicals in wastewater, a multitude of chemical test results confuses industry, regulators, and the public. As a result, the use of surrogates or indicators to detect the general presence of hazardous chemicals is more practical.

- Surrogates: bulk measurements of parameters such as total organic carbon (TOC) that indicate the presence of organic chemicals.
- Indicators: specific measurements of individual chemicals that are representative of other chemicals within a group of similar chemicals.

There are many surrogates: TOC, BDOC (biologically degradable organic carbon), DOC (dissolved organic carbon
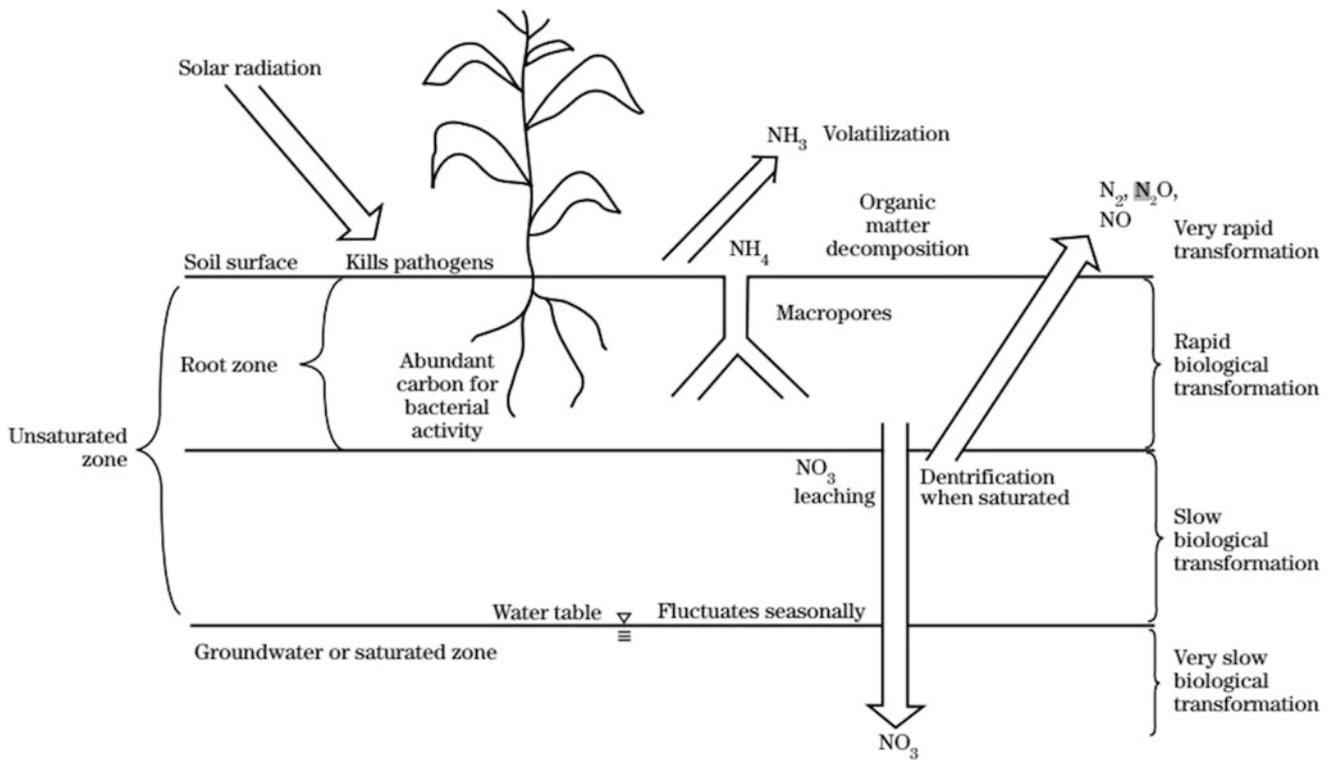
Fig. 23.7 Waste treatment in soil (Credit: NRCS AWMFH)
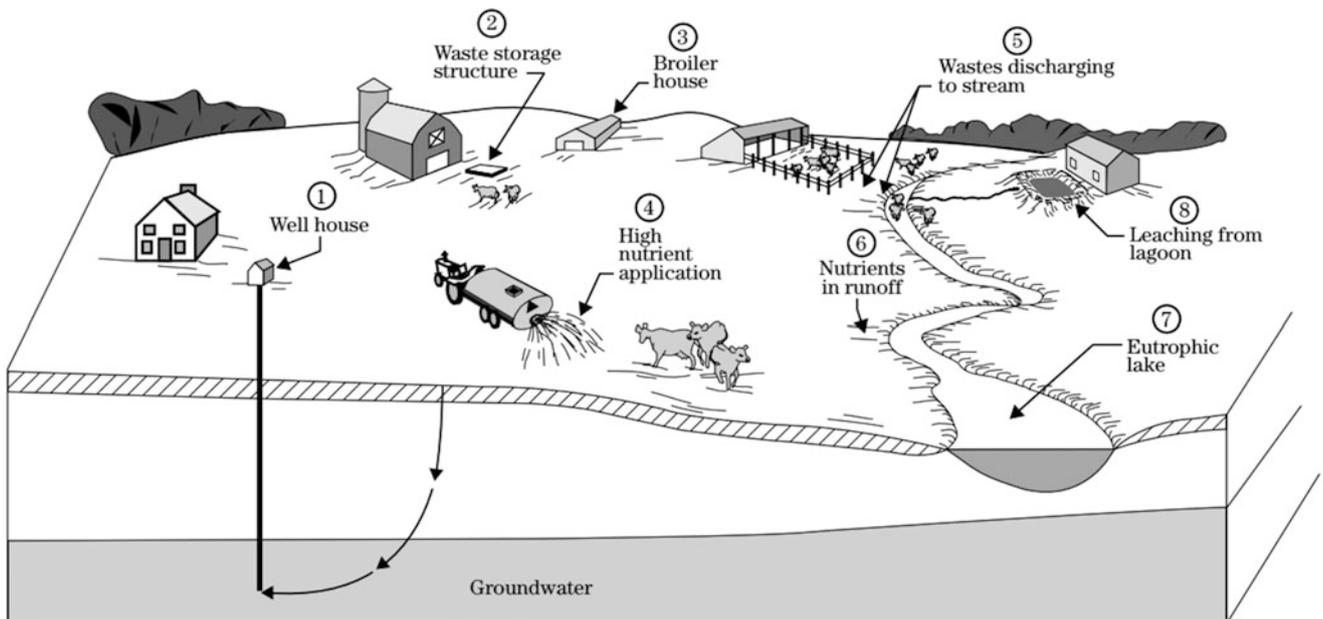
Fig. 23.8 Animal waste management practices that lead to environmental contamination (Credit: NRCS AWMFH)

in clean water after sediments have settled), color, COD (chemical oxygen demand, no microorganisms), BOD (biological oxygen demand) UV absorbance/fluorescence, particle size distribution, absorption analysis, and physical characteristics. The selection of indicators and/or surrogates depends on the types of wastewater treatment processes and the organics of concern. It is important select representative indicators of the different groups of chemicals. The suite of indicators should avoid duplication or gaps. Due to the concern with trace organics, the surrogates used for water testing have changed. The old view was to test for the following surrogates: BOD (organisms consuming oxygen), COD (chemical oxygen demand, no living organisms), TKN (total Kjeldahl nitrogen), VSS (ammonia and other solids that volatilize), pesticides, and solvents. New tests often include DOC, DON (dissolved organic nitrogen), TOC, DBP, endocrine activity (EDC), and PCPP (pharmaceutical chemicals).

Degradation rate is a major factor in the government's assessment of the level of hazard of chemicals. Even within some classes of compounds, slight differences in chemistry can change the degradation rate. For example, among steroids, those with an attached OH group degrade much more slowly than those without the OH group. Even though a chemical degrades, there is more to the story. The metabolites (degradation products) may be more harmful than the original chemical.

In countries with unregulated industrial discharge into sewage systems, there may be high concentration of heavy metals in irrigation water (Cd, Cu, Zn, Ni, Pb). These are generally not removed by conventional wastewater treatment. Chemicals may become concentrated in agricultural crops irrigated by this water. This is of concern because heavy metals cause many diseases when they are in high concentrations. Alternative treatment systems such as wetlands and soil aquifer treatment have in some cases been found to be more effective at removing heavy metals than conventional wastewater treatment systems.

Physical Characteristics

In addition to chemical and biological characteristics, four physical properties are used to describe waste streams: weight, volume, total solids, and moisture content. Total solids are divided into volatile solids and fixed solids. Wastes that are more than 95 % liquid are called liquid waste; wastes with less than 75 % liquid are a solid; wastes with a moisture content between 75 % and 95 % are called a slurry. Physical, as well as chemical and biological waste characteristics, of human and animal waste, as excreted, are given in Table 23.2.

Although physical and chemical characteristics of excrement from humans and animals are similar, raw human sewage (from developed countries) and animal waste effluent may have dramatically different characteristics because of high dilution in human sewage systems (Table 23.3). In a water short country or in low water flow facilities such as mobile home parks, per capita waste flow rate is low, and, as a result, concentration of human waste in sewage is higher.

Table 23.2 Waste characteristics – as excreted (Data from NRCS AWMFH)

		Human – adult	Beef – mature steer	Dairy – lactating cow	Swine – grower	Chicken – layer
Mass/day	kg/d/1,000 kg	30	59	80	63	60
Volume/day	L/d/1,000 kg	34	59	81	62	58
Moisture	%	89	88	88	90	75
TS (total solids)	% w.b.	10.9	11.6	12.5	10	25
TS (total solids)	kg/d/1,000 kg	3.3	6.8	10	6.3	15
VS (volatile solids)	kg/d/1,000 kg	1.9	6.0	8.5	5.4	11
FS (fixed solids)	kg/d/1,000 kg	1.4	0.74	1.5	0.94	4.3
COD (carbonaceous oxygen)	kg/d/1,000 kg	3	6. 1	8.9	6.1	14
BOD$_5$	kg/d/1,000 kg	1.3	1.4	1.6	2.1	3.7
N (elemental nitrogen)	kg/d/1,000 kg	0.2	0.31	0.45	0.42	0.83
P (elemental phosphorous)	kg/d/1,000 kg	0.02	0.11	0.07	0.16	0.31
K (elemental potassium)	kg/d/1,000 kg	0.07	0.24	0.26	0.22	0.34
C:N ratio			11	10	7	7

Table 23.3 Characteristics of human and dairy cow wastewater (Data from NRCS AWMFH)

Component	Units	Raw human WW	Secondary human WW	Raw dairy (Milk house + parlor)	Anaerobic dairy lagoon effluent (MH + MP)	Aerobic dairy lagoon (MH + MP)
Volume (L/d/1000 kg)		5600	5300	37	37	37
L/d/person (50 kg/person)		280	260			
Moisture	%	99.95	99.95	99.4	99.75	99.95
TS (total solids)	mg/L	500	500?	6,000	2500	500
VS (volatile solids)	mg/L	350	0	4,200	1100	200
FS (fixed solids)	mg/L	150	0	1,800	1400	300
COD (carbonaceous)	mg/L	450	0	5,000	1500	150
BOD_5	mg/L	200	25	1,000	350	35
N (elemental)	mg/L	30	20	200	200	20
$NH_4 - N$	mg/L	0	10		120	12
P (elemental)	mg/L	10	10	100	58	10
K (elemental)	mg/L	10	12	300	500	0

Questions

1. What is the fecal-oral pathway of disease transmission?
2. Pathogens come from four kingdoms of life: list and describe them.
3. List viruses that cause waterborne disease.
4. List bacteria that cause waterborne disease.
5. List protozoan parasites that cause waterborne disease.
6. Look up three of the diseases listed in Table 23.1 on the Internet and describe the symptoms.
7. Why are indicator organisms used and how do they distinguish between different sources of disease?
8. List the factors that determine wastewater treatment plant discharge pathogen concentration.
9. Calculate the required contact time in order to remove 99.9 % of remaining E-coli at a chlorine concentration of 3 mg/L
10. What was the key factor that reduced typhoid fever in the United States?
11. Why aren't ozone and chlorine used together?
12. What environmental factors influence pathogen fate in the environment?
13. Give a brief summary (one paragraph) of how the body fights pathogens.
14. How do vaccines help the body fight disease?
15. Why must acid be injected at the same time as chlorine during disinfection?
16. Redo the risk assessment problem. The expected number of salmonella bacteria in wastewater is 10^5 MPN/100 ml, and 200 children are expected to play for 16 hours in the landscaped area.
17. What are the 3 steps of Risk Analysis?
18. What are the 4 steps of Risk Assessment?
19. What is BOD and why is high BOD detrimental when wastewater is discharged to streams?
20. Describe the difference between oxidation and synthesis and endogenous respiration.
21. Calculate the BOD_5 if the dilution factor is 20 to 1, the initial dissolved oxygen concentration is 6 mg/L, and the final dissolved oxygen concentration is 2 mg/L.
22. List the steps in the nitrogen cycle in soils.
23. How is the nitrogen cycle carried to completion in wetlands with herbaceous aquatic plants?

References and Resources

Centers for Disease Control and Prevention (CDC): Water related diseases. http://www.cdc.gov/ncidod/diseases/water/drinking.htm

Kadlec RH, Knight R (1996) Treatment wetlands. CRC Press, Boca Raton

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