

University Curriculum Development for Decentralized Wastewater Treatment

Fundamental Concepts for Environmental Processes

Module Text

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Introduction

Understanding the technologies used in decentralized wastewater treatment requires an understanding of several fundamental concepts. While not every concept will apply to every technology, these fundamental concepts do occur with great enough frequency that they form a good foundation of knowledge for further study in decentralized wastewater treatment. Mastery of these concepts will facilitate greater understanding of how various treatment processes work and how those processes can be efficiently and effectively applied to meet different wastewater treatment needs. This module will address the following fundamental concepts:

- Overview of Water Quality
- Stoichiometry
- Units
- Mass Balance
- Fluid Mechanics
- Reactions
- Sedimentation

By design, this module does not cover these concepts in great detail. Rather, additional detail, especially as it relates to specific decentralized wastewater treatment technologies, is provided in other modules. This fundamental concepts module aims to prepare students for more targeted, in-depth study related to their interests or their course of study.

Application of Fundamental Concepts

The trickling filter system shown in Figure 1 provides an excellent example of how these fundamental concepts apply to decentralized wastewater treatment. Relationships between each of the fundamental concepts covered in this module to the trickling filter system are described below.

Overview of Water Quality: Design and implementation of the trickling filter system is driven by concentration of water quality constituents in the incoming wastewater and by the desired quality of treated effluent as it exits the system. The Overview of Water Quality section of this module describes constituents common to wastewater, environmental and health problems that may be associated with these constituents, and methods commonly used to describe constituents.

Stoichiometry: Chemical reactions are common to decentralized wastewater treatment technologies. Such reactions would occur in the septic tank, trickling filter, and soil absorption field of the system shown in Figure 1. Stoichiometry allows us to predict the ratios of materials at the start of a reaction to those present after the reaction has ended. These ratios can be used determine how completely materials introduced into the process at the beginning are converted to end products and whether or not additional materials are needed to facilitate the reaction.

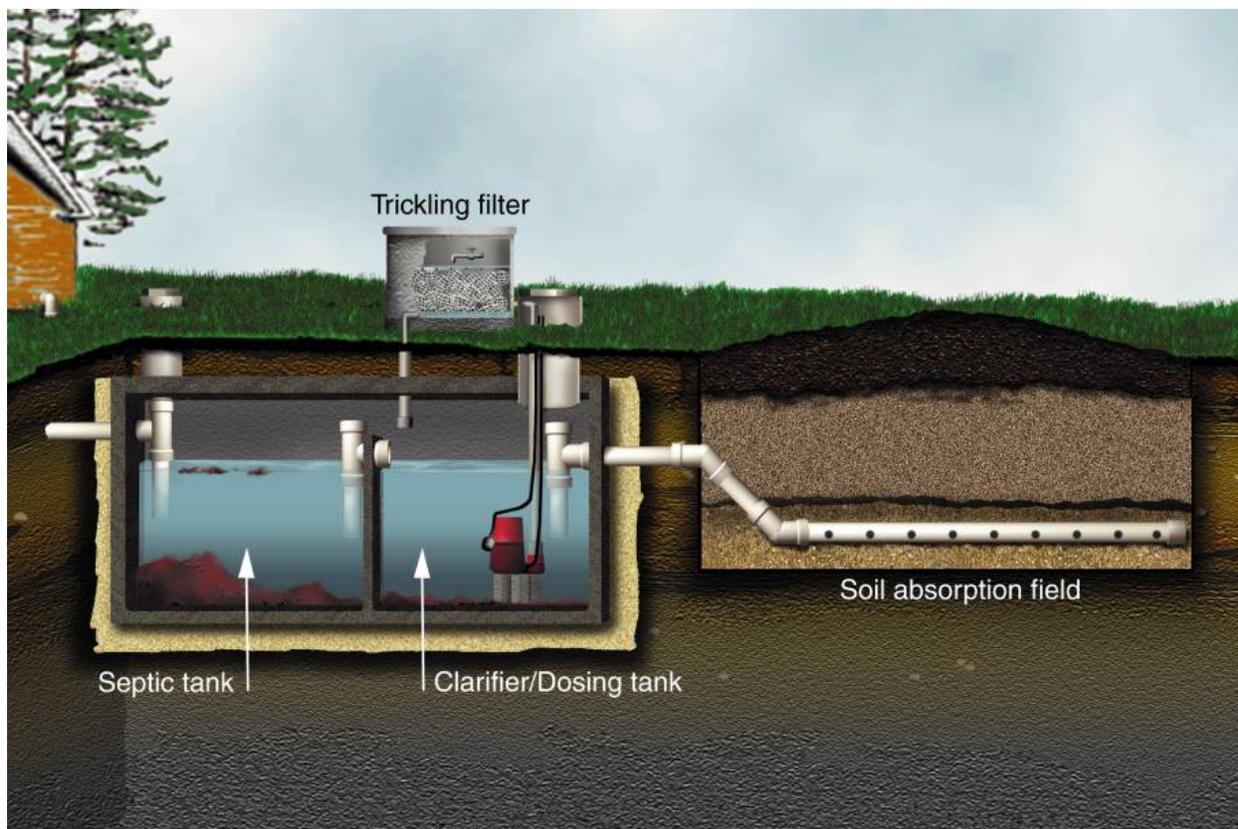


Figure 1. Cross-sectional view of trickling filter system (Onsite Wastewater Treatment program, Texas Cooperative Extension).

Units: Units are used to fully describe quantitative information about treatment technologies. In the trickling filter system example shown, units provide value as they allow more complete and accurate analysis of the treatment process. Units provide more uniform quantitative information regarding the flow rate of wastewater through the system, the concentration of constituents in incoming wastewater and treated effluent, the average amount of time that water resides in any component of the system, the mass of solids trapped in the septic tank, and other numeric values.

Mass Balance: Mass balance, the idea that mass is neither created nor destroyed, allows us to determine how materials move through or are retained within a treatment system. For

example, in the trickling filter system example shown in Figure 1, mass balance principles would allow us to predict the accumulation rate of solids in the septic tank.

Fluid Mechanics: The rate at which wastewater moves through a treatment system is a key component of system design, implementation, and upkeep. In our sample trickling filter system, determination of average and peak wastewater flows would influence the design and sizing of the septic tank and trickling filter. Design flows also influence the sizing of the pump to move wastewater to the trickling filter and the area required for effluent discharge.

Reactions: Reactions are responsible for many of the concentration reductions that occur in wastewater treatment. Stoichiometry, described earlier, describes the ratio between materials at the start and at the end of a reaction. However, stoichiometry does not indicate the rate at which a reaction occurs. If we are interested in how fast a reaction will progress, we must use rate relationships. Such rate relationships would apply to the reduction of organic materials in the trickling filter of the system shown in Figure 1.

Sedimentation: Sedimentation is the settling of solid particles due to gravity. This process is illustrated in the septic tank of the trickling filter system. Gravitational settling draws many of the solid particles to the bottom of the septic tank where they are trapped.

Overview of Water Quality

Water is used for many human purposes: drinking, power production, industry, agriculture and recreation as well as supporting other life forms. We will define water pollution as any condition caused by human activity that adversely affects the quality of streams, lakes, seas, or groundwater in such a way that the water body no longer supports its natural or intended uses. Generally, unpolluted water supports a wide diversity of aquatic organisms. It contains enough dissolved oxygen to support life and contains non-threatening concentrations of organic and inorganic pollutants, suspended matter, and toxins. In contrast, polluted water inhibits the growth of certain aquatic organisms, alters the functions of some, and can create detrimental overgrowth of yet other types of life.

As described earlier in this module, water quality measures and characteristics are used, among other things, to describe wastewater, to determine the presence and concentration of constituents of interest, and to evaluate the quality of effluent following treatment. Water quality constituents and characteristics frequently of interest in decentralized wastewater treatment are described in this section.

To measure water quality, we use different criteria: temperature, dissolved oxygen level, and the concentration of organic and inorganic compounds.

Unpolluted water => wide diversity of aquatic organisms
Polluted water => restricted diversity of aquatic organisms

Water quality criteria:

- Temperature
- Dissolved oxygen concentration
- Concentration of organic compounds
- Concentration of inorganic compounds

Resources

Two publications are widely used as principal sources of information for water and wastewater analysis:

- *Standard Methods for the Analysis of Water and Wastewater*. American Water Works Association and the American Public Health Association. Published about every two years.
- The U.S. Environmental Protection Agency has published a number of methods manuals. Some methods are available at the EPA web site (www.epa.gov) and all are available for purchase through the National Technical Information Service (NIST). Select manuals are listed below:
 - EPA Methods and Guidance for the Analysis of Water, Version 2.0. June 1999. EPA 821/C-99-004.
 - Selected Office of Water Methods and Guidance. September 2000. EPA 821/C-00-002.
 - Selected Office of Water Methods and Guidance. January 2001. EPA 821/C-01-001.
 - Index to EPA Test Methods. Originally published in 1988 but updated periodically. EPA 901/3-88-001.

These references contain information regarding which analytical tests are appropriate for what types of questions or problems along with step-by-step analytical procedures. In many cases these references also provide information on how to handle and preserve samples to provide the best possible analyses.

Organic Compounds

Organic compounds are defined as those that contain carbon. The only inorganic carbon compounds are CO₂ and its relatives (carbonic acid, bicarbonates, carbonates) cyanides, and cyanates. Living organisms consist of water and organic and inorganic chemicals. Because they are a building block of living organisms, organic compounds have been in the environment since before the advent of life on earth. Most organics introduced into the environment by humans

were naturally occurring until the introduction of synthetic organic chemistry in the 1940s and 1950s. Since that time, we have introduced many new organics into the environment.

Knowing and measuring the organic content of water is important for two reasons:

1. because breakdown of organic materials will consume oxygen
2. because organic materials made by humans can cause numerous problems in the environment.

One problem associated with manmade organic chemicals, *bioaccumulation*, is the increase of chemical concentrations in organism tissues. One method of measuring bioaccumulation is achieved by putting a biota sample in a nutrient bath. Then, using the colonies that grow to determine the concentration within biota in the water allows us to estimate bioaccumulation. If this concentration is too high, it could be toxic to aquatic life and other life forms in contact with the water. A high concentration of man-made organics may also contribute to taste, aesthetics and odor problems in recreational and drinking waters.

Examples of Organic Materials:

- Hydrocarbons
- Halogenated organics
- Plastics

Organic materials are important in water characterization because they:

- Consume oxygen
- Cause several problems (bioaccumulation, taste and odor problems)

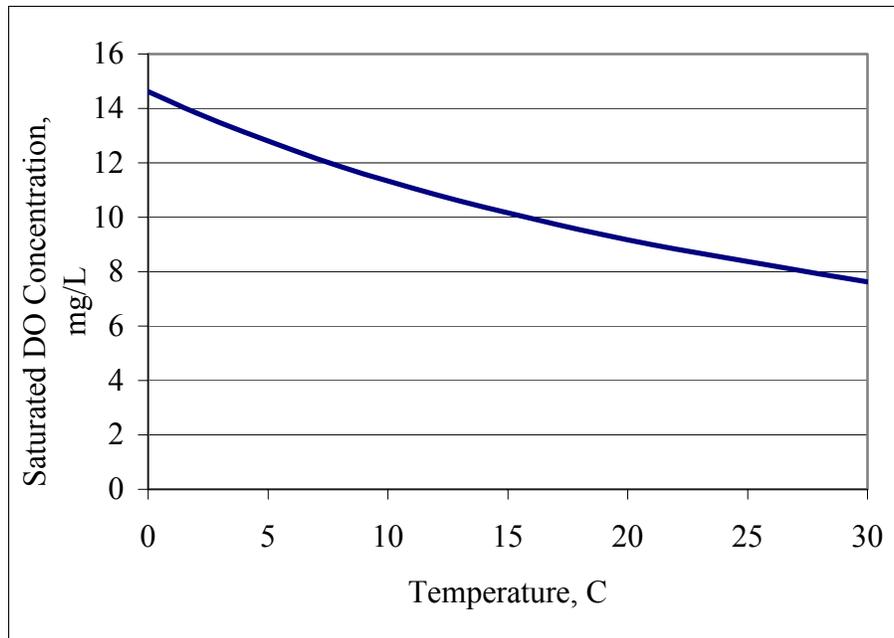
Sewage treatment process technology range in varying levels of pollutant removal. Advanced treatment can eliminate most or all of toxins, solids nutrients and other constituents to the level of reclaimable water. Typically the simplest process is the septic system which provides *primary treatment*. Primary treatment accomplishes some degradation of solids and other sewage constituents but mainly separates solids from liquid. Additional information about septic tanks and their function is available in the [Septic Tank Module](#) and other resources.

In a septic tank, raw sewage enters through the inlet. Most of the sewage is water; however, there are organic (food particles, hair, soap, oils, feces, and urine) and inorganic (detergents, makeup, dirt from showering and washing) portions. The septic tank separates the raw sewage into the floating, and sinking parts, and the part that flows through. In the septic tank, some captured organic matter may be partially digested and some organic matter goes back into solution. Portions of organic matter is classified as *suspended solids* that are buoyant, and floating in the fluid. This can pass thru the tank and flow out with the effluent.

Dissolved Oxygen (DO)

Dissolved oxygen is another criteria of water quality analyses. Water has the ability to dissolve oxygen molecules and many aquatic creatures depend on *dissolved oxygen (DO)* for survival.

When the level of oxygen gets too low, plants and animals may become impaired and even die. The maximum amount of DO water is able to dissolve decreases as water temperature increases. The relationship between temperature and saturated DO concentration is shown in the figure below. As a result of this temperature effect, aquatic life is more frequently subject to DO stress during the summer. In addition, as described in the next section, the breakdown of organic materials in water requires the consumption of DO. Therefore, waters receiving large loads of organic materials may have DO concentrations too low to support healthy aquatic communities. Today, we are able to measure the DO using hand-held or bench-top meters.



Oxygen Demand

Oxygen demand is the amount of oxygen required to aerobically metabolize a waste. Water usually contains organic material consisting of remnants or wastes of plants, animals, and microbial organisms. If organic material is added to water, it will be decomposed by bacteria through biochemical processes. This is known as the *oxidation* or the break down of organic substances. Oxidation uses DO and thus depletes the DO supply available for aquatic life.

Die off of fish and other aquatic life can result from a lack of sufficient residual DO due to oxidation demands of processing organics.

Biochemical Oxygen Demand (BOD)

The amount of oxygen used during the biochemical breakdown of organic material is referred to as *Biochemical Oxygen Demand* or (BOD). This measurement of oxygen demand is considered

an indirect measure of the amount of organic material in water. In other words, changes in DO are measured instead of a direct measurement of the concentration of degradable organic material.

The standard conditions for BOD analysis include incubation of the sample in the dark (to prevent algae from producing oxygen) at 20°C, and with an excess of nutrients for microorganisms (no limitation of growth or stabilization). Usually this incubation for the analysis is conducted over a 5-day period (yielding BOD₅), but it may be continued longer. DO is measured before and after the incubation period. If DO concentrations in the sample are low (1 to 2 mg/L), analysis results may not be accurate.

As time passes during sample incubation, bacteria and chemical processes consume dissolved oxygen to break down organic matter. Given that no oxygen is able to enter the system, the final DO measurement will be less than the original. The difference between initial DO and final DO is used to determine BOD, or the amount of oxygen consumed during the test.

$$BOD_t = \frac{DO_i - DO_f}{\left(\frac{V_s}{V_b}\right)}$$

where:

BOD_t = Biochemical oxygen demand at t days (mg/L)

DO_i = initial DO concentration (mg/L)

DO_f = final DO concentration (mg/L)

V_s = volume of sample (L)

V_b = volume of the BOD bottle (L)

The longer a sample is left to incubate, the greater the amount of oxygen consumed. Hence, BOD will increase with time until the ultimate BOD is detected.

BOD analysis:

- Measure the DO
- Keep the sample of water in the dark, at 20°C, with an excess of nutrients
- At the end of the 5-day period, measure the DO again.

BOD_t = BOD **consumed** = DO **consumed** by breakdown of organic material over t days

The V_s/V_b term allows for sample dilution when organic concentrations are high.

Time ↗ ⇒ BOD consumed ↗

The *ultimate BOD* is the total amount of dissolved oxygen required to completely break down all degradable organic material in a sample over an infinite amount of time. Since not all organic

matter in a sample may be degraded during a BOD test, there is a means of determining the amount of organic matter that can be oxidized under more stringent conditions than just simple biological oxidation in that sample. That test is the chemical oxygen demand test.

Chemical Oxygen Demand (COD)

The equivalent amount of oxygen needed to break down organic matter under strong oxidizing agents is known as Chemical Oxygen Demand or COD. A strong oxidizing agent is added to quickly break down organic material. The process is much faster to perform than BOD testing since an incubation period is not required. COD, like BOD, is only an approximation of the natural degradation of organic materials in nature. The harsh chemicals may break down more of the organic material than a natural process would. Hence, COD is usually greater than the BOD.

COD analysis:

Measure the DO

Add strong oxidizing agents (catalyst + boiling = chemical digestion)

Following oxidation, measure the DO again

$COD \geq BOD$

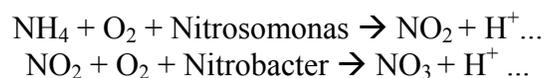
BOD and COD: indirect measurement of organic matter

Carbonaceous Biochemical Oxygen Demand (CBOD) and Nitrogenous Biochemical Oxygen Demand (NBOD)

The carbonaceous biochemical oxygen demand, or the CBOD, is defined as the amount of the BOD that is used by microbial and chemical processes that breakdown organic carbon. Generally, the process of breaking down organic compounds begins immediately once the microbes, sewage, and oxygen interact.

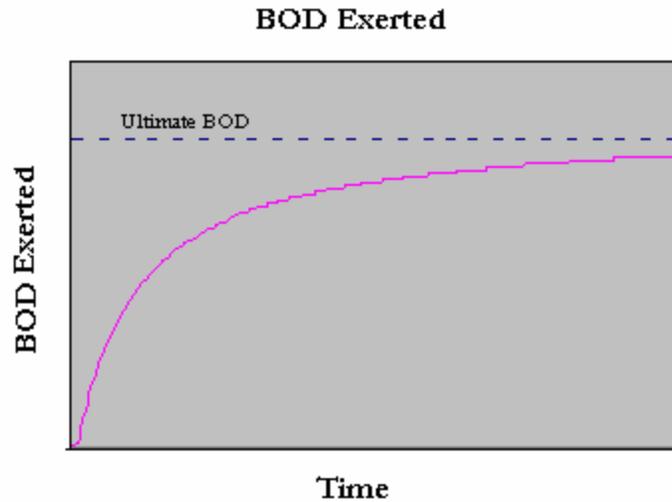


The portion of the BOD that breaks down the nitrogenous compounds, such as protein and ammonium, is called the nitrogenous biochemical oxygen demand or NBOD. The oxygen is used, generally by microbes we call nitrifiers, in the nitrification of compounds that are hydrolysis products of the natural breakdown of such compounds urea, protein, etc (organic nitrogen) to nitrate.

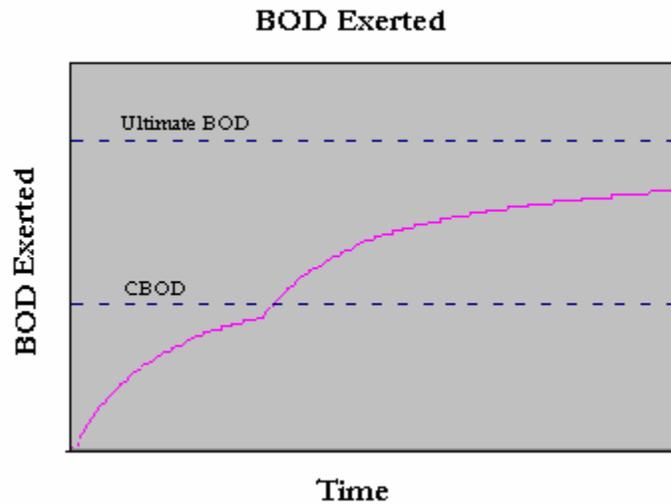


Unlike the CBOD, NBOD demand does not begin immediately. Before nitrification can occur, the population of nitrifiers must grow a significant amount before the NBOD occurs. Because it may take some time for the population to grow in the presence of carbonaceous oxidizing

organisms, the BOD curve may have a hump in it. In many practical cases, however, there are already sufficient nitrifiers present, so this hump may not be visible.



BOD curve when nitrifiers are already present



BOD curve when few nitrifiers are present near beginning.

To separate the NBOD and the CBOD, an inhibiting chemical is introduced. The chemical keeps nitrifying organisms from reproducing and metabolizing the nitrogen-containing compounds. Then, when the analysis is run, we find the CBOD, and the difference between the total BOD and the CBOD is the NBOD.

Other Measurements of Organic Materials

Total Organic Carbon (TOC) is the amount of organic carbon bound in a sample. Special instrumentation has been developed that can quickly and easily determine TOC. It operates by oxidizing organic material to carbon dioxide (CO₂) that can be measured using specially designed, and often very expensive, instrumentation. This instrumentation oxidizes organic carbon and measures the CO₂ given off.

In order to determine the amount of oil and grease, sometimes listed *FOG (fats, oils, and grease)*, it is often unnecessary to know the actual chemical constituency of the greasy substances. Instead, we add a solvent to the sample and measure the amount of material it extracts.

Solids

There are three major types of solids that are of concern in the environment: total suspended solids (TSS), colloidal solids, and dissolved solids. Solids are associated with numerous problems in decentralized wastewater treatment systems and in the environment. These include:

- Movement of solids into the soil around distribution lines in poorly-managed treatment systems
- Mass deposition causes filling of storage areas, blockage of ditches and channels, and degradation of fish spawning areas
- Increased turbidity (colloidal solids) produces a reduction of light penetration to aquatic vegetation, thus detrimental changes in the feeding habits of sight-hunting fish; solids may also create an unappealing appearance
- Interference with mechanical systems (plugs filters and sprinkler heads) complicates water treatment and erodes equipment
- High total dissolved solids concentrations are typically associated with high salt concentrations and implicates taste problems in public drinking water supplies

To avoid these problems, it is important to be able to determine the nature and the quantity of the solids present in wastewater and treated effluents.

Total Solids (TS) is the total matter that is left behind after drying a sample of water at 105°C. Total solids may be separated into several different fractions. The two primary ways fractions are established or classified is *suspended* or *dissolved* and *volatile* or *fixed*.

Suspended and dissolved solids fractions are separated by filtering a water sample through a filter. *Total Suspended Solids (TSS)* is arbitrarily defined as the solid matter caught on the surface of a 1.5 µm filter. *Total Dissolved Solids (TDS)* is the solid matter not caught on a 1.5 µm filter. *Total Solids (TS)* is the sum of the *total suspended solids* plus the *total dissolved solids* in the sample: $TS = TSS + TDS$ Because of the arbitrary nature of this test, it should be noted that one of the most important fractions is split between these two categories. The colloidal solids play a major role in environmental protection, but its nominal size range, i.e., 0.01 to 1.0 microns, includes such things as algae, bacteria, cell fragments, and debris. Colloids can be moved to the

TSS or dissolved categories by different treatment processes and may contain much of the total organic matter in a sample.

Volatile and fixed solids fractions are separated by heating the sample to 550 °C. *Total Volatile Solids (TVS)* is the solid material lost after being heated at 550°C. Volatile solids is a useful approximation of the amount of organic matter present in the sample of water. *Total Fixed Solids (TFS)* is the total solid remaining after heating at 550°C. Fixed solids is a useful approximation of the amount of mineral matter present in the sample of water. *Total solids* is the sum of the *total volatile solids* plus the *total fixed solids* in the sample: $TS = TVS + TFS$

You can also combine two classifications to determine:

- *Volatile Dissolved Solids (VDS)*
- *Volatile Suspended Solids (VSS)*

Where $TVS = VDS + VSS$, and

- *Fixed Dissolved Solids (FDS)*
- *Fixed Suspended Solids (FSS)*

Where $TFS = FDS + FSS$

The relationship between some solids fractions are illustrated in Figure 2.

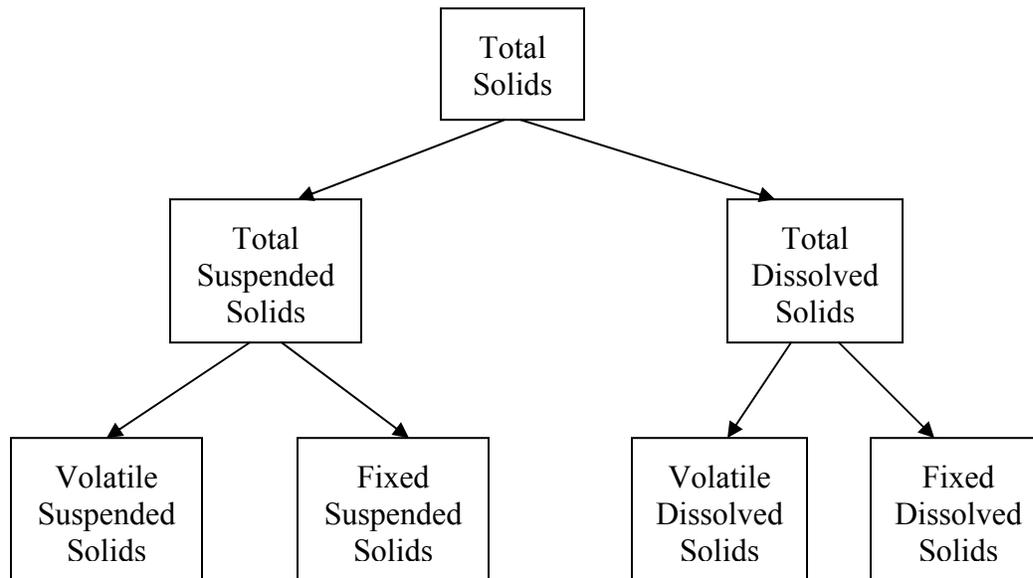


Figure 2. Relationship of solids fractions.

For each classification, the mass of solids per known volume of water is:

$$S = \frac{m_t - m_c}{vol}$$

where:

S = Solids concentration (mg/L)

m_t = Total mass of solids and container (mg)

m_c = Mass of container (mg)

vol = Volume of liquid sample (L)

Example:

100 mL are filtered through a 2 g filter. The resulting dried weight is 2.075 g. What is the TSS?

$$TSS = \frac{2075 - 2000}{0.1} = 75 \text{ TSS} = \underline{75 \text{ mg/L}}$$

The solids are then ashed yielding a total weight of 2.025 g. What are FSS and VSS?

$$FSS = \frac{2025 - 2000}{0.1} = 250 \text{ VSS} = TSS - FSS = 750 - 250 = \underline{500 \text{ mg/L}}$$

Solids problems:

- Clogging soil around distribution lines
- Mass deposition
- Increased turbidity
- Interference with mechanical systems
- High TDS => potential odor and taste problems

TS: dried at 105°C

TS = TSS + TDS

TS = TVS + TFS

Nutrients

Under natural conditions (without human influence) in surface water, nutrients exist at low-level concentrations and generally consist of the macronutrients nitrogen, phosphorus, and potassium. Nitrogen and phosphorus are the primary nutrients of concern in characterizing water quality.

Problems Associated with Nutrients

Excess nutrients act like fertilizer for aquatic plants and cause an increase of their production of organic matter. Such increased productivity and the associated impacts on water quality is known as eutrophication. As discussed earlier, the oxidation of these extra organic compounds uses DO and depletes the DO supply available for aquatic life. Moreover, the decay of the organic compounds may produce odor problems. Finally, extra vegetation near the water surface inhibits light penetration to submerged aquatic vegetation and causes problems in recreational areas since thick vegetation interferes with swimming and boating and can foul beaches.

An important point of water quality and wastewater treatment is to be able to limit plant production in response to nutrients in water. One way to limit plant growth is to control the least abundant nutrients in relation to plants needs. Plants will grow until one of the nutrients is used up. When this nutrient is unavailable, development is impaired and the other nutrients go unused. Phosphorus is most often the limiting factor in fresh water, and as it becomes more abundant, much more productivity is allowed. In marine waters, nitrogen is often the limiting nutrient.

To avoid problems related to nutrients, it is important to be able to determine the nature and the quantity of nutrients.

Nitrogen

Nitrogen readily changes forms depending on ambient conditions. Many of the commonly reported forms are:

- Nitrate (NO₃-N): Greatest oxidation state, inorganic
- Nitrite (NO₂-N): Inorganic
- Ammonia (NH₃-N): Least oxidation state, inorganic
- Organic Nitrogen: Nitrogen bound in organic compounds. Examples: Urea and proteins
- Total Kjeldahl Nitrogen (TKN): Total organic nitrogen and ammonia
- Total Nitrogen: Sum of all forms of nitrogen

In addition to eutrophication discussed earlier, NO₂ and NO₃ may cause methemoglobinemia (blue baby syndrome) in which the oxygen carrying capacity in blood is reduced. Therefore, high nitrate waters should be avoided by pregnant women and children between the ages of 6 months and 1 year. Ammonia concentrations greater than 0.2 mg/L may be toxic to fish, especially trout. Finally, many nitrogen forms are highly soluble and move easily with water as it passes through the soil profile. As a result, nitrogen discharged with treated wastewater effluents may percolate to shallow groundwater resources.

Nitrogen transforms readily from one form to another in the environment. Transformations are also common as wastewater passes through decentralized treatment systems. Transformation is driven by many factors including the presence of oxygen, the types of biological communities, and available energy. Additional information on nitrogen cycling can be found in the Onsite Nitrogen Removal Module.

Phosphorus

Phosphorus is analyzed in several forms, the typically reported ones are:

- orthophosphates (ortho-P): reactive phosphorus, available without prior oxidation, most available to plants
- condensed (poly) phosphates: become reactive with preliminary oxidation or acid hydrolysis
- organic phosphorus: bound in organic matter which must be biotransformed before phosphorus becomes reactive
- total phosphorus (TP): sum of all forms

N, P: primary nutrients

Nutrient problems:

- excess of nutrients = aquatic plant fertilizer = eutrophication
- aquatic life stress
- odor
- inhibition of light penetration
- interference with swimming and boating
- movement of nitrogen through the leach field of a poorly designed wastewater treatment system and into groundwater and nearby surface waters

Microbial Organisms (Pathogens)

Microorganisms are present everywhere: in the air, in the water, in the soil, in and on other life forms including humans. In many circumstances, they serve useful purposes; for example, they are the principal decomposers of many constituents in sewage.

Problems Associated with Microorganisms

Some microorganisms are harmful and are called *pathogenic*. If not removed from wastewater during treatment, they can be dangerous to human health. One important purpose of wastewater treatment (when people may have exposure to contact with treated effluent or it is introduced to potential drinking water sources) is the elimination of pathogenic organisms. Often, subsurface soil dispersion will remove the pathogens before they reach groundwater.

Fecal coliform bacteria are used as an indicator organism for other pathogenic microorganisms. The presence of fecal coliform indicates that water has been polluted with the feces of humans or other warm-blooded animals. Since most pathogenic organisms are carried in feces, presence of fecal coliform indicates the possible presence of pathogenic organisms.

Because wastewaters contain fecal material, fecal coliform are present, frequently in large numbers, in decentralized wastewater treatment systems. Fecal coliform counts at various points in treatment processes have been reported to be 10^6 to 10^8 in typical raw wastewater and about 1-

log less in septic tank effluent, 10^4 to 10^5 in aerobic treatment unit effluent, and 10^1 to 10^3 in sand filter effluent (Onsite Wastewater Treatment Manual. February 2002. EPA/625/R-00/008.).

Fecal coliform counts are done to describe the amount and types of organisms present in water. Water samples are first filtered and then set aside in a nutrient bath. By checking the number of colonies formed in the nutrient bath, the amount of microbial organisms can be determined.

Examples of microorganisms:

- bacteria
- viruses
- parasites

coliform bacteria = indicator organism

Examples of problem associated with pathogenic organisms:

- an outbreak of Cryptosporidium in Milwaukee
- numerous closings of shellfish beds along and in coastal areas

Salts

Large amounts of salt can decrease the usefulness of water. Municipalities cannot use salty water for distribution as drinking water to homes, and agricultural applications require lower levels of salt to prevent damage to crops and to keep livestock healthy. Even industry must be careful with the amount of salt content in water since salt may damage equipment and can react badly with other chemicals being used. Saltwater contamination of fresh water aquifers presents a serious water quality problem in island locations and in coastal areas.

Salts problems:

- increased salinity of domestic wastewater from salts used for water softening
- usefulness for municipalities
- damage crops
- damage equipment
- reactions with chemicals

Metals

Some non-toxic metals (Sodium, Potassium, Calcium...) cause inconvenient problems: bad taste, staining, and pipe encrustations. Toxic metals (Chromium, Mercury, Zinc...) can cause health risks. Even metals essential for human growth are pollutants if present in excessive amounts. Metal detection is possible by using an atomic spectrophotometer.

Metals problems:

- bad taste
- staining
- pipe encrustations
- health risks

Other Water Quality Parameters

Additional water quality characteristics of interest are described below.

Turbidity

Turbidity is a measure of the clarity of the water. The turbidity of water is due to the presence of colloidal particles scattering or absorbing the light. Turbidity is important because it decreases the aesthetic appeal of surface waters, impedes light penetration for submerged aquatic vegetation, and decreases habitat value of water resources. It is usually measured with a photoelectric turbidimeter device.

Hardness

A measure of the concentration of multivalent cations is hardness. Hard water leaves scale in pots, pipes, and hot-water heaters, and also requires increased amounts of soap for washing and bathing. Soft water has fewer of these cations and allows soap to suds and lather easily. Hard water is considered to have less human health risk for human consumption. It might be difficult to remove soap residue if water is very soft. Hardness is usually measured as equivalent amounts of calcium carbonate. Most of the multivalent cations found in water supplies are calcium, magnesium, iron, and manganese.

Alkalinity

Alkalinity is the capacity of water to absorb hydrogen ions without significant pH change (i.e., to neutralize acids). Bicarbonates, carbonates and hydroxides (originate from the salts of weak acids and strong bases) are the three chemical forms that contribute to alkalinity. It is measured by titrating a water sample with a 0.02N sulfuric acid solution to a final pH (generally 4.5). Alkalinity is important to many processes used in wastewater treatment such as nitrification, the transformation of ammonia to nitrate. Nitrification requires an alkalinity of 7.14 mg CaCO₃ per mg ammonia-nitrogen.

pH

The negative log of the Hydrogen ion concentration is known as pH. pH affects biological and chemical reactions. Thus, it is a common measure for most waters. pH is easily measured with a hand-held or desk-top meter.

Stoichiometry

The principle of mass balance, discussed later in this module, is that mass is neither created nor destroyed. When chemicals go through a reaction, some molecules may be unchanged and some others may be rearranged into different chemicals; but the total mass of the reactants will be the same as the total mass of the products. This principle does not apply to many biochemical reactions, but generally to chemical ones.

Stoichiometry is the analysis of the quantities and ratios of products and reactants in a chemical reaction. It is used to balance equations and thus to determine how much of a particular chemical will be needed as reactant or produced by the chemical reaction.

Mass, Moles, and Molecular Weight

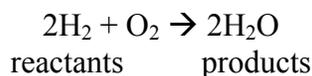
Mass

Chemical equations are given in terms of mass (such as grams or kilograms).

Moles

A molecule is so light and small that we usually consider the chemical reaction at a larger scale: the scale of the mole. A mole is a group of 6.02×10^{23} molecules. The number: 6.02×10^{23} is known as *Avogadro's number* and is derived from the number of atoms that would be present in exactly twelve grams of carbon.

For example, the formation of water, H_2O , from the combustion of diatomic hydrogen H_2 and diatomic oxygen O_2 can be symbolized by the following equation:



This equation shows that two moles of H_2 react with one mole of O_2 to produce two moles of H_2O .

Molecular Weight

At given temperature and pressure, we know that the mass of a specific molecule is always the same. Thus at given temperature and pressure, the mass of a mole of this specific molecule is always the same. The *molecular weight* of a material is the mass of one mole of that material. The *molecular weight* can be used to find the number of moles present in a sample, by dividing the total weight of a compound by its *molecular weight*.

$$M = \frac{m_{total}}{MM}$$

where: M = number of moles (moles)
 m_{total} = total mass (g or kg)
 MM = Molecular weight (g/mole)

Comments:

- Be aware: the terms weight and mass are sometimes used interchangeably.
- Be careful: do not confuse molecules and atoms. The diatomic hydrogen H_2 is a molecule composed by two atoms of hydrogen H.

Balancing Chemical Equations

Balancing a chemical equation means determining the ratios between chemicals. Usually we know the products and reactants of a chemical reaction, but we need to determine the ratios between the chemicals. To balance a chemical equation, we need to remember the principle of conservation of the mass: mass is neither created nor destroyed. Thus each atom present in the reactants will also be present in the products. At the scale of the mole, each mole present in the reactants will also be present in the products.

Example:

Take the formation of water H_2O from the combustion of diatomic hydrogen H_2 and diatomic oxygen O_2 as an example:

1. Knowing the products and the reactants we first write the **unbalanced** equation:



We obtain this summary table:

	Reactants	Products
H	2 moles	2 moles
O	2 moles	1 mole

Considering the conservation of the mass we should have the same number of moles in the products and the reactants for each kind of atom. Thus one mole of oxygen is missing in the products.

2. Consider in which chemical the oxygen atom is present, and try to equilibrate the number of moles of oxygen.

Oxygen is present:

- in the diatomic oxygen O_2 , two moles of oxygen per mole of diatomic oxygen
- in the water molecule H_2O , one mole of oxygen per mole of water

We can add moles, but not delete them, so multiply the number of moles of oxygen in water by two (i.e. multiply the number of moles of oxygen by two in the products).

We obtain the following equation and summary table:



	Reactants	Products
H	2 moles	4 moles
O	2 moles	2 moles

Thus the equation is still unbalanced, two moles of hydrogen are missing in the reactants.

3. Consider in which chemical the hydrogen atom is present and try to equilibrate the number of moles of hydrogen.

The hydrogen is present: - in the diatomic hydrogen H_2 , two moles of hydrogen per mole of diatomic hydrogen
 - in the water molecule H_2O , two moles of hydrogen per mole of water

Again, we can add, but not delete moles, so multiply the number of moles of diatomic hydrogen by two (i.e. multiply the number of moles of hydrogen by two in the reactants).

We obtain the following equation and summary table:



	Reactants	Products
H	4 moles	4 moles
O	2 moles	2 moles

We have just balanced the chemical equation of the formation of water: H_2O from the combustion of diatomic hydrogen H_2 and diatomic oxygen O_2 .

Comment:

Always balance chemical equations using the number of moles missing and not the number in excess.

Example:

The oxidation of glucose $C_6H_{12}O_6$ by the diatomic oxygen of the air O_2 produces carbon dioxide CO_2 and water H_2O .

1. Knowing the products and the reactants we first write the **unbalanced** equation:



We obtain this summary table:

	Reactants	Products
C	6 moles	1 mole
H	12 moles	2 moles
O	8 moles	3 moles

Five moles of carbon, 10 moles of hydrogen and 5 moles of oxygen are missing in the products.

Comment:

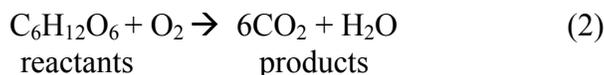
At first, start by equilibrating the atom which is only present in only one kind of molecule of reactants and one kind of molecule of products. It is much easier.

2. Carbon and hydrogen are both present in only one molecule of the reactants and one molecule each in the products. We could start with either one. Using carbon:

The carbon is present: - in the glucose $C_6H_{12}O_6$, six moles of carbon per mole of glucose
 - in the carbon dioxide CO_2 , one mole of carbon per mole of carbon dioxide

Multiply the number of mole of CO_2 by six (i.e. multiply the number of moles of carbon by six in the products).

We obtain the following equation and summary table:



	Reactants	Products
C	6 moles	6 moles
H	12 moles	2 moles
O	8 moles	13 moles

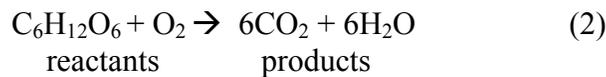
Ten moles of hydrogen are missing in the products and 5 moles of oxygen are missing in the reactants.

3. Continue by equilibrating hydrogen which is present in only one kind of molecule of reactants and one kind of molecule of products.

The hydrogen is present: - in the glucose $C_6H_{12}O_6$, twelve moles of hydrogen per mole of glucose
 - in the water molecule H_2O , two moles of hydrogen per mole of water

Multiply the number of mole of water per six (i.e. multiply the number of mole of hydrogen per six in the products).

We obtain the following equation and summary table:



	Reactants	Products
C	6 moles	6 moles
H	12 moles	12 moles
O	8 moles	18 moles

Ten moles of oxygen are missing in the reactants.

4. Consider in which chemical the oxygen atom is present and try to equilibrate the number of moles of oxygen.

The oxygen is present: - in the glucose $C_6H_{12}O_6$, six moles of oxygen per mole of glucose
 - in the diatomic oxygen O_2 , two moles of oxygen per mole of carbon dioxide
 - in the carbon dioxide CO_2 , two moles of oxygen per mole of carbon dioxide
 - in the water molecule H_2O , one mole of oxygen per mole of water

Multiply the number of moles of diatomic oxygen per six (i.e. add ten moles of oxygen to the products).

We obtain the following equation and summary table:



	Reactants	Products
C	6 moles	6 moles
H	12 moles	12 moles
O	18 moles	18 moles

We have just balanced the chemical equation for the oxidation of glucose $C_6H_{12}O_6$ by the diatomic oxygen from the air, O_2 , producing carbon dioxide CO_2 and water H_2O .

Limiting Reagents

In practice, it is very possible that there will not be exactly the right ratio of each reactant, so there may well be several chemicals that have moles remaining after the process is completed or in other words are not completely used. The one chemical that the process runs out of, causing the reaction to stop, is called the *limiting reagent*. Because it will be the one to determine how much product will be created, its initial mass must be the one considered when doing stoichiometric analysis.

The first step, then, is to determine which of the chemicals provided is the limiting reagent. The mass of the limiting reagent can then be used to find the mass of the products and also how much of the other materials are used in the process. The concept of a limiting reagent applies to eutrophication. In this application, one nutrient required for biological productivity will be in comparatively short supply and will be the limiting nutrient. When the limiting nutrient is used up, biological productivity will slow.

Biological Concepts

Importance of Biology to Decentralized Systems

Living organisms play an important role in wastewater treatment. These biological communities, usually various types of microorganisms, are largely responsible for reduction of organic material in wastewater. The organisms use organic matter as a food supply to support the growth of biomass. For example, in the sand filter shown in Figure 3, a biological community forms on the surface of sand particles. As pretreated wastewater passes through the sand, the microbes use organic matter dissolved in the wastewater to grow. By using the organic material, the microbial communities reduce the concentration.

Organisms and Oxygen

Microorganisms, especially bacteria, are classified according to the oxygen conditions they prefer. *Aerobic* organisms perform best when waters are well aerated and contain relatively high concentrations of dissolved molecular oxygen. In contrast, *anaerobic* organisms perform best in conditions with little or no molecular oxygen. These bacteria obtain the oxygen they need from molecules that contain oxygen, such as nitrate or sulfate, or by breaking down organic materials that contain oxygen. *Facultative* organisms prefer aerobic conditions but easily adapt low oxygen circumstances.

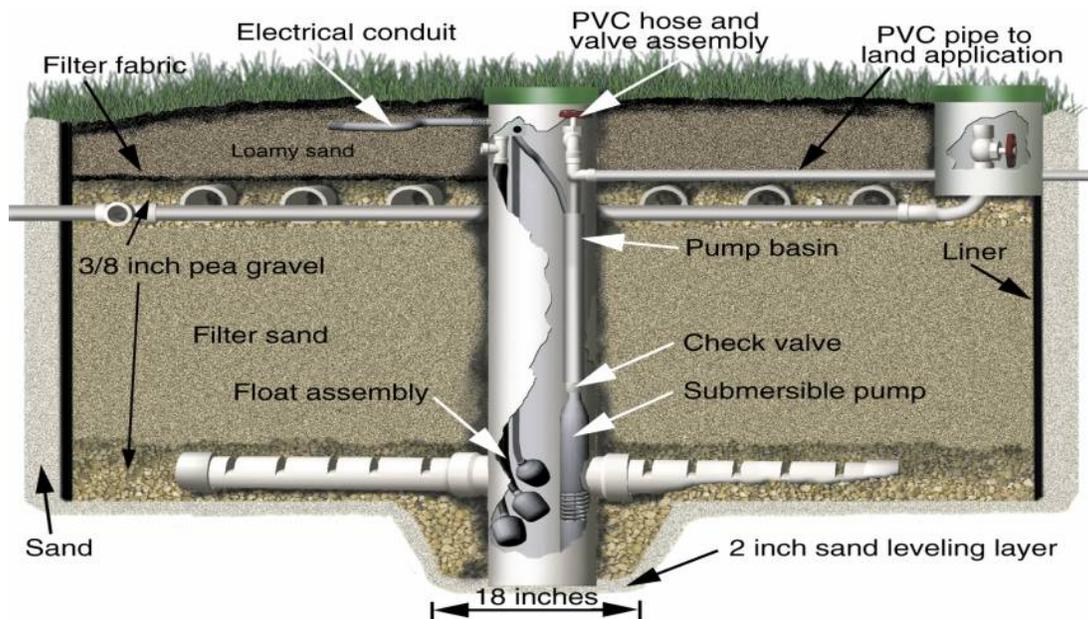


Figure 3. Cross-sectional view of a sand filter (Onsite Wastewater Treatment program, Texas Cooperative Extension).

Temperature and Biomass Growth

Between temperatures of 0 and 55 °C, rates of biomass production by microbes common in wastewater treatment increase as temperature increases. Extreme temperatures above and below this range may interfere with metabolic processes or harm the organisms. In some cases, temperature extremes may be lethal. Generally, the rate of biomass production will double for a temperature increase of 10 °C.

Toxicity

While many microbial organisms are able to adapt to changes in their environment, adaptation is usually most successful if changes occur gradually. Sudden changes or introduction of toxic materials may be harmful or lethal to the biological community. Such sudden changes could include wide, quick variation in wastewater loading rate, sharp changes in pH, or changes in salt concentrations. In addition, sudden introduction of toxic substances (for example, discharge of household bleach into an on-site wastewater treatment system) may prove detrimental.

Units

Units provide critical information about quantitative values. Given a value of three, the quantity could be applied to flow velocity, flow rate, concentration, length, or any other dimension. Units provide us the ability to communicate fully the meaning of a quantitative value.

Units are important to decentralized wastewater treatment for two primary reasons. First, units facilitate clear, specific communication about quantitative information regarding a technology or system. Second, the mathematical relationships used to size systems or evaluate their performance require consistent use of units to yield correct results.

Unit Systems

Two systems of units are commonly used in the US: the SI or metric system and the US Customary or English system. The basics of each of these systems are summarized in the following text.

International System of Units (SI)

Several standard systems of values have been developed to make communication between different people possible. The most commonly used unit system worldwide is called the *International System of Units (SI)*, also called the metric system. This system has a group of base units from which other important units can be derived. Base units are as follows:

Dimension	Unit	Abbreviation
Length	meter	m
Mass	kilogram	kg
Temperature	Kelvin	K
Time	second	s

Other units may be derived from the above four. For example, velocity is the distance traveled in a given amount of time. In other words, it is meters traveled per second. Some common examples of derived units are given below:

Dimension	Unit	Abbreviation
Area	length squared	m ²
Volume	length cubed	m ³ , L, cm ³
Speed	length per time	m/s
Acceleration	length per time squared	m/s ²
Density	mass per volume	kg/m ³

Some derived units have been given special names:

Dimension	Derived Units	Special Unit	Abbreviation
Force	m·kg·s ⁻²	Newton	N
Pressure	N/m ²	Pascal	Pa
Energy	N·m	Joule	J
Power	J/s	Watt	W

The metric system is based in multiples of ten. For instance, the amount of solids captured in a septic tank would probably not be expressed in grams. The resulting numbers would be very large. Instead, new units are created by adding on prefixes to the base units. For example, “kilo-“ means one thousand, so one *kilogram* means the same thing as one thousand grams, just as one kilometer is 1×10^3 meters. The following are a list of common prefixes:

Prefix (Abbreviation)	Multiplier
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
hecto (h)	10^2
deka (da)	10^1
base unit	1
deci (d)	10^{-1}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}
nano (n)	10^{-9}

US Customary System (USCS)

In the United States, a common system of units is called the *U.S. Customary System (USCS)*. Like the metric system, the USCS has base units from which other units are derived. Base units for the USCS are as follows:

Dimension	Unit	Abbreviation
Length	foot or inch	ft or in
Mass	slug	slug
Temperature	Rankin	R
Time	second	s

Some derived units are as follows:

Dimension	Units	Abbreviation
Area	length squared	ft ²
Volume	length cubed	ft ³ , gallon
Speed	Length per time	ft/s
Acceleration	length per time squared	ft/s ²
Density	mass per volume	slug/ft ³
Energy	force times distance	ft-lb
Pressure	Force per area	lb/ft ² or psf
Force	slug·ft/s ² or pound (e.g., weight)	lb

Converting Units

The process of changing a given set of numbers into different units is called converting units. To change the units the given numbers must be multiplied or divided by a given number called a *conversion factor*. While many conversion factors, such as 12 inches per foot, are common knowledge, most conversion factors can be located in tables or on the web. The Weights and Measures division of the National Institute of Standards and Technology has an excellent summary of units including conversion tables. At the time of this writing, their document could be found at:

<http://ts.nist.gov/ts/htdocs/230/235/h4402/appenc.pdf>

Example:

How many feet are in one meter if 1 meter = 3.28 feet?

$$1m * 3.28 ft / m = 3.28 ft$$

It is possible to work more complex unit conversions by applying several conversion factors. Starting with the given values, different conversion factors may be multiplied and/or divided until the needed units are obtained.

Example:

How many feet are in 10.3 meters if 2.54cm = 1 inch?

$$10.3m * \frac{100cm}{1m} * \frac{1in}{2.54cm} * \frac{1ft}{12in} = 33.79 ft$$

Example:

Convert 10 ^{cc}/_{sec} into ^{gal}/_{min} using the following conversion factors:

- 1 cubic centimeter = .000001 cubic meters
- 1 cubic meter = 264.167 gallons
- 60 seconds = 1 minute

$$\frac{10cc}{1sec} * \frac{.000001m^3}{1cc} * \frac{264.176gal}{1m^3} * \frac{60sec}{1min} = .1585 \frac{gal}{min}$$

Dimensional Homogeneity

An equation and all input variables should have consistent units. To maintain *dimensional homogeneity*, both sides of the equation should yield the same units. Or stated another way, the unit form used should be matched and consistent throughout an equation. Centimeters and meters, for example, should not be mixed in the same calculation. The following example demonstrates the importance of dimensional homogeneity in mathematical calculations.

Example:

Using the equation given, how much mass does a particle have if, when it accelerates at 3 cm/s², it creates a force of 1 Newton $\left(N = \frac{kg \cdot m}{s^2} \right)$?

$$\text{mass} = \text{force/acceleration}$$

Solution: The problem statement includes mismatched units for lengths. The acceleration is given with length units of cm while the force units of Newtons uses length units of m. If no unit conversions are done prior to working with the equation, the following occurs:

$$kg = \frac{kg \cdot m / s^2}{cm / s^2} \rightarrow \text{Only the time units (square seconds) will cancel.}$$

$kg \neq \frac{kg \cdot m}{cm} \rightarrow$ Units for the right side of the equation do not equal those for the left. Therefore, the equation is not dimensionally homogeneous.

We must, therefore, convert the centimeters in the acceleration variable into meters since meters are a base unit for Newtons.

$$\text{acceleration} = \frac{3cm}{1s} * \frac{1m}{100cm} = .03m/s^2$$

Now, both the meters and seconds cancel and we are left with kg on both sides of the equation.

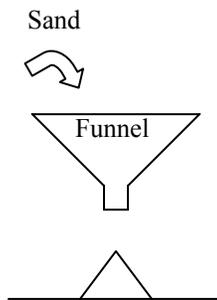
$$kg = \frac{1 \text{ kg} \cdot m / s^2}{.03 m / s^2} = 33.33 \text{ kg}$$

Mass Balance

Mass balance is based on the principle: mass can be neither created nor destroyed. To illustrate this concept, imagine a quick experiment in which sand is poured into a funnel. We will focus on one single grain of sand. As the particle of sand is poured into the funnel, there are two possible paths it might take:

- It can go into the funnel and then fall out of it
- It may remain inside the funnel

Therefore, all the sand poured into the funnel can be accounted for either in the amount leaving the funnel or in the amount that is still contained within it.



How can we determine the movement of sand through this process? How can we determine what enters, how much exits, and how much is retained in the treatment system? How can we determine the efficiency of the process? How much of the incoming material was captured during the treatment?

Mass balance accounts for the movement of material through or storage within a system. The principle referred to as mass balance indicates that the difference in the amount of material entering and leaving a control system must equal the change of material stored in the system. The main application is to determine the efficiency of the various types of treatment processes and to track the movement or retention of materials within the system.

Applications of Conservation of Mass:

- Estimation of the rate at which solids accumulate in a septic tank
- Estimating the amount of debris filtered out of the water that is prepared for distribution through a drip irrigation system

Conservation of Mass

What enters into a system must either come back out or remain inside the system.

- Input is the material that goes into the system
- Output is the material that leaves the system

To make mass balance easier, we will use an equation to describe the process.

$$\text{Change in Storage} = \text{Input} - \text{Output}$$

Note that inputs and outputs may be mixed, material may change phase and form and may combine or may separate. But, the mass of each individual component remains constant.

Examples of the Mass Balance Principle

Mass balance may include multiple inputs and outputs. For instance, cookie dough may have several separate inputs including eggs, shortening, flour, leavening agents, and chocolate. Even though the inputs will mix together within the system, the inputs will again leave as one combined output. Would there be any accumulation during the process (initial storage equals zero)? Perhaps some of the dough gets stuck on the beaters, or some might not be completely removed from the mixing bowl.

It is also possible that several input materials chemically react within a system. In a combustion engine, for example, fuel (usually an organic compound containing carbon) and oxygen ignite to form carbon dioxide, water, and mineral ash. Although the molecules in the fuel and the oxygen in the air have rearranged into different molecules, all the same atoms are still there. If at first you have 12 atoms of carbon in the fuel, after ignition you will have 12 atoms of carbon in carbon dioxide form. Some of those carbons may not be combusted completely and may be left in the tank while the rest are expelled in the exhaust. Mass balance still works since mass is never created or destroyed.

Types of Processes

There are three kinds of processes: continuous batch and continuous flow cyclic reactor (CFCR).

The batch process results in a fixed amount of output. Batches are processed one-at-a-time. Fermentation during brewing is a good example of a batch process. Mash is placed into the

fermenter where it is held over time. After the fermentation period has ended, all materials are removed from the reactor. The fermenter is cleaned and another batch is started. Note that for a batch process, mass balance is based on weight, mass, or volume.

$$\text{Change in stored mass} = \text{Input mass} - \text{Output mass}$$

By comparison, continuous processes experience a steady flow of materials through the system. Water treatment plants serve as a good example of continuous processes because they generally have a constant flow of water to be processed. Water is constantly being added and removed from the system. Note that for a continuous process, mass balance is based on mass or volume flow rate (mass per unit time or volume per unit time).

$$\text{Rate of storage} = \text{Rate of input} - \text{Rate of output}$$

Some decentralized wastewater treatment technologies use a combination of batch and continuous processes. As a hybrid of both continuous flow and batch processes, the continuous flow cyclic reactor (CFCR, Figure 4) is unique. In a CFCR, the inflow is accommodated at all times and the amount of output is dependent upon the volume of influent. Although similar to a batch process, a cyclic reactor processes wastewater constituents existing in the reactor basin even though no new waste has been introduced, processes waste constituents during the aeration cycle and/or processes waste constituents during the air off and decant phases of the cycle. Therefore the process can occur with the input of aeration (for example) and yet little or wastewater influent may be introduced over the time period of the cycle. Therefore, no discharge of effluent is necessary for that particular cycle yet processing of organics and Nutrient removal is still accomplished. Thus, typically a 24 hour mass balance transfer is used to determine the processing of waste with a CFCR system.

Using Concentrations

Many processes will be based on movement of air or liquid through the treatment process. Sometimes, instead of a mass, a flow rate or flow volume and an average concentration will be given. To determine the mass or mass flow rate of the particulate, simply use:

$$\text{Mass flow rate} = \text{Concentration} \times \text{Flow rate}$$

(mass/time) (mass/volume) (volume/time)

$$\text{Mass} = \text{Concentration} \times \text{Flow volume}$$

(mass) (mass/volume) (volume)

Using Percent Composition

Sometimes very concentrated solutions (slurries) will be described as having a percent composition by weight, typically percent solids by weight. To determine the mass of the solid, multiply the fraction composition (the percent composition divided by 100) by the total weight of the slurry.

$$\text{Constituent mass} = \text{Total mass} \times \text{Fraction composition}$$

$$\text{Water mass} = \text{Total mass} - \text{Constituent mass}$$

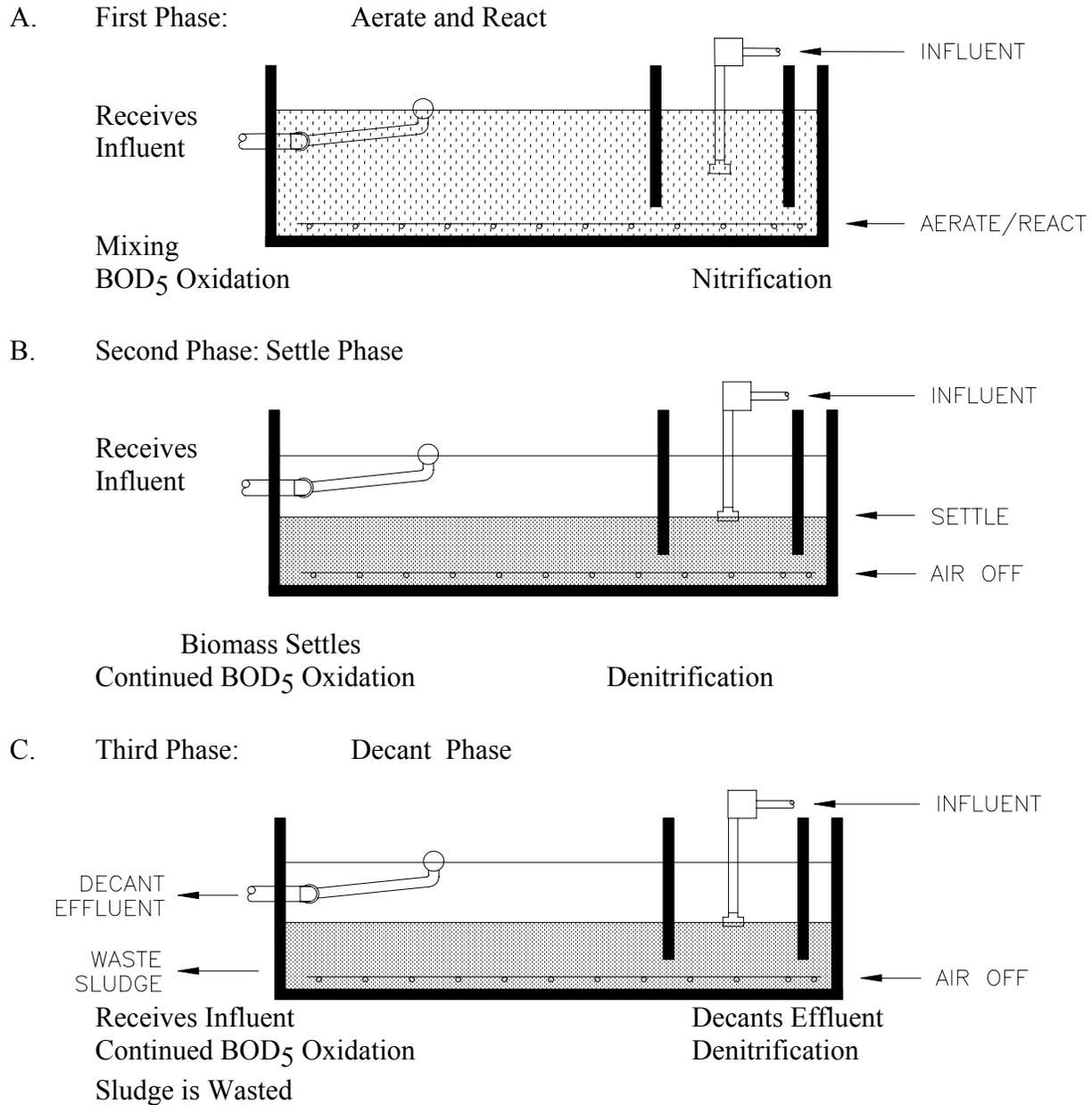


Figure 4. Intermittent Decant Extended Aeration (IDEA) system shown in three operational phases: A) a 2-hour aeration phase, B) a 1-hour settling phase with no aeration, and C) 1-hour decant phase with no aeration (Advanced Environmental Systems).

Applications of Percent Composition:

100kg of slurry with 30% solids would have 30kg of solids and 70kg of water.

A Cookbook Procedure for Setting Up Mass Balance Problems

1. Identify the system and define the system boundaries—you choose based on your needs.
2. Determine whether the process is batch or continuous. Determine whether the materials involved change form or composition.
3. Identify all inputs and outputs—diagram as needed.
4. Identify known quantities of mass or flow rates.
5. Identify unknown quantities and assign a variable to each.
6. Use mass balance equations to determine unknowns and solve.

Example:

A septic tank receives 2000 m³/d water containing 200 mg/L solids. Water leaves the tank at the same flow rate but with a solids content of 20 mg/L. What is the solids accumulation rate in the tank?

Hints: Mass flow rate = fluid flow rate* concentration, mg/L = g/m³

Using the “cookbook procedure” to set up the problem:

1. System: sedimentation tank
2. Process: continuous
3. Inputs: water and solids
 Outputs: water and solids
 Storage: solids
4. Input rates: Water = 2000 m³/d
 Solids = 2000 m³/d*200g/m³ = 400,000 g/d = 400 kg/d
 Output rates: Water = 2000 m³/d
 Solids = 2000 m³/d*20g/m³ = 40,000 g/d = 40 kg/d
5. Storage rate: unknown, use Sa
6. Mass balance:
 Sa = Solids in - solids out = 400 kg/d - 40 kg/d = 360 kg/d

Fluid Mechanics

A fluid is any non-solid material, including both liquids and gases. We describe the movement of these fluids in order to determine how fast and how much fluid will flow through a system. These descriptions help us determine how big to make parts in a system and how fast the fluid will enter and leave that system.

Examples of Fluids

- Water
- Oil
- Air

Fluid mechanics drive many important decisions in sizing or designing decentralized wastewater treatment systems. For example, many reaction tanks are sized based on the average amount of time wastewater must stay in the tank and the flow rate of water through the system. Another example of fluid mechanics principles in decentralized wastewater treatment would be the pump tank shown in Figure 5. Fluid mechanics would be necessary to determine flow rates into the tank, levels at which the float switch would be activated, and to specify the pump size required to move water out of the tank.

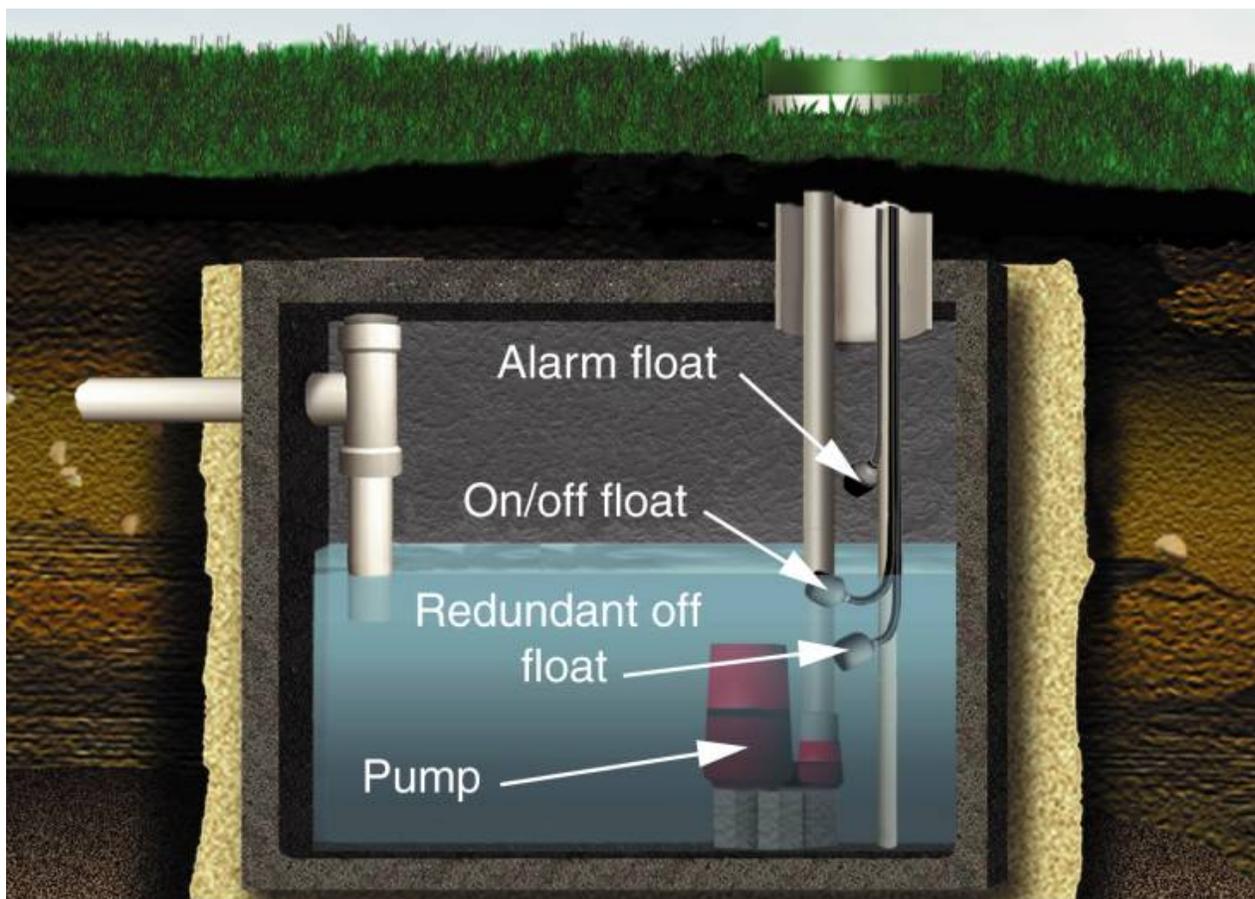


Figure 5. A pump tank used for moving wastewater to a distribution system (Onsite Wastewater Treatment program, Texas Cooperative Extension).

Flow Rate

The flow rate of a fluid tells us how much fluid will go through a specific cross-sectional area. It may be determined by using following equation:

$$q = vA$$

where:

q= flow rate, volume/time (cfs, m³/s, gpd)

v = flow velocity, length/time (ft/s, m/s)

A = cross-sectional area, length squared (ft², m²)

If we have a pipe with a circular opening and we want to know how much water will be pumped out of it every second, we need to know two things:

1. How fast the water is traveling (the flow velocity)
2. How big the opening of the pipe is (the cross- sectional area)

Example:

Determine the flow rate in a 1 m² cross-sectional area pipe with a flow velocity of 3 m/s?

$$q = vA = 3 \times 1 = \underline{3 \text{ m}^3/\text{s}}$$

Continuity

Flow is a mass balance of fluid. Considering a continuous mass balance, based on mass flow rate we can use:

$$\begin{aligned} \text{Fluid mass rate} &= \text{flow rate times} \times \text{density} \\ m &= q\rho \end{aligned}$$

If we assume no storage during the process, what goes in must come out:

$$\dot{m}_{in} = \dot{m}_{out}$$

Thus, we get

$$Q_{in}\rho_{in} = Q_{out}\rho_{out}$$

For liquids, ρ remains constant, so $\rho_{in} = \rho_{out}$. Then:

$$Q_{in} = Q_{out} \text{ or } A_{in}V_{in} = A_{out}V_{out}$$

A more detailed discussion of fluid continuity is provided in Hydraulics I—Fundamentals (Trotta).

Handy Area Equations

These equations are used to determine the cross sectional area for different kind of conduits:

- Circle: pipes (based on inside diameter)

$$A = \frac{\pi d^2}{4}$$

where: A = cross-sectional area
d = inside diameter

- Rectangle: rectangular channels or ducts

$$A = wh$$

where: w = channel width
h = channel depth

- Trapezoid: trapezoidal channels

$$A = \frac{(w_b + w_t)h}{2}$$

where: w_b = width at the bottom of the channel
 w_t = width at the top of flow

- Triangle: triangular channels

$$A = \frac{w_t h}{2}$$

Example:

Water entering a settling tank is carried at 0.5 m/s in a rectangular channel 2m wide by 0.3m deep. This same flow rate exits the tank in a channel measuring 3m wide by 0.3 m deep. What is the flow velocity in the exit channel?

$$A_i V_i = A_e V_e$$

With: $A_i = 2\text{m} \times 0.3\text{m} = 0.6\text{m}^2$
 $V_i = 0.5 \text{ m/s}$
 $A_e = 3\text{m} \times 0.3\text{m} = 0.9\text{m}^2$

So: $0.6\text{m}^2 \times 0.5 \text{ m/s} = 0.9 \text{ m}^2 V_e$

$$\Rightarrow V_e = \underline{0.33 \text{ m/s}}$$

Example:

Flow in a 4 inch i.d. (inside diameter) pipe has a velocity of 2 ft/s. What is the flow rate?

$$q = vA$$

With: $v = 2 \text{ ft/s}$

$$A = \frac{\pi d^2}{4} = \frac{\pi \left(\frac{4}{12}\right)^2}{4} = 0.087 \text{ ft}^2$$

$$q = 2(0.087) = \underline{0.175 \text{ cfs}}$$

Head

Head is the amount of mechanical energy per unit weight of material being pumped. It may also be thought of as the height water would be pumped to with a given amount of energy and is given in terms of that relative height. Total head is composed of static head, velocity head, and frictional head.

Static head is the difference in height between the free surface (the elevation of the water/air interface) of the source and the free surface of the receiving body of water. If the discharge is not submerged, the head is measured from the free surface of the initial source to the height of the outlet pipe. Also, we must remember that water levels in either body of water may change with time. For example, the water level in a well may increase or decrease depending on the amount of rain the area has received. If the water level in the well falls, the water will, in effect, need to be measured from the lowest possible level of the source to the maximum possible level in the receiving body of water.

The movement of water through a pipe also requires energy. To simplify problems, we refer to the energy from velocity in terms of head. For instance, if water has three feet of velocity head, it has enough energy to raise it three feet. The velocity head can be calculated with this equation:

$$H_v = \frac{v^2}{2g}$$

where

H_v = velocity head (m or ft)

v = flow velocity (m/s or ft/s)

g = gravitational acceleration (m/s^2 or ft/s^2)

As water flows through a pipe, it loses some of its energy through frictional losses. To compensate for the head loss from friction we must add in a term to the total required head. Frictional head can be found with the Darcy-Weisbach equation:

$$H_f = f \left(\frac{L}{D} \right) \left(\frac{v^2}{2g} \right)$$

where

H_f = frictional head (m or ft)

f = friction factor (dimensionless)

L = length of the pipe

D = Inside diameter of pipe (m or ft)

v = flow velocity (m/s or ft/s)

g = gravitational acceleration (m/s^2 or ft/s^2)

Total required head is the sum of the static head, velocity head, and the friction head.

$$H_t = H + H_v + H_f$$

where

H_t = total required pumping head

H = static head

H_v = velocity head

H_f = friction head

Total head and flow rate are key factors used to select pumps. Additional information on head and fluid energy is available in the [Hydraulics II—Energy](#) module (Trotta). Likewise, further information on pumps and pump sizing is available in the [Hydraulics III—Pumps](#) module (Trotta).

Reactions

Reactions are processes that transform the arrangement of one group of molecules into a different arrangement of molecules. The amount of matter and the type of atoms are not changed. They are simply moved around into different groups.

The different terms use to describe a reaction are:

- Reactants: the original compounds prior to the reaction
- Products: the compounds formed by the reaction
- Reaction rate: speed at which the process takes place
- Reactors: systems used to facilitate the reaction - usually designated as a type of tank

A combustion reaction, such as the one that would occur in an engine, is a good example of a reaction. We begin with a fuel such as methane (CH₄) and oxygen (O₂), and add heat to force a chemical reaction between the two molecules. Both the methane and oxygen are pulled apart and realign into new molecules—carbon dioxide (CO₂) and water (H₂O).



The combustion of methane, for example, is very fast and takes little time to complete. Its reaction rate is very high. The reactor for this chemical change can be very small, such as an engine. Diamonds too will react with air and very slowly turn to graphite. That reaction, however, has a very, very slow reaction rate and will take millions of years to complete.

The trickling filter shown in Figure 5 is a good example of a reactor used in decentralized wastewater treatment. As water moves through the trickling filter, BOD is degraded and utilized by microbial communities growing on the surface of the filter media. The reaction characteristics would drive how water is passed through the system and the size of system required to achieve treatment goals.

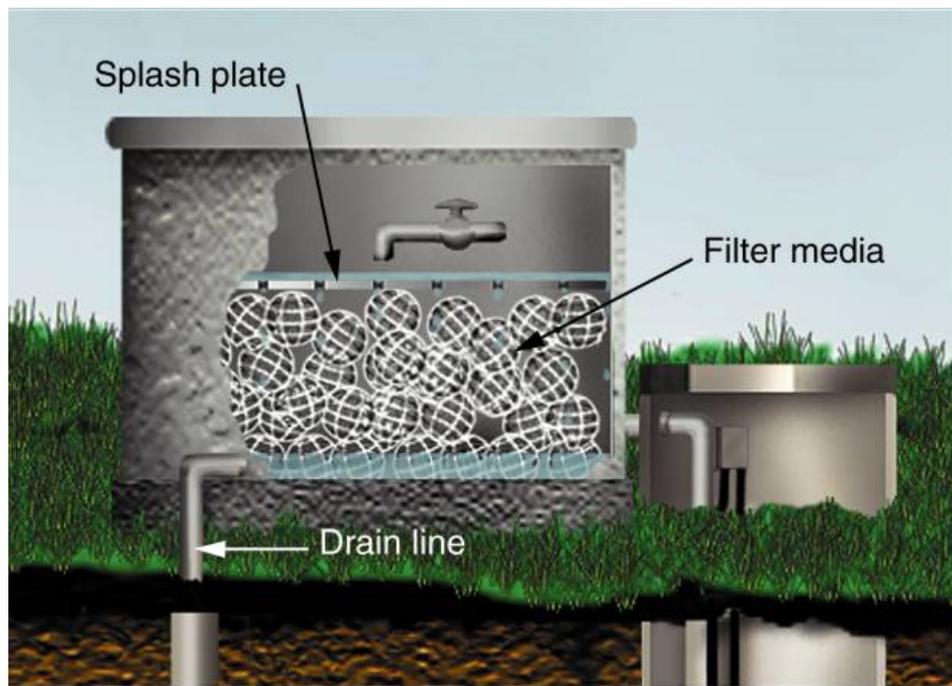


Figure 5. A trickling filter used to reduce BOD concentrations in wastewater flows (Onsite Wastewater Treatment program, Texas Cooperative Extension).

Reaction Types

There are two kinds of reactions: irreversible and reversible. In irreversible reactions, reactants form a product which cannot return to the original state. These processes cannot operate backwards.

Example of an Irreversible Reaction:

The combustion reaction cannot be reversed. Once something has been burned, it is not possible to return it to its original state.

Reactants:

- CH₂O
- O₂

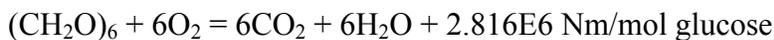
Products:

- CO₂
- H₂O

In reversible reactions, the reaction process works in both directions. The rate of reaction may be different depending on the direction (faster forming product than returning to original reactants).

Example of a Reversible Reaction:

Aerobic oxidation of glucose



Reactants:

- CH₄
- O₂

Products:

- CO₂

Hydraulic Retention Time

Hydraulic retention time (HRT) is the average amount of time that flow spends in a reactor. The longer the hydraulic retention time is, the more time the reactants have to react and thus the purer the products are. But, if the efficiency of treatment increases with greater HRT, the costs for treatment also rise. Therefore, a balance between the desired treatment levels and the treatment costs must be found. HRT is defined as:

$$\theta = \frac{V}{Q}$$

where:

V = Volume of the reactor tank (volume)

Q = Fluid flow rate (volume /time)

θ = Hydraulic retention time (time)

Types of Reactors

There are three principal kinds of reactors: batch reactors, continuous stirred tank reactors and plug flow reactors.

Batch Reactors

- All the reactants are placed into the reactor and mixed well; the products are removed at the end
- No material enters or leaves the reactor during the reaction progress
- The concentration of the reactants depends on time

To find the concentration of the reactants at a particular time, use the following equation:

$$C_A = C_{A0}e^{-kt}$$

where:

C_A = concentration at time t , (mass/volume)

C_{A0} = concentration at the beginning of reaction (mass/volume)

k = reaction rate coefficient (1/time)

t = time since reaction started (time)

Continuously Stirred Tank Reactors (CSTR)

- All the reactants are placed into the reactor and mixed well
- There is a continuous flow in and out

To find the concentration of the reactants at a particular time, use the following equation:

$$C_A = \frac{C_{A0}}{(\theta k + 1)}$$

where:

C_A = Concentration at time t (mass per unit volume)

C_{A0} = Concentration at start of reaction (mass per unit volume)

k = reaction rate coefficient (1/time)

θ = hydraulic retention time (time)

Plug Flow Reactors (PFR)

- The reactants are not mixed;

- There is a continuous flow in and out.

To find the concentration of the reactants at a particular time, use the following equation:

$$C_A = C_{A0}e^{-k\theta}$$

where:

C_A = concentration at time t, (mass/volume)

C_{A0} = concentration at the beginning of reaction (mass/volume)

k = reaction rate coefficient (1/time)

θ = hydraulic retention time (time)

Batch Reactors

$$C_A = C_{A0}e^{-kt}$$

CSTR

$$C_A = \frac{C_{A0}}{(\theta k + 1)}$$

PFR

$$C_A = C_{A0}e^{-k\theta}$$

Example:

Water with 200 mg/L of a degradable compound is passed through a reactor. The flow rate through the reactor is 500 m³/day and the reactor has a volume of 250 m³. The reaction rate coefficient for the reaction is 2 d⁻¹.

1. What is the existing concentration of reactants for a batch reactor after one day?
2. For a CFST reactor?
3. For PFR reactor?

Equation for a batch reactor: $C_A = C_{A0}e^{-kt}$

$$\text{Application: } C_A = 200e^{(-2*1)} = \underline{27.1 \text{ mg/L}}$$

Equation for a CFST reactor: $C_A = \frac{C_{A0}}{(\theta k + 1)}$

$$\text{Application: With } \theta = \frac{Vol}{Q} = \frac{250m^3}{500 \frac{m^3}{day}} = 0.5 \text{ days}$$

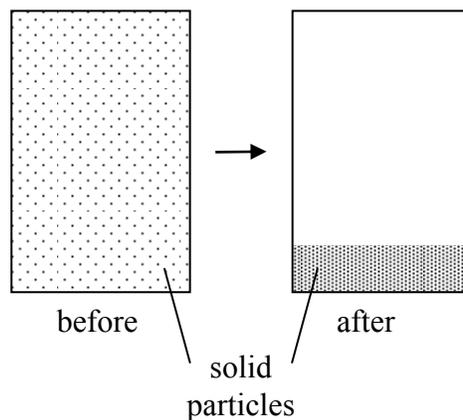
$$\text{So, } C_A = \frac{200}{(.5 * 2) + 1} = \underline{100\text{mg/L}}$$

Equation for a PFR reactor: $C_A = C_{A0}e^{-k\theta}$

$$\text{Application: } C_A = 200e^{(-2*.5)} = \underline{73.7 \text{ mg/L}}$$

Sedimentation

Sedimentation is the gravitational accumulation of particles (essentially solid particles) at the bottom of a fluid (air or water).



Uses of Sedimentation

Sedimentation principles apply to removal of solids from waste water. Solids removal occurs in:

- Septic tanks
- Lagoons
- Last stage of aerobic treatment units

Types of Sedimentation

The concentration of solid particles significantly influences the rate of sedimentation. Thus, we consider different kinds of sedimentation:

Discrete settling occurs when there is a low concentration of solids in the fluid. Each particle settles independently and rarely affects the sedimentation of other particles.

Flocculant settling occurs when the concentration of particles is great enough to cause individual particles to stick together and form flocs. The flocs settle freely and are unhindered by other particles.

Hindered settling occurs when the concentration of particles becomes great enough to inhibit water movement between particles during settling. Water must move through spaces between particles.

Compression occurs when the concentration of particles is sufficiently high that the weight of the particles on top compresses the mass below.

Influencing Factors

The speed at which the particles settle is directly related to several factors related to the particle and the fluid through which it moves.

Particle Factors

- Size: bigger particles settle faster than smaller.
- Density: denser particles settle faster than those with lower density.
- Shape: spherical particles settle faster than large, flat particles.
- Charge: a water molecule is made up of two hydrogen atoms and one oxygen atom. The oxygen atom tends to have a slight negative charge, while the hydrogen atoms have a slight positive charge. Thus, the water molecule is a polarized molecule. Some particles (clays) carry an electric charge which interacts with polarity of water.

Illustrations:

- Drop a tiny grain of sand and a large stone into a fluid. The large stone will take much less time to settle.
- Take two identical sheets of paper. Make a paper ball with one of them. Drop the ball and the flat sheet in a fluid. The ball will settle much faster.

Fluid Factors

- Flow velocity: particles settle faster when there is no fluid movement, velocity causes turbulence that keeps particles suspended (greater velocity allows suspension of larger, denser particles)
- Fluid density: determines amount of buoyancy (weight of displaced water), denser fluids provided greater buoyancy and slower settling. If the fluid is comparatively denser than the particle, the particle will float and never settle, just like a cork sitting on top of water. If, however, the fluid is much less dense than the particle, like a rock dropped in water, the particle will settle more quickly
- Fluid viscosity (fluid thickness): greater drag occurs with more viscous fluids, slowing the rate of sedimentation.

Determining Sedimentation Rate with Stoke's Law

To find the particle settling velocity in a very quiet fluid Stokes' Law is as follows:

$$v_p = \frac{(\rho_p - \rho_w)d^2g}{18\mu}$$

where:

v_p = particle settling velocity (m/s or ft/s)

ρ_p = particle density (kg/m³ or lb/ft³)

ρ_w = fluid density (kg/m³ or lb/ft³)

d = particle diameter (m or ft)

g = gravitational acceleration (9.81 m/s² or 32.2 ft/s²)

μ = fluid viscosity (g/m·s or lb/ft·s)

Typical Values for ρ and μ

- Particle densities for mineral sediments (mineral fraction of soil) is $\rho = 2650 \text{ kg/m}^3$
- Water densities at 20 °C is $\rho = 998 \text{ kg/m}^3$
- Water viscosity at 20 °C $\mu = 1.01 \times 10^{-3} \text{ kg/m}\cdot\text{s}$ or 0.00101 kg/m·s

Example:

Determine the settling velocity for a 0.5mm particle with a density of 2000 kg/m³ in 20°C water.

$\rho_p = 2000 \text{ kg/m}^3$

$\rho_w = 998 \text{ kg/m}^3$

$d = 0.5\text{mm} = 0.0005 \text{ m}$

$g = 9.81 \text{ m/s}^2$

$\mu = 0.00101 \text{ kg/m}\cdot\text{s}$

$$v_p = \frac{(2000 - 998)(0.0005)(9.81)}{18(0.00101)}$$

$$v_p = \underline{0.14 \text{ m/s}}$$

Applications to Settling Basins

- The surface area of a settling tank or basin needed to trap particles of a given size and density can be determined using Stoke's Law.
- The critical settling velocity is set equal to the settling velocity of the smallest particle to be trapped.
- The overflow rate (similar to a vertical velocity) is equal to the flow rate into the tank divided by the surface area (just like $Q = VA$)
- Setting the overflow rate equal to the critical settling velocity will allow time for capture of the smallest particles of interest (assuming no other disturbances):

$$OFR = v_c = \frac{Q}{A}$$

where

OFR = the overflow rate (m/s or ft/s)

v_c = the critical settling velocity (m/s or ft/s)

Q = the flow rate into the basin (m^3/s or cfs)

A = the surface area of the basin (m^2 or ft^2)

Example:

A flow has 2000 kg/m^3 particles ranging in size from 0.2 to 1.5 mm. The flow rate into a settling basin is $2,000,000 \text{ m}^3/\text{d}$. How large a tank is needed to capture particles 0.5 mm and larger? The temperature is 20°C .

We need v_p for 0.5mm particles which we will use as the critical velocity.

From the previous example, we know that $v_p = 0.14 \text{ m/s}$ for a 0.5mm particle with a 2000 kg/m^3 density

$$v_c = 0.14 = \frac{2,000,000(1/24)(1/3600)}{A}$$

$$\underline{A = 165 \text{ m}^2}$$

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