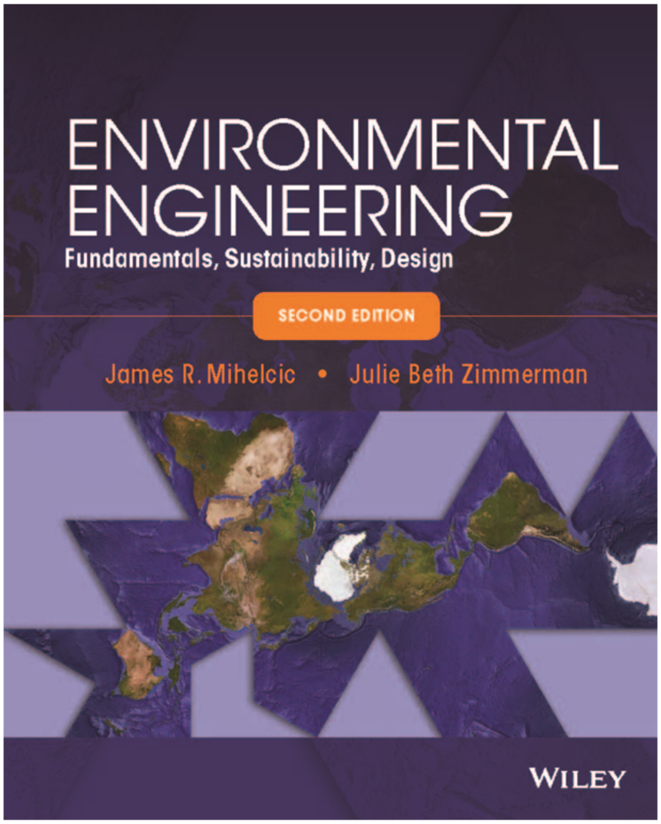
Solutions Manual for:

Environmental Engineering: Fundamentals, Sustainability, Design

John Wiley & Sons, 2014. (James R. Mihelcic & Julie B. Zimmerman)
ISBN: 978-1-118-74149-8

2nd Edition Solution Manual written by:
Colleen C. Naughton
Civil & Environmental Engineering, University of South Florida

1st Edition solutions provided by:
Dr. Heather E. Wright Wendel (University of South Florida)
&
Dr. Ziad Katirji (Michigan Technological University)



Version 1; November 21, 2013

Chapter 1. Sustainable Design, Engineering, and Innovation

1.1 Write an official 1-page office memo to your instructor that provides definitions for: (a) Sustainable Development (by the Bruntland Commission), (b) Sustainability (according to the American Academy of Environmental Engineers (AAEE) Body of Knowledge), (c) Sustainability (according to the American Society of Civil Engineers (ASCE) Body of Knowledge), and, (d) Sustainable Development (according to the National Society of Professional Engineers (NSPE) Code of Ethics).

Solution:

Student responses will vary. See the next page for a full example memo.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

Date: February 10, 2010
To: James R. Mihelcic, Civil & Environmental Engineering
Subject: Definitions of Sustainable Development

The Bruntland Commission defines **sustainable development** as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[1]

The American Society of Civil Engineers (ASCE) Body of Knowledge defines **sustainability** as “the ability to meet human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and enhancing environmental quality and the natural resource base essential for the future.”[2]

The American Academy of Environmental Engineers (AAEE) Body of Knowledge defines **sustainability** as “a condition in which the use of natural resources and cycles in human and industrial systems does not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment.”[3] This definition is based on that of Mihelcic et al. (2003).[4]

The National Society of Professional Engineers (NSPE) defines **sustainable development** as “the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development”.[5]

All these definitions are similar to the broadest definition of sustainability by the Bruntland Commission . ASCE, AAEE, and NSPE definitions add more detail to the definition of development in relation to their respective fields with infrastructure and the environment. Between the three engineering societies, ASCE and NSPE are almost identical in defining sustainability as meeting human needs for engineering systems without compromising the future. However, the definition by AAEE is unique and incorporates quality of life as opposed to human needs, social conditions, and human health.

---

[1] World Commission on Environment and Development. (1987). *Our common future.* Oxford: Oxford University Press.

[2] American Society of Civil Engineers. (2008). *Civil engineering body of knowledge for the 21st century, Preparing the civil engineer for the future*, (2nd. Ed.). Body of Knowledge Committee of the Committee on Academic Prerequisites for Professional Practice. Reston, VA.

[3] American Academy of Environmental Engineers. (2009). *Environmental engineering body of knowledge.* The Environmental Engineering Body of Knowledge Task Force, Baltimore, MD.

[4] Mihelcic, J.R., Crittenden, J.C., Small, M.J., Shonnard, D.R., Hokanson, D.R., Zhang, Q., Chen, H., Sorby, S.A., James, V.U., Sutherland, J.W., Schnoor, J.L. (2003). “Sustainability science and engineering: Emergence of a new metadiscipline,” *Environmental Science & Technology*, 37(23):5314-5324.

[5] National Society of Professional Engineer. (2007). *Code of ethics for engineers*, Alexandria, VA.

1.2 Write your own definition of sustainable development as it applies to your engineering profession. Explain its appropriateness and applicability in 2-3 sentences.

Solution:

Student responses will vary.

1.3 Identify three definitions of sustainability from three sources (for example, local, state or federal government; industry; environmental organization; international organization; financial or investment organization). Compare and contrast those definitions with the Brundtland Commission definition. How do the definitions reflect their sources?

Solution:

Student responses will vary.

1.4 Relate the "Tragedy of the Commons" to a local environmental issue. Be specific on what you mean in terms of the "commons" for this particular example, and carefully explain how these "commons" are being damaged for current and future generations.

Solution:

Student responses will vary.

1.5 Research the progress that two countries of your choice (or your instructor's choice) have made in meeting each of the eight Millennium Development Goals (MDGs). Summarize the results in a table. Among other sources, you might consult the UN's MDG Web site, www.un.org/millenniumgoals/.

Solution:

The Millennium Development Indicator's website has country and regional snap shot tables for each of the goals and indicators (http://mdgs.un.org/unsd/mdg/Host.aspx?Content=Data/snapshots.htm). A summary of the progress made in Mali and Ghana (Students may have chosen different countries) are displayed in the table below.

		Mali					**Ghana**				
		First Year		**Latest Year**			**First Year**		**Latest Year**		
Target	**Indicator**	*Value*	*Year*	*Value*	*Year*	**Progress**	*Value*	*Year*	*Value*	*Year*	**Progress**
Goal 1: Eradicate Extreme Poverty and Hunger											
Reduce extreme poverty by half	Proportion of population living below $1.25 (PPP) per day (%)	86.1	1994	50.4	2010	On track	51.1	1992	28.6	2006	On track
Reduce hunger by half	Proportion of population below minimum level of dietary energy consumption (%)	25.3	1991	7.9	2011	Achieved	40.5	1991	<5	2011	Achieved
Goal 2: Achieve Universal Primary Education											
Universal primary schooling	Net enrolment ratio in primary education (enrollees per 100 children)	42.2	1999	67.2	2011	On track	61.5	1999	84.2	2011	Below target
Goal 3: Promote Gender Equality and Empower Women											
Equal girls' enrolment in primary school	Ratio of girls to boys in primary education	0.61	1991	0.88	2011	Below target	0.86	1991	1	2011	Achieved
Women's share of paid employment	Share of women in wage employment in the non-agricultural sector (%)	27.3	1997	34.6	2004	Below target			31.7	2000	Below target
Women's equal representation in national parliaments	Proportion of seats held by women in national parliament (single or lower house only-%)	2.3	1997	10.2	2012	Off track	9	1998	8.3	2012	Off track

		Mali					**Ghana**				
		First Year		**Latest Year**			**First Year**		**Latest Year**		
Target	**Indicator**	*Value*	*Year*	*Value*	*Year*	**Progress**	*Value*	*Year*	*Value*	*Year*	**Progress**
Goal 4: Reduce child mortality											
Reduce mortality of under-five-year-old by two thirds	Under-five mortality rate (deaths of children per 1,000 births)	257	1990	175.6	2011	Off track	121	1990	77.6	2011	Below target
Goal 5: Improve maternal health											
Reduce maternal morality by three quarters	Maternal mortality ratio (maternal deaths per 100,000 live births)	1100	1990	540	2010	Off track	580	1990	350	2010	Off track
Access to universal reproductive health	Contraceptive prevalence rate (percentage of women aged 15-49, married or in union, using contraception)	6.7	1996	8.2	2006	Off track	17.2	1992	23.5	2008	Off track
	Unmet need for family planning (percentage of women aged 15-49, married or in union, with unmet need for family planning)	27.5	1996	27.6	2006	Off track	36.9	1993	35.7	2008	Off track
Goal 6: Combat HIV/AIDS, malaria and other diseases											
Halt and begin to reverse the spread of HIV/AIDs	HIV incidence rate (number of new HIV infections per year per 100 people aged 15-49)	0.09	2001	0.06	2009	Below target	0.18	2001	0.15	2009	Off track
Halt and begin to reverse spread of tuberculosis	Incidence rate and death rate associated with tuberculosis	163/41	1990	68/9.7	2010	On track	155/36	1990	86/8.7	2010	On track

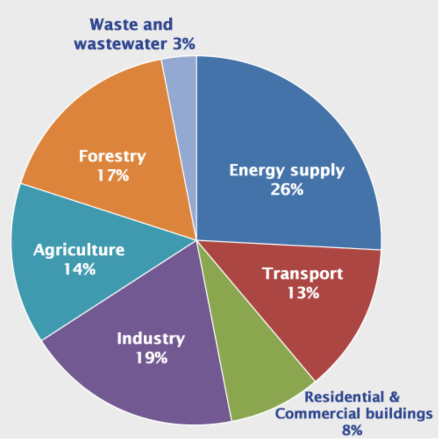
		Mali					**Ghana**				
		First Year		**Latest Year**			**First Year**		**Latest Year**		
Target	**Indicator**	*Value*	*Year*	*Value*	*Year*	**Progress**	*Value*	*Year*	*Value*	*Year*	**Progress**
Goal 7: Ensure environmental sustainability											
Reverse loss of forests	Proportion of land area covered by forest (%)	11.5	1990	10.2	2010	Below target	32.7	1990	21.7	2010	Below target
Halve proportion without improved drinking water	Proportion of population using an improved drinking water source (%)	28	1990	64	2010	Achieved	53	1990	86	2010	On track
Halve proportion without sanitation	Proportion of population using an improved sanitation facility (%)	15	1990	22	2010	Off track	7	1990	14	2010	Off track
Improve the lives of slum-dwellers	Proportion of urban population living in slums (%)	94.2	1990	65.9	2009	Below target	65.5	1990	40.1	2009	Below target
Goal 8: Develop a global partnership for development											
Internet users	Internet users per 100 in habitants	0	1990	2	2011	Off track	0	1990	14.1	2011	Below target

1.6 Go to the U.S Department of Energy's website (www.doe.gov), and research energy consumption in the household, commercial, industrial, and transportation sectors. Develop a table on how this specific energy consumption relates to the percent of U.S. and global CO_2 emissions. Identify a sustainable solution for each sector that would reduce energy use and CO_2 emissions.

Solution:

Students will need to do some research on the web for this item. Energy consumption values can be found on the Annual Energy Review website (http://www.eia.gov/totalenergy/data/annual/index.cfm) . Greenhouse gas emissions by sector can be found on the EPA (http://www.epa.gov/climatechange/ghgemissions/global.html) or IPPC web pages.

Sector	**Total U.S. Energy Consumption in 2012 (trillion Btu)**	**Percent of U.S. Emissions (2012)**	**Percent Global Emissions (2004)**	**Sustainable Solution (Students answers may vary)**
Household	20,195	21.3%	8% (includes household & commercial	Solar panels
Commercial	17,507	18.4%	(see above)	LED light fixtures
Industrial	30,562	32.2%	19%	Carbon tax
Transportation	26,712	28.1%	13%	Public transportation infrastructure
Total	94,977	100%	See figure below for more details	



Global greenhouse gas emissions by source (commercial and residential are grouped) (EPA reference to IPCC 2007 for global emissions in 2004)

1.7 As a consumer interested in reducing your carbon emissions, (a) which should you do: (1) install more efficient lighting for your home or (2) buy a car that gets higher miles per gallon? To answer this, consider that a 100w light bulb that is run 3 hours a day every day will use around 100 kWh a year. A high efficiency light uses about 25% of a conventional light bulb. Replacing it with a 25w Compact Fluorescent Bulb would save 75 kwh a year. This would equal 150 lbs of carbon dioxide or the same amount of carbon dioxide emissions associated with burning 7.5 gallons of gasoline. (b) Given that the average US household uses 10,000 kWh a year of which 8.8% is lighting, how many gallons of gas and lbs of CO2 could be saved by switching all of the bulbs in a home? (c) For comparison, if you drove 12,000 miles a year and upgraded from a car that gets the national average of 20 mpg to one that got 30 mpg, how much would you reduce your gas consumption and CO2 emissions on an annual basis? (d) What if you upgraded from a car that get 30 mpg to 37 mpg? (combustion of 100 gallons of gasoline releases 2,000 lbs. of carbon dioxide).

Solution:

a. You should choose depending on how many light bulbs you use in your home and for how long each day and how much you drive each year. By performing the calculations for parts b and c, you should choose to **install more efficient lighting for your home.**

b.

$$10{,}000 kWh \times 0.088 \times 0.75 \times \frac{150\ lbs\ CO_2}{75\ kWh} = \boldsymbol{99,000\ lbs\ CO_2}$$

$$10{,}000 kWh \times 0.088 \times 0.75 \times \frac{7.5\ gallons}{75\ kWh} = \boldsymbol{4,950\ gallons}$$

c.

$$(12{,}000\ miles \times \tfrac{1\ gallon}{20\ miles}) - (12{,}000\ miles \times \tfrac{1\ gallon}{30\ miles}) = \boldsymbol{200\ gallons}$$

$$200\ gallons \times \frac{2{,}000\ lbs\ CO_2}{1000\ gallons} = \boldsymbol{400\ lbs\ CO_2}$$

d. Switching from a 20mpg vehicle to 30 mpg vehicle results in a 10 mpg savings.

$$(12{,}000\ miles \times \tfrac{1\ gallon}{30\ miles}) - (12{,}000\ miles \times \tfrac{1\ gallon}{37\ miles}) = \boldsymbol{76\ gallons}$$

$$76\ gallons \times \frac{2{,}000\ lbs\ CO_2}{1000\ gallons} = \boldsymbol{152\ lbs\ CO_2}$$

1.8 Visit EPA's Presidential Green Chemistry Challenge Award website at www.epa.gov/greenchemistry/pubs/pgcc/past.html. Select a past award-winning project. Based on the description of this project, what are the environmental, economic and social benefits of this green chemistry advance?

Solution:

Student responses will vary. An example of an award-winning project of the Green Chemistry Challenge Award is for Buckman's Maximyze Enzymes. These enzymes are made of natural catalysts that reduce the energy and wood fiber needed to manufacture high-quality paper. In one case, paper was able to be reduced by 3 pounds per 1,000 square feet which not only reduces the amount of raw pulp materials but also lowers shipping and energy costs. With increased paper strength, more recycled fibers can be used in the paper which is beneficial to the environment and reduces costs. Overall, this new enzyme translates into a social benefit with less deforestation and a cleaner environment for a healthier society. For more information on this specific green chemistry challenge award winning project, see the link below:

http://www.buckman.com/about-us/news/562-buckman-wins-presidential-green-chemistry-challenge-award

1.9 Discuss whether shoe A (leather) or shoe B (synthetic) is better for the environment based on the data in Table 1.8. Is it possible to weight one aspect (air, water, land pollution or solid waste) as being more important than another? How? Why? Who makes these decisions for our society?

Table/1.8 Hypothetical Life Cycle Environmental Impacts of Shoes on a basis of per 100 pairs of shoes produced

Product	Energy use (BTU)	Raw material consumption	Water use (gallons)	Air pollution (lbs.)	Water pollution	Hazardous and solid waste
Shoe A (leather)	1	Limited supply; some renewable	2	4	2 lb. organic chemicals	2 lb. hazardous sludge
Shoe B (synthetic)	2	Large supply; not renewable	4	1	8 lb. inert inorganic chemicals	1 lb. hazardous sludge; 3 lb. nonhazardous sludge

Solution:

Student responses will vary.

While shoe A uses less energy, nonrenewable resources and water, it uses more water and results in higher hazardous and solid waste. On the other hand Shoe B uses more energy and water but emits less air pollution and produces less hazardous and solid waste. You will need to develop a weighting system to rate each option, in each environmental impact category to develop an overall score to compare the two options. Environmental regulators and the general population make these decisions for society.

1.10 To compare plastic and paper bags in terms of acquisition of raw materials, manufacturing and processing, use and disposal, we'll use data provided by Franklin Associates, a nationally known consulting firm whose clients include the U.S. Environmental Protection Agency as well as many companies and industry groups. In 1990, Franklin Associates compared plastic bags to paper bags in terms of their energy and air/water emissions in manufacture, use, and disposal. Table 1.9 presents the results of their study:

Table/1.9 Results of Study Comparing Plastic and Paper Bags

Life Cycle Stages	Air Emissions (pollutants) oz/bag		Energy Required BTU/bag	
	Paper	Plastic	Paper	Plastic
Materials manufacture, product manufacture, product use	0.0516	0.0146	905	464
Raw materials acquisition, product disposal	0.0510	0.0045	724	185

(a)Which bag would you choose if you were most concerned about air pollution? (Note that the information does not tell you if these are toxic air emissions or greenhouse gas emissions) (b) If you assume that two plastic bags equal one paper bag, does the choice change? (c) Compare the energy required to produce each bag. Which bag takes less energy to produce?

Solution:

a) For paper: 0.0516 + 0.0510 = 0.1026 oz/bag
For plastic: 0.0146 + 0.0045 = 0.0191 oz/bag

Plastic; however, the nature of the air emissions may be of concern.

b) For paper: 0.0516 + 0.0510 = 0.1026 oz/bag
For plastic: (0.0146 + 0.0045) * 2 = 0.0382 oz/bag

No. Plastic still has a lower life cycle air emissions than paper even with using twice as many bags.

c) For paper = 905 + 724 = 1629 BTU/bag
For plastic = 464 + 185 = 649 BTU/bag

Plastic bags take less energy to produce (even at the 2:1 ratio).

1.11 You are preparing a life cycle analysis of three different electrification options for powering your 1,200 square foot home in rural Connecticut. The options you're considering include: 1) just using your local grid, 2) putting in a solar installation on your roof, or 3) building a transmission extension to join up with your neighbor's already-built wind turbine. Write a possible goal, scope, function, and functional unit for this LCA. Explain your reasoning.

Solution:

Student's answers may vary.

Goal: Determine which of the following electrification options have the least environmental impact: 1) just using your local grid, 2) putting in a solar installation on your roof, or 3) building a transmission extension to join up with your neighbor's already-built wind turbine.

Scope: This LCA will consider the resource extraction, manufacturing, and use-phase but will not consider transportation and end-of-life stage.

Function: Provide enough energy to light and run appliances in a 1,200 square foot home in rural Connecticut.

Functional unit: The energy to power 1,2000 square foot home in rural Connecticut.

1.12 Consider the full life cycle of each of the three electrification options (possibly beyond whatever you've selected for the scope of your LCA) in Problem 1.11. Discuss which of the life cycle stages is most impactful for each electrification type. You will need to take into account the life cycle impacts of primary through final energy in each case. As a reminder, life cycle stages typically include: resource extraction, manufacture, transportation, use, and end of life.

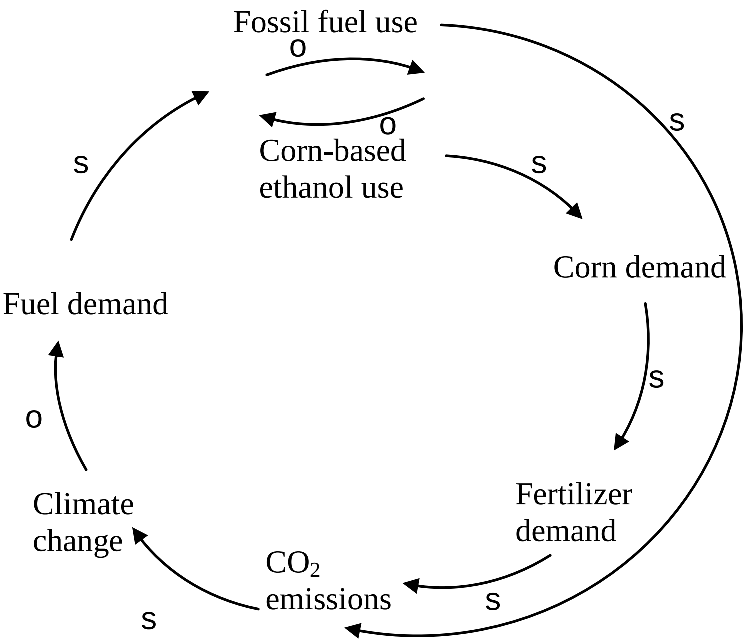
Solution:

Student responses will vary but below is an example solution.

Electrification Option	**Impactful life stage**
1) Just using your local grid	Material extraction of non-renewable resource such as coal and the burning of such during the use-phase.
2) Putting in a solar installation on your roof	Material extraction of metals for solar panels. End-of-use in recycling/disposal of solar panels.
3) Building a transmission extension to join up with your neighbor's already-built wind turbine	Material extraction for materials to build the extension.

1.13 Draw causal loop diagram for corn-based ethanol production using the following variables: climate change, corn-based ethanol use, fertilizer demand, CO_2 emissions, Fuel demand, Fossil fuel use, and Corn demand.

Solution:



1.14 (a) Is centralized drinking water treatment and distribution more or less resilient than point of use water treatment technologies? Why or why not? (b) Does it matter whether these water treatment systems are implemented in the developing or developed world?

Solution:

Student responses will vary.

1.15 The design team for a building project was formed at your company last week and they have already held two meetings. Why is it so important for you to get involved immediately in the design process?

Solution:

It is at the design stage where there is the most power and potential to influence the ultimate "greenness" or sustainability of a design. It is at this stage that there is an ability to specify inherently benign materials, to design for end of life handling, and consider the entire life cycle. At the design stage there is an opportunity to impart new performance and capabilities. This is also the most economical place to focus due to the fact that costs are committed at this point although they are not incurred until much later in the process.

1.16 Provide an example of a product either commercially available or currently under development that uses biomimicry as the basis for its design. Explain how the design is mimicking a product, process, or system found in nature.

Solution:

Student responses will vary.

1.17 Two reactants, benzyl alcohol and tosyl chloride, react in the presence of an auxiliary, triethylamine, and the solvent toluene to produce the product sulfonate ester (see Table 1.10). Calculate the E factor for the reaction. What would happen to the E factor if the solvents and auxiliary chemicals were included in the calculation? Should these types of materials and chemicals be included in an efficiency measure? Why or why not?

Table 1.10. Useful information needed to solve Problem 1.17

Reactant	Benzyl alcohol	10.81 g	0.10 mole	MW 108.1 g/mole
Reactant	Tosyl chloride	21.9 g	0.115 mole	MW 190.65 g/mole
Solvent	Toluene	500 g		
Auxiliary	Triethylamine	15 g		MW 101 g/mole
Product	Sulfonate ester	23.6 g	0.09 mole	MW 262.29 g/mole

Solution:

Without solvent:

$$E-factor=\frac{(10.81+21.9)}{23.6}=1.4$$

$$\Rightarrow \boxed{1.4 \text{ kg waste produced / kg of product}}$$

With solvent and auxiliary:

$$E-factor=\frac{(10.81+21.9+500+15)}{23.6}=23.2$$

$$\Rightarrow \boxed{23.2 \text{ kg waste produced / kg of product}}$$

If solvents and auxiliary chemicals are included the E factor increases 20-fold. These chemicals should be included if they are not recovered and recycled because they also contribute to the total waste of the process. These chemicals are also important because many solvents are VOCs and toxics.

1.18 Choose three of the principles of green engineering. For each one, (a) explain the principle in your own words; (b) find an example (commercially available or under development), and explain how it demonstrates the principle; and (c) describe the associated environmental, economic, and societal benefits, identifying which ones are tangible and which ones are intangible.

Solution:

Application 1.10 in Chapter 1 lists the twelve Principles of Green Engineering. Students can build their solution to this problem by reviewing this table and associated reading material.

1.19 (a) Develop five sustainability metrics or indicators for a corporation or an industrial sector analogous to those presented for communities in Table 1-X. (b) Compare them with traditional business metrics or indicators. (c) Describe what new information can be determined from the new sustainability metrics or indicators.

Solution:

Student responses will vary.

1.20 A car company has developed a new car, ecoCar, that gets 100 miles per gallon (mpg), but the cost is slightly higher than cars currently on the market. What type of incentives could the manufacturer offer or ask Congress to implement to encourage customers to buy the new ecoCar?

Solution:

Students' responses will vary. Here is an example response:

First, the manufacturer would need to demonstrate how a higher capital cost of the vehicle will be made up in the savings with higher fuel efficiency. The manufacturer could also offer better warranties or payment plans for the vehicle to attract consumers. They may request that congress provide tax write offs or subsidies for consumers who buy more fuel efficient vehicles. Moreover, the manufacturer could lobby for tax breaks on their ecoCar facility property taxes and revenue. Those savings could then reduce the market price of the vehicle for consumers.

1.21 Do you agree or disagree with the following statement? Why or why not? (3-5 sentences) “Technology-forcing pollution regulations are preferable to standards- or outcome-based regulations”.

Solution:

Student responses will vary.

1.22 You are about to buy a car that will last 7 years before you have to buy a new one, and Congress has just passed a new tax on greenhouse gases. Assume a 5% annual interest rate. You have two options: (a) Purchase a used car for \$12,000, upgrade the catalytic converter at a cost of \$1,000, and pay a \$500 annual carbon tax. This car has a salvage value of \$2,000. (b) Purchase a new car for \$16,500 and pay only \$100 annually in carbon tax. This car has a salvage value of \$4,500. Based on the annualized cost of these two options, which car would you buy?

Solution:

a. $PV = 13{,}000 + \frac{500}{1.05} + \frac{500}{1.05^2} + \cdots + \frac{500-2{,}000}{1.05^7} = \$14{,}472 A = 14{,}472\left(\frac{0.05}{1-(1+i)^{-7}}\right) = \$\mathbf{2,501}$

b. $PV = 16{,}600 + \frac{500}{1.05} + \frac{500}{1.05^2} + \cdots + \frac{500-4{,}500}{1.05^7} = \$13{,}881 A = 13{,}881\left(\frac{0.05}{1-(1+i)^{-7}}\right) = \$\mathbf{2,399}$

Chapter 2. Environmental Measurements

2.1 (a) During drinking water treatment, 17 lb. of chlorine (Cl) are added daily to disinfect 5 million gallons of water. What is the aqueous concentration of chlorine in mg/L? (b) The *chlorine demand* is the concentration of chlorine used during disinfection. The *chlorine residual* is the concentration of chlorine that remains after treatment so the water maintains its disinfecting power in the distribution system. If the residual concentration is 0.20 mg/L, what is the chlorine demand in mg/L?

Solution:

a) 17 lb. chlorine added to 5 million gallons of water. Chlorine dosage in mg/L:

$$\frac{17\ lb/day}{5\times10^{6}\ gal/day}\times\frac{454\ g}{1\ lb}\times\frac{1000\ mg}{1g}\times\frac{1\ gal}{3.78\ L}=\boxed{0.41\ mg/L}$$

b) Chlorine demand:

$$0.41\ mg/L-0.20\ mg/L=\boxed{0.21\ mg/L}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.2 A water sample contains 10 mg NO_3^-/L. What is the concentration in (a) ppm_m, (b) moles/L, (c) mg NO_3^--N/L, and (d) ppb_m?

Solution:

10 g NO_3^-/L in various units.

a) 1 L water = 1 kg water (in water, mg/L = ppm)

$$\frac{10\ mg/L}{1\ kg/L} = \boxed{10\ ppm\ as\ NO_3^-}$$

b) 62 grams NO_3^- = 1 mole NO_3^-

$$\frac{10\ mg}{L} \times \frac{1\ g}{1,000\ mg} \times \frac{1\ mole}{62\ g} = \boxed{1.6 \times 10^{-4}\ moles\ NO_3^-/L}$$

c) 62 grams NO_3^- = 1 mole NO_3^-; 14 grams N = 1 mole N; 1 mole NO_3^- = 1 mole N

$$\frac{10\ mg\ NO_3}{L} \times \frac{1\ mole\ NO_3}{62\ g\ NO_3} \times \frac{1\ mole\ N}{1\ mole\ NO_3} \times \frac{14\ g\ N}{1\ mole\ N} = \boxed{2.3\ mg\ \mathrm{NO_3\text{-}N/L}}$$

d) 1 L water = 1 kg water; 1 kg = 10^6 mg; 1 billion = 10^3 million

$$\frac{10\ mg/L}{1\ kg/L} \times \frac{1000\ million}{1\ billion} = \boxed{10,000\ ppb\ as\ NO_3^-}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.3 A liquid sample has a concentration of iron (Fe) of 5.6 mg/L. The density of the liquid is 2,000 g/L. What is the Fe concentration in ppm_m?

Solution:

$$2000\ g = 2\ kg$$

$$\frac{5.6\,\frac{mg}{L}}{2.0\,\frac{kg}{L}} = \boldsymbol{2.8\ ppm_m}$$

2.4 Coliform bacteria (for example, *E. coli)* are excreted in large numbers in human and animal feces. Water that meets a standard of less than one coliform per 100 mL is considered safe for human consumption. Is a 1 L water sample that contains 9 coliforms safe for human consumption?

Solution:

Standard requires < 1 coliform/100 mL, or 10 coliform/1 L

$$\frac{9\ coliforms}{L} \times \frac{L}{10\ coliforms\ (100\ mL)} = \boxed{0.9\ coliforms / 100\ mL}$$

<u>This value is < 1 coliform/100 mL; therefore, water is safe.</u>

2.5 The treated effluent from a domestic wastewater-treatment plant contains ammonia (NH_3) at 9.0 mg N/L and nitrite (NO_2^-) at 0.5 mg N/L. Convert these concentrations to mg NH_3/L and mg NO_2^-/L.

Solution:

17 g NH_3 = 1 mole NH_3

46 g NO_2^- = 1 mole NO_2^-

1 mole N = 1 mole NH_3 = 1 mole NO_2^-

$$\frac{9.0\ mg\ NH_3 - N}{L} \times \frac{1\ mole\ N}{14\ g\ N} \times \frac{1\ mole\ NH_3}{1\ mole\ N} \times \frac{17\ g\ NH_3}{1\ mole\ NH_3} = \boxed{10.9\ mg\ NH_3 / L}$$

$$\frac{0.5\ mg\ NO_2 - N}{L} \times \frac{1\ mole\ N}{14\ g\ N} \times \frac{1\ mole\ NO_2}{1\ mole\ N} \times \frac{46\ g\ NO_2}{1\ mole\ NO_2} = \boxed{1.6\ mg\ NO_2 / L}$$

2.6 Nitrate concentrations exceeding 44.3 mg NO_3^-/L are a concern in drinking water due to the infant disease, methemoglobinemia. Nitrate concentrations near three rural wells were reported as 0.01 mg NO_3^- N/L, 1.3 mg NO_3^- N/L, and 20.0 mg NO_3^- N/L. Do any of these three wells exceed the 44.3 ppm_m level?

Solution:

Convert the regulatory value to units of "as N". Then compare to the measured concentrations.

$$\frac{44.3\ mg\ \ NO_3}{L} \times \frac{1\ mole\ \ NO_3}{62.0\ g\ \ NO_3} \times \frac{1\ mole\ \ N}{1\ mole\ \ NO_3} \times \frac{14.0\ g\ \ N}{1\ mole\ \ N} = 10.0\ mg\ \ NO_3 - N / L$$

<u>The third well (20.0 mg NO_3^--N/L) exceeds the 10 ppm level.</u>

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.7 Sulfate (SO_4^{2-}) concentration is 10 mg SO_4^{2-}/L and monohydrogen sulfide (HS^-) concentration is 2 mg HS^-/L. What is the total inorganic sulfur concentration in mg S/L?

Solution:

Convert Sulfate (SO_4^{2-}) to molarity and then use the molar concentration of sulfur to convert to the concentration of sulfur. Add together the concentration of sulfur from both sulfate (SO_4^{2-}) and monohydrogen sulfide (HS^-) to get the total inorganic sulfur concentration.

$$\frac{10\, mg\ \mathrm{SO_4}^{2-}}{L} \times \frac{1\, mole\ \mathrm{SO_4}^{2-}}{96.07\ g} \times \frac{1\, mole\ \mathrm{S}}{1\, mole\ \mathrm{SO_4}^{2-}} \times \frac{32.07\ g}{mole\ S} = \frac{3.34\, mg\ \mathrm{SO_4}^{2-} - \mathrm{S}}{L}$$

$$\frac{2\, mg\ \mathrm{HS}^-}{L} \times \frac{1\, mole\ \mathrm{HS}^-}{33.08\ g} \times \frac{1\, mole\ \mathrm{S}}{1\, mole\ \mathrm{HS}^-} \times \frac{32.07\ g}{mole\ S} = \frac{1.94\, mg\ \mathrm{HS}^- - \mathrm{S}}{L}$$

$$total\ sulfur\ concentration = 3.34 + 1.94 = \boldsymbol{\frac{5.28\, mg\ S}{L}}$$

2.8 Suppose you must determine the amount of hydrogen halides (HCl, HBr and HF) in the flue gas leaving a chemical reactor. The emission sampling train for hydrogen halide determination calls for a total of 200 mL of 0.1 N H_2SO_4 as an absorbing solution. The absorbing solution will be located on the impingers of the sampling train. (a) How many grams of H_2SO_4 should be added to water to create 200 mL of a 0.1 N H_2SO_4 solution? (b) Calculate the molarity of the 0.1 N H_2SO_4 solution. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

Solution:

a) $0.1\ \mathrm{N\ H_2SO_4} \times \frac{2\ \mathrm{eqv}}{\mathrm{mole}} \times \frac{1\ \mathrm{mol\ H_2SO_4}}{\mathrm{L}} \times \frac{98.07\mathrm{g}}{\mathrm{mol\ H_2SO_4}} \times \frac{1\ \mathrm{L}}{1000\ \mathrm{L}} \times 200\mathrm{ml}\ = \mathbf{3.9\ g}$

b) $0.1\ \mathrm{N\ H_2SO_4} \times \frac{2\ \mathrm{eqv}}{\mathrm{mole}} \times \frac{1\ \mathrm{mol\ H_2SO_4}}{\mathrm{L}} = 0.2 \frac{\mathrm{mol}}{\mathrm{L}}\ \mathrm{H_2SO_4}\ = \mathbf{0.2\ M\ H_2SO_4}$

2.9 The concentration of cadmium (Cd) in a liquid is known to be 130 ppm at 20°C. Calculate the total quantity of cadmium present in a one-gallon sample. The sample has a density of 62.4 lb/ft3. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

Solution:

1 L water = 1 kg water (in water, mg/L = ppm). The density of water is 62.4 lb/ft^3

$$130\ ppm = 130\frac{mg}{L} \times \frac{3.7854\ L}{gal} = 492\frac{mg}{gal}$$

$$\boldsymbol{= 490\ mg\ or\ .490\ g\ Cd\ in\ a\ one - gallon\ sample}$$

2.10 As a quality control check, a sample of acetone is taken from a process to determine the concentration of suspended particulate matter. An 850-mL sample was placed in a beaker and evaporated. The remaining suspended solids were determined to have a mass of 0.001 gm. The specific gravity of acetone is 0.79 gm/cm^3. (a) Determine the concentration of the sample as mg/L. (b) Determine the concentration of the sample as ppm. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

a)

$$Concentration = \frac{0.001g}{850\ mL} \times \frac{1000mL}{1\ L} \times \frac{1000\ mg}{1g} = \boldsymbol{1.2\frac{mg}{L}}$$

b)

$$Concentration = 0.079\frac{g}{cm^3} \times \frac{1\ cm^3}{1\ mL} \times \frac{1000L}{1\ L} \times \frac{1kg}{1000g} = 0.079\frac{kg}{L}$$

$$\frac{1.2\frac{mg}{L}}{0.079\frac{kg}{L}} = \boldsymbol{15\ ppm_m}$$

2.11 A paper mill produces paper from wood pulp. Pulp production (at the pulp plant) begins with digesting the wood chips in a solution of sodium hydroxide and sodium sulfide. The sodium hydroxide is diluted with water (shown in the reaction below) prior to being sent to the digester.

$NaOH + H_2O \rightarrow Na^+ + OH^- + H_2O$

If 4 kg of sodium hydroxide is added for each 1000 L of water, determine the following: (a) the molarity of the resulting solution, (b) the normality of the resulting solution. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

a) $\frac{4\ kg\mathrm{NaOH}}{1000L} \times \frac{10^6}{kg} \times \frac{1\ mole\ \mathrm{NaOH}}{39.99\ g\ \mathrm{NaOH}} \times \frac{1\ mole\ \mathrm{Na}^+}{1\ mole\ \mathrm{NaOH}} = 100\ \frac{mole\ \mathrm{Na}^+}{L} = \mathbf{100}\ \boldsymbol{M}\ \mathbf{Na^+}$

$$\frac{4\ kg\mathrm{NaOH}}{1000L} \times \frac{10^6}{kg} \times \frac{1\ mole\ \mathrm{NaOH}}{39.99\ g\ \mathrm{NaOH}} \times \frac{1\ mole\ \mathrm{OH}^-}{1\ mole\ \mathrm{NaOH}} = 100\ \frac{mole\ \mathrm{OH}^-}{L} = \mathbf{100}\ \boldsymbol{M}\ \mathbf{OH^-}$$

b)

$$100\ \frac{mole\ \mathrm{OH}^-}{L} \times \frac{1\ eqv}{mole} = \frac{100\ eqv}{mole} = \mathbf{100\ N\ OH^-}$$

$$100\ \frac{mole\ \mathrm{Na}^+}{L} \times \frac{1\ eqv}{mole} = \frac{100\ eqv}{mole} = \mathbf{100\ N\ Na^+}$$

2.12 In Florida, advanced wastewater treatment standards require that treated effluent have no more than 5 ppm BOD_5, 5 ppm TSS, 3 ppm total nitrogen (TN), and 1 ppm total phosphorus (TP). a) What is the wastewater standard for TN and TP in mg/L? b) If all of the nitrogen is transformed to nitrate during the advanced treatment, what is the effluent limit of nitrate in mg/L? c) If your laboratory had obtained and processed 200-mL sample of treated wastewater for the TSS test , how many mg of suspended solids were captured on the filter for this sample?

Solution:

a) 1 L water = 1 kg water (in water, mg/L = ppm)

$$3\,ppm\ \text{TN} = \mathbf{3\,\frac{mg\ N}{L}}$$

$$1\,ppm\ \text{TP} = \mathbf{1\,\frac{mg\ P}{L}}$$

b) $3\,\frac{mgN}{L} \times \frac{1\,mole\,N}{14.01\,g} \times \frac{1\,mole\,NO_3-}{1\,mole\,N} \times \frac{62\,g}{1\,mole\,NO_3-} = \boldsymbol{13\,\frac{mgNO_3-}{L}}$

c) $5\,ppm\ \text{TSS} = 5\,\frac{\text{mg TSS}}{\text{L}} \times 200\text{L} \ = \mathbf{1,000\ mg\ suspended\ solids}$

2.13 Mirex (MW = 540) is a fully chlorinated organic pesticide that was manufactured to control fire ants. Due to its structure, mirex is very unreactive; thus, it persists in the environment. Lake Erie water samples have had mirex measured as high as 0.002 µg/L and lake trout samples with 0.002 µg/g. (a) In the water samples, what is the aqueous concentration of mirex in units of (i) ppb_m, (ii) ppt_m, (iii) µM? (b) In the fish samples, what is the concentration of mirex in (i) ppm_m, (ii) ppb_m?

Solution:

a) i) in dilute solutions µg/L = ppb, thus the concentration is 0.002 ppb_m

ii) 1,000 ppt = 1 ppb, therefor, the concentration is 2 ppt_m

iii)

$$\frac{0.002\ \mu g}{L} \times \frac{1\ mole}{540\ g} = \boxed{3.7 \times 10^{-6}\ \mu M}$$

b) i)

$$\frac{0.002\ \mu g}{g} = \boxed{0.002\ ppm}$$

ii) In solids, ppb = µg/kg

$$\frac{0.002\ \mu g}{g} \times \frac{1000\ million}{1\ billion} = \boxed{2\ ppb}$$

2.14 Total mercury concentrations in the San Francisco Bay Area are reported to be 1.25 ng/L in water, 8 mg/L in rain, 2.1 mg/m^3 in air, and 250 ng in one gram of dry sediment. (a) Report all these concentrations in ppt. Assume the air temperature is 20^{o}C.

$$1.25\frac{ng}{L}Hg \times \frac{1\ g}{10^9 ng} \times \frac{1.0\ L\ \mathrm{H_2O}}{1000\ g\ \mathrm{H_2O}} \times \frac{1\ g}{1000\ mg} = \frac{1.25\times10^{-12} g}{g} \times \frac{10^{12}\ ppt}{mass\ fraction} = \boldsymbol{1.25\ ppt\ Hg}$$

$$8\frac{mg}{L}Hg = 8\ ppm\ Hg\ \times \frac{10^6 ppt}{1\ ppm} = \boldsymbol{8.0 \times 10^6\ ppt\ Hg}$$

Solving for ppm$_v$ in equation 2.9:

$$ppm_v = \frac{\mu g}{m^3} \times \frac{1}{MW} \times \frac{RT}{1000P}$$

$$ppm_v = \ 2.1\frac{mg}{m^3} \times \frac{10^3 \mu g}{mg} \times \frac{1\ mole}{200.6g\ Hg} \times \frac{\frac{0.08205\ atm}{mol\ K} \times (20^o C + 273)}{1000\ (1\ atm)}$$
$$= 0.217\ ppm_v\ \times \frac{10^6 ppt}{1\ ppm} = \boldsymbol{252 \times 10^3\ ppt_v\ Hg}$$

$$250\frac{ng}{g\ sediment} = \boldsymbol{250\ ppt\ Hg}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.15 Leachate is produced when precipitation infiltrates a sanitary landfill , contacts the waste material, and appears at the bottom of the stored waste. Assume 6 kg of benzene (molecular formula of C_6H_6) were placed in the landfill and it is all dissolved in the 100,000 gallons of leachate produced during one year. What is the benzene concentration in the leachate during this one year in (a) mg/L; (b) ppb_m; and (c) moles/L?

Solution:

a) $\frac{6\,kg\ \mathrm{C_6H_6}}{1.0\times10^{6} gallons} \times \frac{3.7584\ gallons}{L} \times \frac{1000g}{1\ kg} \times \frac{1000\ mg}{1\ g} = \mathbf{23}\,\frac{\boldsymbol{mg}\ \mathbf{C_6H_6}}{\boldsymbol{L}}$

b) 1 L water = 1 kg water (in water, mg/L = ppm)

$$23\,\frac{mg\ \mathrm{C_6H_6}}{L} = 23\ ppm_m\ \mathrm{C_6H_6} * \frac{10^3\mathrm{ppb}}{1\ \mathrm{ppm}} = \mathbf{2.3\ \times 10^4 ppb_m\ C_6H_6}$$

c) $23\,\frac{mg\ \mathrm{C_6H_6}}{L} \times \frac{1\ mole}{78\ g} = \mathbf{3.3 \times 10^{-2}}\,\frac{\boldsymbol{mole}}{\boldsymbol{L}}\ \ \mathbf{C_6H_6}$

2.16 Chlorophenols impart unpleasant taste and odor to drinking water at concentrations as low as 5 mg/m^3. They are formed when the chlorine disinfection process is applied to phenol-containing waters. What is the unpleasant taste and odor threshold in units of (a) mg/L, (b) µg/L, (c) ppm$_m$, (d) ppb$_m$?

Solution:

a) in mg/L

$$\frac{5\ mg}{m^3}\times\frac{1\ m^3}{1000\ L}=\boxed{5\times10^{-3}\ mg/L}$$

b) in µg /L

$$\frac{5\ mg}{m^3}\times\frac{1\ m^3}{1000L}\times\frac{1000\ \mu g}{1\ mg}=\boxed{5\ \mu g/L}$$

c) in water, mg/L=ppm

$$\frac{5\ mg}{m^3}\times\frac{1\ m^3}{1000\ L}\times\frac{1\ L}{1\ kg}=\boxed{5\times10^{-3}\ \ ppm}$$

d) in water, µg/L = ppb

$$\frac{5\ mg}{m^3}\times\frac{1\ m^3}{1000\ L}\times\frac{1\ L}{1\ kg}\times\frac{1000\ million}{1\ billion}=\boxed{5\ ppb}$$

2.17 The concentration of monochloroacetic acid in rain water collected in Zurich was 7.8 nanomoles/L. Given that the formula for monochloroacetic acid is $CH_2C1COOH$, calculate the concentration in μg/L.

Solution:

The molecular weight of monochloroacetic acid equals 94.5 g/mole.

$$\frac{7.8\ nmoles}{L} \times \frac{94.5\ ng}{1\ nmole} \times \frac{1\ \mu g}{1000\ ng} = \boxed{0.74\ \mu g / L}$$

2.18 Assume that concentrations of Pb, Cu, and Mn in rainwater collected in Minneapolis were found to be 9.5, 2.0, and 8.6 µg/L, respectively. Express these concentrations as nmole/L, given that the atomic weights are 207, 63.5, and 55, respectively.

Solution:

$$\frac{9.5\ \mu g\ Pb}{L} \times \frac{1\ \mu mole}{207\ \mu g\ Pb} \times \frac{1000\ nmole}{1\ \mu mole} = \boxed{45.9\ nmole\ /\ L}$$

$$\frac{2.0\ \mu g\ Cu}{L} \times \frac{1\ \mu mole}{63.5\ \mu g\ Cu} \times \frac{1000\ nmole}{1\ \mu mole} = \boxed{31.5\ nmole\ /\ L}$$

$$\frac{8.6\ \mu g\ Mn}{L} \times \frac{1\ \mu mole}{55\ \mu g\ Mn} \times \frac{1000\ nmole}{1\ \mu mole} = \boxed{156.4\ nmole\ /\ L}$$

2.19 The dissolved oxygen (DO) concentration is measured as 0.5 mg/L in the anoxic zone and 8 mg/L near the end (of a 108-ft-long aerated biological reactor). What are these two DO concentrations in units of (a) ppm_m, (b) moles/L?

Solution:

In water, mg/L = ppm

a)

$$\frac{0.5\ mg\ O_2}{L} \times \frac{1\ L}{1\ kg} = \boxed{0.5\ ppm}$$

$$\frac{8\ mg\ O_2}{L} \times \frac{1\ L}{1\ kg} = \boxed{8\ ppm}$$

b)

$$\frac{0.5\ mg\ O_2}{L} \times \frac{1\ mole\ O_2}{32\ g\ O_2} \times \frac{1\ g}{1000\ mg} = \boxed{1.6 \times 10^{-5}\ moles\ O_2 / L}$$

$$\frac{8\ mg\ O_2}{L} \times \frac{1\ mole\ O_2}{32\ g\ O_2} \times \frac{1\ g}{1000\ mg} = \boxed{2.5 \times 10^{-4}\ moles\ O_2 / L}$$

2.20 Assume that the average concentration of chlordane – a chlorinated pesticide now banned in the United States – in the atmosphere above the Arctic Circle in Norway was found to be 0.6 pg/m^3. In this measurement, approximately 90 percent of this compound is present in the gas phase; the remainder is adsorbed to particles. For this problem, assume that all the compound occurs in the gas phase, the humidity is negligibly low, and the average barometric pressure is 1 atm. Calculate the partial pressure of chlordane. The molecular formula for chlordane is $C_{10}C1_8H_6$. The average air temperature through the period of measurement was -5°C.

Solution:

First, find concentration in ppm$_v$. The molecular weight equals 409.8.

$$\frac{0.6\ pg}{m^3}\times\frac{\mu g}{10^6\ pg}=0.6\times10^{-6}\ \mu g/m^3$$

ppm$_v$ = nRT/PV = Q*(RT)/MW*P; MW=mass/n; Q=mass/V

$$ppm_v=\frac{\left(0.6\times10^{-6}\frac{\mu g}{m^3}\right)\left(0.08205\frac{L-atm}{mole-K}\right)\times268\ K}{\left(409.8\ \frac{g}{mole}\right)\times\left(1000\frac{L}{m^3}\right)\times1\ atm}$$

$$ppm_v = 3.2 \times 10^{-11}$$

Now find partial pressure,

$$3.2\times10^{-11}=\frac{Pi}{1\ atm}\times10^6$$

Solve for $\boxed{Pi = 3.2 \times 10^{-17}\ atm}$

2.21 What is the concentration in (a) ppm_v, and (b) percent by volume, of carbon monoxide (CO) with a concentration of 103 μg/m^3? Assume a temperature of 25°C and pressure of 1 atm.

Solution:

a) R = 0.08205 L-atm/mole-°K.

$$\frac{103\ \mu g\ CO}{m^3} = \frac{ppm \times \left(28.0\ \frac{g}{mole}\right) \times \left(1000\frac{L}{m^3}\right) \times (1\ atm)}{\left(0.08205\frac{L-atm}{mole-K}\right) \times (298\ K)} = \boxed{8.9 \times 10^{-2}\ \ ppm}$$

b)

$$[CO] = \frac{8.9 \times 10^{-2}\ \ mg}{10^6\, mg} \times 100\ \% = \boxed{0.0000089\ \%}$$

2.22 Ice resurfacing machines use internal combustion engines that give off exhaust containing CO and NO_x. Average CO concentrations measured in local ice rinks have been reported to be as high as 107 ppm_v and as low as 36 ppm_v. How do these concentrations compare to an outdoor-air-quality 1-h standard of 35 mg/m^3? Assume the temperature equals 20°C.

Solution:

Convert the regulatory standard to ppm_v and compare to stated values.

$$35\ mg/m^3 \times 10^3\ \mu g/mg = 35{,}000\ \mu g/m^3$$

$$35{,}000\ \mu g/m^3 = \frac{ppm_v \times \left(28.0\ \frac{g}{mole}\right) \times \left(1000\ \frac{L}{m^3}\right) \times (1\ atm)}{\left(0.08205\ \frac{L-atm}{mole-K}\right) \times (293\ K)}$$

<u>ppm_v = 30; therefore, both are above the standard</u>

2.23 Formaldehyde is commonly found in the indoor air of improperly designed and constructed buildings. If the concentration of formaldehyde in a home is 0.7 ppm_v and the inside volume is 800 m^3, what mass (in grams) of formaldehyde vapor is inside the home? Assume T = 298 K, P = 1 atm. The molecular weight of formaldehyde is 30.

Solution:

$$\mu g / m^3 = \frac{0.7\ ppm_v \times \left(30 \frac{g}{mole}\right) \times \left(1{,}000 \frac{L}{m^3}\right) \times 1\ atm}{\left(0.08205 \frac{L-atm}{mole-K}\right) \times 298\ K}$$

Solve for concentration which equals 858.9 μg/m^3

The mass of formaldehyde equals

$$\frac{858.9\ \mu g}{m^3} \times 800\ m^3 \times \frac{g}{10^6\ \mu g} = \boxed{0.7\ g}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.24 The concentration of ozone (O_3) in Beijing on a summer day (T = 30°C, P = 1 atm) is 125 ppb_v. What is the O_3 concentration in units of (a) µg/m^3, and (b) number of moles of O_3 per 106 moles of air?

Solution:

a) By definition, ppb_v is related to the volume 0_3 / volume total.

$$\frac{125\ m^3\ O_3}{10^9\ m^3\ air}\times\frac{1\ atm}{8.205\times10^{-5}\ \frac{m^3-atm}{mole-K}\times303\ K}=5\times10^{-6}\ \frac{mole\ O_3}{m^3\ air}$$

$$\frac{5\times10^{-6}\ mole\ O_3}{m^3 air}\times\frac{48\ g\ O_3}{1\ mole\ O_3}\times\frac{10^6\ \mu g}{1g}=\boxed{241\ \mu g\ /\ m^3}$$

b)

$$125\ ppb_v=\frac{125\ mole\ O_3}{10^9\ mole-air}=\frac{0.125\ mole\ O_3}{10^6\ mole-air}$$

$$\frac{0.125\ mole\ O_3}{10^6\ mole-air}\times106\ mole-air=\boxed{1.3\times10^{-5}\ mole\ of\ O_3}$$

2.25 The National Ambient Air Quality Standard (NAAQS) for sulfur dioxide (SO_2) is 0.14 ppm$_v$ (24-hr average). (a) What is the concentration in μg/m^3 assuming an air temperature of 25^{o}C? (b) What is the concentration in moles SO_2 per 10^6 moles of air?

Solution:

b)

$$0.14ppm_v = \frac{0.14\ m^3\ \mathrm{SO_2}}{10^6\ m^3\ \text{air solution}} \times \frac{1\ atm}{8.205\times10^{-5}\frac{m^3\ atm}{mole\ K}\times(25+273)}$$

$$= \mathbf{6.0\ \times 10^{-6}\frac{\boldsymbol{mole}\ SO_2}{10^6\ \boldsymbol{m}^3\ air}}$$

a) $6.0\ \times 10^{-6}\frac{mole\ \mathrm{SO_2}}{10^6\ mole\ \text{air}} \times \frac{64\ g\mathrm{SO_2}}{mole\ \mathrm{SO_2}} \times \frac{10^{\ -6}\mu g}{g} = \mathbf{384}\ \frac{\boldsymbol{\mu g}}{\boldsymbol{m}^3}$

2.26 An empty balloon is filled with exactly 10 g of nitrogen (N_2) and 2 g of oxygen (O_2). The pressure in the room is 1 atm and the temperature is 25°C. (a) What is the oxygen concentration in the balloon in units of percent by volume? (b) What is the volume of the balloon after it's blown up, in L?

Solution:

a)

$$2\ g\ O_2 \times \frac{1\ mole}{32\ g\ O_2} = 6.3 \times 10^{-2}\ mole\ O_2$$

$$10\ g\ N_2 \times \frac{1\ mole}{28\ g\ N_2} = 0.4\ mole\ N_2$$

$$\frac{vol\ O_2}{vol - total} = \frac{moles\ O_2}{moles - total} = \frac{6.3 \times 10^{-2}}{\left(6.3 \times 10^{-2} + 0.4\right)} = 0.136 \times 100\ \% = \boxed{13.6\ \%}$$

b) The balloon's volume can be found using the ideal gas law, PV= nRT where n is from part a)

$$V = \frac{nRT}{P} = \frac{\left(6.3 \times 10^{-2}\ moles + 0.4\ moles\right) \times \frac{0.08205\ L - atm}{mole - K} \times 298\ K}{1\ atm} = \boxed{11.3\ L}$$

2.27 A gas mixture contains 1.5 × 10^{-5} mole CO and has a total of 1 mole. What is the CO concentration in ppm_v?

Solution:

Remember, the determination of ppm_v can use volume, moles, or partial pressure. In this case we are provided information on the number of moles.

Therefore, $ppm_v = (1.5\text{x}10^{-5}\text{mole}/1\text{mole}) \times 10^6 = \boxed{15\ ppm_v}$

2.28 “Clean” air might have a sulfur dioxide (SO_2) concentration of 0.01 ppm_v, while “polluted” air might have a concentration of 2 ppm_v. Convert these two concentrations to $\mu g/m^3$. Assume a temperature of 298 K.

Solution:

$$\frac{\mu g}{m^3} = ppm \times MW \times \frac{1000 \times P}{RT} = ppm \times 64.1\frac{g}{mol} \times \frac{1000L/m^3}{0.08205\frac{L \times atm}{mol \times K} \times 298K}$$

$$1 \times 10^{-2} \times 64.1\frac{g}{mol} \times \frac{1000L/m^3}{0.08205\frac{L \times atm}{mol \times K} \times 298K} = \boxed{26\frac{\mu g}{m^3}}$$

$$2 \times 64.1\frac{g}{mol} \times \frac{1000L/m^3}{0.08205\frac{L \times atm}{mol \times K} \times 298K} = \boxed{5,243\frac{\mu g}{m^3}}$$

2.29 Carbon monoxide (CO) affects the oxygen carrying capacity of your lungs. Exposure to 50 ppm_v CO for 90 min has been found to impair one's ability to time/interval discriminate; thus, motorists in heavily polluted areas may be more prone to accidents. Are motorists at a greater risk to accidents if the CO concentration is 65 mg/m^3? Assume a temperature of 298 K.

Solution:

$$65\ \text{mg/m}^3 = 65{,}000\ \mu\text{g/m}^3$$

$$65,000\,\frac{\mu g}{m^3} = ppm \times MW \times \frac{1000 \times P}{RT} = ppm \times \frac{28\ g/mol \times 1000\ L/m^3}{0.08205\,\frac{m^3 \times atm}{mole \times K} \times 298\ K}$$

$$\boxed{ppm = 57\ which\ is > 50\ so\ yes}$$

2.30 Humans produce 0.8 to 1.6 L of urine per day. The annual mass of phosphorus in this urine on a per capita basis ranges from 0.2 to 0.4 kg P. a) What is the maximum concentration of phosphorus in human urine in mg P/L? b) What is the concentration in moles P/L? c) Most of this phosphorus is present as HPO_4^{2-}. What is the concentration of phosphorus in mg HPO_4^{2}-/L?

Solution:

a) $[P]_{max} = \frac{0.4\ kg}{year} \times \frac{1000g}{1\ kg} \times \frac{1000\ mg}{1\ g} \times \frac{1day}{0.8\ L} \times \frac{year}{365\ days} = \mathbf{1369} \frac{\boldsymbol{mg}}{\boldsymbol{L}.}$

b) $1369 \frac{mg}{L} \times \frac{1\ g}{1000\ mg} \times \frac{1\ mol\ \mathrm{P}}{30.97\ g} = \mathbf{0.04}\ \frac{\boldsymbol{mol}\ \mathbf{P}}{\boldsymbol{L}}$

c) $0.04\ \frac{mol\ \mathrm{P}}{L} \times \frac{1\ mol\ \mathrm{HPO_4}^{2-}}{1\ mol\ \mathrm{P}} \times \frac{95.97\ g}{1\ mol\ \mathrm{HPO_4}^{2-}} \times \frac{1000\ mg}{1\ g} = \mathbf{3838} \frac{\boldsymbol{mg}}{\boldsymbol{L}}$

2.31 Assume 66% of phosphorus in human excrement in found in urine (the remaining 34% is found in feces). Assume humans produce 1 L of urine per day and the annual mass of phosphorus in this urine is 0.3 kg P. If indoor water usage is 80 gallons per capita per day in a single individual apartment, what is the concentration (in mg P/L) in the wastewater that is discharged from the apartment unit? Account for phosphorus in urine and feces.

Solution:

First, solve for x, the total mass of phosphorous in feces and urine.

$$0.66 \times x = 0.3\ kg$$

$$x = \frac{0.3\ kg}{.66} = 0.45\ kg\ \mathrm{P}$$

$$\frac{0.45\ kg\ \mathrm{P}}{(80+1)L} \times \frac{1000\ g}{1\ kg} \times \frac{1000\ mg}{1\ g} = \mathbf{5.5 \times 10^{3}} \frac{\boldsymbol{mg}\ \mathbf{P}}{\boldsymbol{L}}$$

2.32 A dry cleaning facility owned by JMA Inc. has been observed to have impacted 6,000 gallons of groundwater with 0.70 pounds of tetrachloroethylene (PCE). Assuming all the PCE is present in the dissolved phase and the chemical pollutant is evenly distributed throughout the impacted volume of the groundwater, what is the concentration of PCE In groundwater in ppm?

Solution:

$$[\mathrm{PCE}] = \frac{0.7\ lbs}{6{,}000\ gallons} \times \frac{1\ kg}{2.205\ lbs} \times \frac{1000g}{1\ kg} \times \frac{1\ gallon}{3.785\ L} \times \frac{1.0\ L\ H_2O}{1000\ gH_2O}$$

$$= \frac{13.98 \times 10^{-6} g\ \mathrm{PCE}}{g\ total} \times \frac{10^{g} ppm}{mass\ fraction} = \mathbf{14}\ \boldsymbol{ppm_m}\ \mathbf{PCE}$$

2.33 A dry cleaning facility has been observed to have impacted 20 m^3 of a saturated groundwater aquifer (porosity of 0.30) with 0.70 pounds of tetrachloroethylene (PCE) (molecular formula of C_2Cl_4). A bioremediation system is utilized which degrades all of the PCE present to ethene through the process of reductive dechlorination (molecular formula of ethene is C_2H_4). How many moles/L of chlorine are present in the impacted volume of aquifer after all the PCE is dechlorinated? Porosity is defined as the number of voids (that can fill with air or water) divided by the volume (that includes voids and solids).

Solution:

When the problem says PCE goes to Ethene, write a simple equation which will help later when converting to moles of chlorine

$$\mathrm{C_2Cl_4} + \ 2\mathrm{H_2} \xrightarrow{\text{yields}} \mathrm{C_2Cl_4} + 4\mathrm{Cl^-}$$

$$\frac{0.7\ lbs}{(0.3)(20m^3)} \times \frac{1\ kg}{2.205\ lb} \times \frac{1000g}{1\ kg} \times \frac{1000\ mg}{1\ g} \times \frac{1\ m^3}{1000\ L} = 52.9\frac{mg}{L}\ \mathrm{C_2Cl_4}$$

$$52.9\frac{mg}{L}\ \mathrm{C_2Cl_4} \times \frac{1\ mole\ \mathrm{C_2Cl_4}}{94.92\ g} \times \frac{4\ mol\ Cl\text{-}}{1\ mol\ \mathrm{C_2Cl_4}} = \mathbf{2.2}\ \frac{\boldsymbol{mol\ Cl\text{-}}}{\boldsymbol{L}}$$

2.34 Copper was used as a fungicide in citrus orchards which are being considered for a stormwater retention project as part of the Everglades restoration effort. Copper accumulates in apple snails, a primary food source of the federally endangered bird called the Everglades Snail kite. The professional engineer at BTA Inc. is considering two former citrus production areas for construction of a stormwater treatment area – a 1,500-acre site with soils having a copper content of 220 ppm and a 2,000-acre site with 160 pounds of copper uniformly distributed in the top 6-8 inches of soil. Which site would our female engineer recommend for the project if the ecological threshold to support the Everglades Snail Kite is 85 mg Cu/kg? Ecological threshold means that the soil concentration of copper can't exceed this value. Assume the plow layer of soil (upper 6-8 inches) for the 2,000-acre site weighs 2,000,000 pounds.

Solution:

For Cu= 220 ppm on the 1,500-acre site:

$$\frac{220\ \times 10^{-6} g\ TCE}{g\ \text{total}} \times \frac{1000\ mg}{1\ g} \times \frac{1000\ g}{1\ kg} = 220\frac{mg\ \text{Cu}}{kg}$$

For 160 lbs uniformly distributed in top 6-8 inches of soil on the 2,000 acre site:

$$\frac{160\ lbs}{2\ \times 10^{6} lbs} \times \frac{2.205\ lb}{kg} \times \frac{1\ kg}{2.205\ lb} \times \frac{1000\ g}{kg} \times \frac{1000\ mg}{1\ g} = 80\frac{mg\ \text{Cu}}{\text{kg}}$$

$80\frac{mg\ \text{Cu}}{\text{kg}} < 85\frac{mg\ \text{Cu}}{\text{kg}}\ \ and\ 220\frac{mg\ \text{Cu}}{kg} > 85\frac{mg\ \text{Cu}}{\text{kg}}\ \ \therefore \boldsymbol{the\ 2,000\ acre\ site\ is\ recommended}$

2.35 The Department of Environmental Quality determined that toxaphene concentrations in soil exceeding 60 μg/kg (regulatory action level) can pose a threat to underlying groundwater. (a) If a 100 g sample of soil contains 10^{-5} g of toxaphene, what are the (a) toxaphene soil and (b) regulatory action level concentrations reported in units of ppb_m?

Solution:

a) In soil, ppb = μg/kg

$$60\,\frac{\mu g}{kg} = 60\ ppb$$

$$\frac{10^{-5}\,g\ toxaphene}{100g - soil} \times \frac{1000\ g}{1\ kg} \times \frac{10^{6}\,\mu g}{g} = 100\ \frac{\mu g}{kg} = \boxed{100\ ppb}$$

b) 100 ppb > 60 ppb; therefore, the sample may pose a threat

2.36 Polycyclic aromatic hydrocarbons (PAHs) are a class of organic chemicals associated with the combustion of fossil fuels. Undeveloped areas may have total PAH soil concentrations of 5 µg/kg, while urban areas may have soil concentrations that range from 600 µg/kg to 3,000 µg/kg. What is the concentration of PAHs in undeveloped areas in units of ppm_m?

Solution:

In soil mg/kg = ppm

$$5\,\frac{\mu g}{kg}\times\frac{1\,mg}{1000\,\mu g}=\boxed{5\times10^{-3}\ mg/kg}$$

2.37 The concentration of toluene (C_7H_8) in subsurface soil samples collected after an underground storage tank was removed indicated the toluene concentration was 5 mg/kg. What is the toluene concentration in ppm_m?

Solution:

$$5\,\frac{mg}{kg} = \boldsymbol{5\ ppm_m}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.38 While visiting Zagreb, Croatia, Mr. Arthur Van de Lay visits the Mimara Art Museum and then takes in the great architecture of the city. He stops at a café in the old town and orders a bottle of mineral water. The reported chemical concentration of this water is: $[Na^+]$ = 0.65 mg/L, $[K^+]$ = 0.4 mg/L, $[Mg^{2+}]$ = 19 mg/L, $[Ca^{2+}]$ = 35 mg/L, $[Cl^-]$ = 0.8 mg/L, $[SO_4^{2-}]$ = 14.3 mg/L, $[HCO_3^-]$ = 189 mg/L, $[NO_3^-]$ = 3.8 mg/L. The pH of the water is 7.3. (a) What is the hardness of the water in mg/L $CaCO_3$? (b) Is the chemical analysis correct?

Solution:

a) To determine the total hardness of a water sample, identify all the divalent cations, convert to units of mg/L as $CaCO_3$, then sum up to find the total hardness.

$$Ca^{2+} = 35\ mg/L \times \frac{100\ g/2\ eqv}{40.1\ g/2\ eqv} = 87\ mg/L\ as\ CaCO_3$$

$$Mg^{2+} = 19\ mg/L \times \frac{100\ g/2\ eqv}{24.3\ g/2\ eqv} = 78\ mg/L\ as\ CaCO_3$$

Total hardness = 87 + 78 = 165 mg/L as $CaCO_3$

b) Convert the concentration of the major cations and anions to equivalents/L. Then sum up the cations and anions to see if they are within 5%.

$$Ca^{2+} = 35\frac{mg}{L} \times \frac{g}{10^3 mg} \times \frac{2\ eqv}{40.1\ g} = 1.7 \times 10^{-3}$$

$$Mg^{2+} = 19\frac{mg}{L} \times \frac{g}{10^3 mg} \times \frac{2\ eqv}{24.3\ g} = 1.6 \times 10^{-3}$$

$$K^{+} = 0.4\frac{mg}{L} \times \frac{g}{10^3 mg} \times \frac{1\ eqv}{39.1\ g} = 1 \times 10^{-5}$$

$$Na^{+} = 0.65\frac{mg}{L} \times \frac{g}{10^3 mg} \times \frac{1\ eqv}{23.0\ g} = 2.8 \times 10^{-4}$$

Sum of cations equals 3.6x10^{-3} eqv/L

$$HCO_{3^-} = 189\frac{mg}{L} \times \frac{g}{10^3\ mg} \times \frac{1\ eqv}{61.0\ g} = 3.1 \times 10^{-3}$$

$$Cl^{-} = 0.8\frac{mg}{L} \times \frac{g}{10^3\ mg} \times \frac{1\ eqv}{35.5\ g} = 2 \times 10^{-5}$$

$$SO_{4^{2-}} = 14.3\frac{mg}{L} \times \frac{g}{10^3\ mg} \times \frac{1\ eqv}{96.1\ g} = 1.49 \times 10^{-4}$$

Sum of anions equals 3.3x10^{-3} eqv/L

Because the sum of all cations and anions (after we converted them to common units of eqv/L) are within 5% of each other, we can assume that the analysis is correct.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.39 The city of Melbourne, Florida has a surface water treatment plant that produces 20 MGD of potable drinking water. The water source has hardness measured as 94 mg/L as $CaCO_3$ and after treatment, the hardness is reduced to 85 mg/L as $CaCO_3$. (a) Is the treated water, soft, moderately hard, or hard? (b) Assuming all the hardness is derived from calcium ion, what would the concentration of calcium be in the treated water (mg Ca^{2+}/L). (c) Assuming all the hardness is derived from magnesium ion, what would the concentration of magnesium be in the treated water (mg Mg^{2+}/L).

Solution:

See figure 8.10 in chapter 8 for ranges for water hardness
Soft water: 0-55 mg/L
Moderately hard water: 55-120 mg/L
Hard water: 120-250 mg/L
Very hard water: 250+ mg/L

a) Both the water source hardness (94 mg/L as $CaCO_3$) and after treatment (85 mg/L as $CaCO_3$) are in the **moderately hard** water range.

b) $$85\,\frac{mg}{L} \times \frac{\left(\frac{40\ g\mathrm{CaCO_3}}{2\ eqv}\right)}{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)} = \mathbf{34}\,\frac{\boldsymbol{mg}\ \mathbf{Ca^{2+}}}{\boldsymbol{L}}$$

c) $$85\,\frac{mg}{L} \times \frac{\left(\frac{24\ g\mathrm{CaCO_3}}{2\ eqv}\right)}{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)} = \mathbf{20.4}\ \frac{\boldsymbol{mg}\ \mathbf{Mg^{2+}}}{\boldsymbol{L}}$$

2.40 A laboratory provides the following analysis obtained from a 50-ml sample of water. [Ca^{2+}] = 60 mg/L, [Mg^{2+}] = 10 mg/L, [Fe^{2+}] = 5 mg/L, [Fe^{3+}] = 10 mg/L, Total solids = 200 mg/L, suspended solids = 160 mg/L, fixed suspended solids = 40 mg/L, and volatile suspended solids = 120 mg/L. (a) What is the hardness of this water sample in units of mg/L as $CaCO_3$? (b) What is the concentration of total dissolved solids of this sample? (c) If this sample was filtered through a glass-fiber filter, then the filter was placed in a muffle furnace at 550°C overnight, what would be the weight of the solids (in mg) remaining on the filter after the night in the furnace?

Solution:

a) See example 2.14.

$$60\frac{mg\ \mathrm{Ca}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{40\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=150\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$10\frac{mg\ \mathrm{Mg}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{24\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=41.7\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$5\frac{mg\ \mathrm{Mg}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{56\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=8.93\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$total\ hardness=\ 150\frac{mg\ \mathrm{CaCO_3}}{L}+\ 41.7\frac{mg\ \mathrm{CaCO_3}}{L}+\ 8.93\frac{mg\ \mathrm{CaCO_3}}{L}=\mathbf{201}\ \frac{\boldsymbol{mg}\ \mathbf{CaCO_3}}{\boldsymbol{L}}$$

b) TDS= TS – TSS

$$\mathrm{TDS}\ =200\frac{\mathrm{mg}}{\mathrm{L}}-\ 160\frac{\mathrm{mg}}{\mathrm{L}}=\mathbf{40}\frac{\mathbf{mg}}{\mathbf{L}}$$

c) See example 2.16.

$$\mathrm{FSS}\ =40\frac{\mathrm{mg}}{\mathrm{L}}=\frac{\mathrm{X}}{50\ \mathrm{ml}}\times\frac{1000\ \mathrm{mL}}{1\ \mathrm{L}}=\frac{\mathrm{x}}{0.05\ \mathrm{L}}$$

Solve for x

$$x=40\frac{mg}{L}\times 0.05\ \mathrm{L}=\mathbf{2\ mg}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.41 In 2010 landfills in the U.S. produced approximately 107.8 Tg CO_2e of methane emissions. Wastewater treatment plants emitted 16.3 Tg CO_2e of methane. (a) How many pounds and metric tons of methane (reported as CO_2 equivalents) did landfills and wastewater plants emit in 2010? (b) What percent of the total 2010 methane emissions (and greenhouse gas emissions) do these two sources contribute (total methane emissions in 2010 were 666.5 Tg CO_2e and total greenhouse gas emissions in 2010 were 6,821.8 CO_2e).

Solution:

a) $\mathbf{Tg\ CO_{2e}} = (\text{Tg of gas}) \times \text{GWP}$ (Note: GWP = 25 for methane from table 2.4)

$$\mathbf{Tg\ CO_{2e\,landfills+WWTP}} = (107.8 + 16.3) \times 25 = 3103\ \mathbf{Tg\ CO_{2e}}$$

$$3103\ \mathbf{Tg\ CO_{2e}} \times \frac{1*10^9 kg}{1\,Tg} \times \frac{1\ ton}{1000\ kg} = \mathbf{3.10 \times 10^9}\ \boldsymbol{metric\ tons}$$

$$3103\ \mathbf{Tg\ CO_{2e}} \times \frac{1*10^9 kg}{1\,Tg} \times \frac{2.205\ lb}{1\ kg} = \mathbf{6.84 \times 10^{12}}\ \boldsymbol{lbs}$$

b) Total methane $= 107.8\ \mathbf{Tg\ CO_{2e}} + \mathbf{16.3\ Tg\ CO_{2e}} = \mathbf{124.1\ Tg\ CO_{2e}\ methane}$

$$\%\ of\ total\ 2010\ methane\ emissions = \frac{124.1\mathbf{Tg\ CO_{2e}}}{666.5\ \mathbf{Tg\ CO_{2e}}} \times 100 = \mathbf{18.6}\%$$

$$\%\ of\ total\ 2010\ GHG\ emissions = \frac{3103\ \mathbf{Tg\ CO_{2e}}}{666.5\ \mathbf{Tg\ CO_{2e}}} \times 100 = \mathbf{45.5}\%$$

2.42 Mobile combustion of N_2O in 2010 emitted 20.6 Tg CO_2e. How many Gg of N_2O was this?

Solution:

$$20.6\,Tg = CO_{2e}\ of\ N_20 = Gg\ N_20\ \times 310\ \times \frac{Tg}{1000\ Gg} = \mathbf{6.4\ Gg\ N_20}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

2.43 Reverse osmosis is used to treat brackish groundwater water and requires 1 kWh of energy per 1 m^3 of treated water. In comparison, reverse osmosis of seawater requires 4 kWh of energy per 1 m3 of treated water (this difference is because of the higher TDS concentration of seawater). According to eGRID, the carbon dioxide equivalent emission rate is 1,324.79 lb CO_2e/MWh in Florida and 727.26 lb CO_2e/MWh in California. Estimate the carbon footprint of using reverse osmosis to desalinate 1 m^3 brackish groundwater and 1 m^3 sea water in Florida and California. Ignore line losses in your estimate.

Solution:

FL brackish water

$$\frac{1\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{1{,}324.79\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{1.32\ lb\frac{CO_{2e}}{m^3}}$$

CA brackish water

$$\frac{1\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{727.26\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{0.73\ lb\frac{CO_{2e}}{m^3}}$$

FL sea water

$$\frac{4\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{1{,}324.79\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{5.28\ lb\frac{CO_{2e}}{m^3}}$$

CA sea water

$$\frac{4\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{727.26\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{2.92\ lb\frac{CO_{2e}}{m^3}}$$

2.44 Your home in Texas averages 24 kwh/day of electricity use. (a) what is your annual estimate of individual greenhouse gas emissions of CO_2, CH_4, and N_2O for operating the home? (b) What is the carbon footprint (in lb CO_2e) for living in the home for one year with and without line losses included in the estimate?

Solution:

For this problem, visit the website in table 2.8 (http://www.epa.gov/egrid) and click on link for "eGRID subregion GHG output emission rates (PDF)". From the color coded map at the bottom you can see that Texas is in the ERCT eGRID subregion. See example 2.15 for calculation methods.

a)

$$24\,\frac{KWh}{day} \times 365\,\frac{days}{yr} = 8760\,\frac{KWh}{yr}$$

$$Annual\ CO_2\ emissions = \frac{8760\ KWh}{yr} \times \frac{1\ MWh}{10^3 KWh} \times \frac{1181.73\ lbCO_2}{MWh} = \mathbf{1.04\ \times 10^4\ \frac{lb\ CO_2}{yr}}$$

$$Annual\ CH_4\ emissions = \frac{8760\ KWh}{yr} \times \frac{1\ GWh}{10^6 KWh} \times \frac{16.70\ lb}{GWh} = \mathbf{0.15\,\frac{lb\ CO_2}{yr}}$$

$$Annual\ N_2O\ emissions = \frac{8760\ KWh}{yr} \times \frac{1\ GWh}{10^6 KWh} \times \frac{13.10\ lb}{GWh} = \mathbf{0.12\,\frac{lb\ CO_2}{yr}}$$

b) In this case we will use the U.S. values for CO_{2e} in table 2.8.

Without line losses the carbon footprint for one year is:

$$Carbon\ footprint = \frac{8760\ KWh}{yr} \times \frac{1\ MWh}{10^3 KWh} \times \frac{1336.31\ lbCO_2e}{MWh} = \mathbf{1.17\ \times 10^4\ \frac{lb\ CO_{2e}}{yr}}$$

With line losses we use the amount for Texas and method described in box 2.1:

$$Carbon\ footprint = 1.17\ \times 10^4\ \frac{\mathbf{lb\ CO_{2e}}}{\mathbf{yr}} \times \frac{1}{1-\left(\frac{6.177\%}{100}\right)} = \mathbf{1.25\ \times 10^4\ \frac{lb\ CO_{2e}}{yr}}$$

2.45 You are considering installing a 10kW solar system that will provide 14,000 kW-hr of electricity per year (assume you live in the E-Grid subregion, SERC Midwest). Assuming your electricity consumption remains the same, how much is your carbon footprint reduced every year (in pounds of CO_2) if you install the solar panels?

Solution:

For this problem, use table 2.8 for the SERC Midwest emissions data per kWh

$$14000\frac{kW}{h}\times 24\frac{hr}{day}\times 365\frac{days}{yr}\times\frac{1MWh}{10^6 kWh}\times\frac{1830.5\ lb}{MWh}=\mathbf{2.24\ \times 10^5\frac{lb\ CO_2}{yr}}$$

2.46 You are considering purchasing a new television set and wish to factor in the energy consequences of your purchase. You are considering a 55-inch screen model (screen is 49.75 inches high and 29.75 inches wide) and a 32-inch screen model (screen is 29.1 inches wide and 17.5 inches high). Research shows that for these particular models, the 55-inch screen consumes 0.10 Watts/in^2 and the 32-inch screen consumes 0.17 Watts/in^2. (a) Compare the two televisions by determining the power rating (number of Watts) associated with each television size. Report your answer in Watts, N-m/sec, and joules/sec. (b) How many kW-hr of energy are consumed by each screen if you operate the television for 3 hours per day (? (c) Assuming that operating the television for 1kW-hr produces 0.5453 kg of CO_2, compare the two screen sizes in terms of their carbon footprint calculated over a 365-day year (assume you operate the television 3 hours per day).

Solution:

a) Note: Watts= kg m^2/s^3 and 1 N= 1 kg m/s^2 and 1 J= kg m^2/s^2, therefore 1 Watt=1 N-m/s= 1 J/s

For the 55 inch:

$$0.10\frac{watts}{in^2} \times [(49.75\ in) \times\ (29.75\ in)] = \mathbf{148\ Watts = 148\ N - \frac{m}{s} = 148\ \frac{J}{s}}$$

For a 32 inch:

$$0.17\frac{watts}{in^2} \times [(17.5\ in) \times\ (29.1\ in)] = \mathbf{86.6\ Watts = 86.6\ N - \frac{m}{s} = 86.6\ \frac{J}{s}}$$

b)

For the 55 inch:

$$148\ Watts \times \frac{1kW}{1000\ Watts} \times 3hrs = \mathbf{0.44\ kWhr}$$

For the 32 inch:

$$86.6Watts \times \frac{1kW}{1000\ Watts} \times 3hrs = \mathbf{0.26\ kWhr}$$

c)

For the 55 inch:

$$\frac{0.5453\ kg\ CO_2}{kWhr} \times 0.44\ kWhr\ \times \frac{1\ day}{24\ hrs} \times \frac{365\ days}{yr} = \mathbf{3.65}\frac{\boldsymbol{kgCO_2}}{\boldsymbol{yr}}$$

For 32 inch:

$$\frac{0.5453\ kg\ CO_2}{kWhr} \times 0.26\ kWhr\ \times \frac{1\ day}{24\ hrs} \times \frac{365\ days}{yr} = \mathbf{2.16}\frac{\boldsymbol{kgCO_2}}{\boldsymbol{yr}}$$

2.47 A laboratory provides the following solids analysis for a wastewater sample: TS = 200 mg/L; TDS = 30 mg/L; FSS = 30 mg/L. (a) What is the total suspended solids concentration of this sample? (b) Does this sample have appreciable organic matter? Why or why not?

Solution:

a)

$$TSS = TS - TDS = 200\frac{mg}{L} - 30\frac{mg}{L} = \boxed{170\frac{mg}{L}}$$

b)

$$VSS = TSS - FSS = 170\frac{mg}{L} - 30\frac{mg}{L} = 140\frac{mg}{L}$$

Because volatile solids consist primarily of organic matter, it can be concluded that approximately 70% (140/200) of the solids are organic.

2.48 A 100-mL water sample is collected from the activated sludge process of municipal wastewater treatment. The sample is placed in a drying dish (weight = 0.5000 g before the sample is added), and then placed in an oven at 104°C until all the moisture is evaporated. The weight of the dried dish is recorded as 0.5625 g. A similar 100-mL sample is filtered and the 100-mL liquid sample that passes through the filter is collected and placed in another drying dish (weight of dish before sample is added is also 0.5000 g). This sample is dried at 104°C and the dried dish's weight is recorded as 0.5325 g. Determine the concentration (in mg/L) of (a) total solids, (b) total dissolved solids, (c) total suspended solids, and (d) volatile suspended solids, (Assume that VSS = 0.7 x TSS.)

Solution:

a)

$$TS = \frac{0.5625\ g - 0.5000\ g}{100\ mL} \times \frac{1000\ mL}{L} \times \frac{1000\ mg}{g} = \boxed{625\frac{mg}{L}}$$

b)

$$TDS = \frac{0.5325\ g - 0.5000\ g}{100\ mL} \times \frac{1000\ mL}{L} \times \frac{1000\ mg}{g} = \boxed{325\frac{mg}{L}}$$

c)

$$TSS = TS - TDS = 625\frac{mg}{L} - 325\frac{mg}{L} = \boxed{300\frac{mg}{L}}$$

d)

$$VSS = 0.7 \times TSS = 0.7 \times 300\ \frac{mg}{L} = \boxed{210\ \frac{mg}{L}}$$

Chapter 3: Chemistry

3.1 How many grams of NaCl would you need to add to a 1 L water sample (pH = 7) so the ionic strength equaled 0.1M?

Solution:

$$0.1\ \mathrm{M} = 1/2\{[\mathrm{Na}^+]\,(+1)^2 + [\mathrm{Cl}^-](-1)^2\}$$

The concentration of Na and Cl^- are the same because 1 mole of Na and 1 mole of Cl^- are produced when dissolving 1 mole NaCl.

$$0.2\ \mathrm{M} = [\mathrm{Na}^+] + [\mathrm{Cl}^-]\text{ ; therefore, }[\mathrm{Na}^+] = [\mathrm{Cl}^-] = [\mathrm{NaCl}] = 0.1\mathrm{M}$$

$$\frac{0.1\,mole}{L} \times \frac{58\ g\ NaCl}{1\,mole\ NaCl} = \boxed{5.8\ g}$$

3.2 You are studying the feasibility of using a reverse osmosis membrane system to desalinate seawater (TDS = 35,000 mg/L) and inland brackish groundwater (TDS typically ranges from 1,000 to 10,000 mg/L). a) Estimate the ionic strength of the seawater and brackish water. b) A conductivity meter provides a reading of 7,800 µmho/cm when placed in one of these water samples. Which water source is the sample from?

Solution:

a) Use equation 3.2 to calculate the ionic strength

$$\mu = 2.5 \times 10^{-5} \times TDS$$

$$\mu_{sewater} = 2.5 \times 10^{-5} \times 35{,}000 \frac{mg}{L} = \mathbf{0.088} \frac{\boldsymbol{mol}}{\boldsymbol{L}}$$

$$\mu_{brackish\ water_L} = 2.5 \times 10^{-5} \times 1{,}000 \frac{mg}{L} = \mathbf{0.025} \frac{\boldsymbol{mol}}{\boldsymbol{L}}$$

$$\mu_{brackish\ water_L} = 2.5 \times 10^{-5} \times 10{,}000 \frac{mg}{L} = \mathbf{0.25} \frac{\boldsymbol{mol}}{\boldsymbol{L}}$$

b) Use equation 3.3 to calculate specific conductance

$$\mu = 1.6 \times 10^{-5} \times Specific\ Conductance$$

$$\mu = 1.6 \times 10^{-5} \times 7{,}800 \frac{\mu mho}{cm} = 0.125 \frac{mol}{L}$$

From answers in part a, we see that 0.125 mol/L is between the values for brackish water. Therefore, **the water sample is from brackish water**.

3.3 Calculate the ionic strength and individual activity coefficients for a 1 L solution in which 0.02 moles of $Mg(OH)_2$, 0.01 moles of $FeCl_3$, and 0.01 moles of HCl are dissolved.

After the two components are placed in water, they will completely dissociate to form: 0.02 M Mg^{2+}, 0.01 M Fe^{2+}, 0.02 OH^-, 0.01 M H^+, 0.04 M Cl^- (0.03 from $FeCl_3$ and 0.01 from HCl**)**

Solution:

Equation 3.1 is used to calculate iconic strength

$$\mu = \frac{1}{2}\sum_i C_i {Z_i}^2$$

$$\mu = \frac{1}{2}\left[0.02\,(2^+)^2 + 0.01\,(3^+)^2 + 0.02\,(1^-)^2 + 0.01\,(1^+)^2 + 0.04(1^-)^2\ \right] = \mathbf{0.12}\,\frac{\boldsymbol{mol}}{\boldsymbol{L}}$$

This answer is less than 0.5 M in figure 3.1, therefore we use the Davie's approximation for the activity coefficients.

$log_{10}\gamma = -AZ^{\,2}(\frac{I^{\frac{1}{2}}}{1+I^{\frac{1}{2}}} - 0.3\ I)$, A= 0.51 at 25°C

$$log_{10}\gamma(\mathrm{Mg}^{2+}) = -0.51\,(2^+)^2\left[\frac{0.12^{\frac{1}{2}}}{1+0.12^{\frac{1}{2}}} - 0.3\,(0.12)\right] = -0.45$$

$$\gamma(\mathrm{Mg}^{2+}) = 10^{-0.45} = \mathbf{0.35}$$

$$log_{10}\gamma(\mathrm{Fe}^{3+}) = -0.51\,(3^+)^2\left[\frac{0.12^{\frac{1}{2}}}{1+0.12^{\frac{1}{2}}} - 0.3\,(0.12)\right] = -1.016$$

$$\gamma(\mathrm{Fe}^{3+}) = 10^{-1.016} = \mathbf{0.096}$$

$$log_{10}\gamma(\mathrm{OH}^-) = -0.51\,(1^-)^2\left[\frac{0.12^{\frac{1}{2}}}{1+0.12^{\frac{1}{2}}} - 0.3\,(0.12)\right] = -0.113$$

$$\gamma(\mathrm{OH}^-) = 10^{-0.113} = \mathbf{0.77}$$

The activity coefficients for Cl^- and H^+ will be the same as OH^-

$\gamma(\mathrm{Cl}^-) = \mathbf{0.77}$
$\gamma(\mathrm{H}^+) = \mathbf{0.77}$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.4 Hydrogen sulfide is an odor-causing chemical found at many wastewater collection and treatment facilities. The following expression describes hydrogen sulfide gas reacting with aqueous phase hydrogen sulfide (a diprotic acid).

$H_2S_{\text{(gas)}} = H_2S_{\text{(aqueous)}}$

Use your understanding of chemical equilibrium and thermodynamics to determine the Henry's constant (moles/L-atm) for this reaction at 25°C. The change in free energy of formation at standard conditions (units of kcal/mole) are as follows: $H_2S_{\text{(gas)}} = -7.892$, $H_2S_{\text{(aqueous)}} = -6.54$, $HS^-_{\text{(aqueous)}} = +3.01$, $SO_4^{2-} = -177.34$.

Solution:

Use the Gibbs free energy equation (3.4).

$$\Delta G = \Delta G° + RTln(Q)$$

At equilibrium $\Delta G = 0 \therefore 0 = \Delta G° + RTln(Q)$

$$\Delta G° = \sum products - \sum reactants = \left(-6.54\frac{kcal}{mole}\right)(1\ mole) - \left(-7.892\frac{kcal}{mol}\right)(1\ mole)$$
$$= 1.35\ kcal$$

At equilibrium the reaction quotient, Q, is the equilibrium constant, K., and in this case, Henry's constant. Solving for h in the free energy equation:

$$K_H = e^{-\Delta G°/RT} = e^{-\frac{1.35}{1.987*10^{-3}kcal/molK*(25+273K)}} = \mathbf{0.102}\frac{\mathbf{mol}}{\mathbf{L*atm}}$$

3.5 The reaction of divalent manganese with oxygen in aqueous solution is given as follows:

$Mn^{2+} + \frac{1}{2} O_{2\ (aqueous)} + H_2O = MnO_{2\ (solid)} + 2H^+$

The equilibrium constant (K) for this reaction is 23.7. It has been found that a lake water sample that contains no oxygen at 25°C, pH = 8.5, originally contained 0.6 mg/L of Mn^{2+}. The sample was aerated (atmospheric conditions so the dissolved oxygen concentration s 9.2 mg/L) and after 10 days of contact with atmospheric oxygen, the Mn^{2+} concentration was 0.4 mg/L. The molecular weight of Mn is 55, O is 16, and H is 1. The change in free energy of formation at standard conditions (units of kcal/mole) are as follows: Mn^{2+} = -54.4, $O_{2\ (aqueous)}$ = +3.93, H_2O = -56.69, $MnO_{2\ (solid)}$ = -111.1, H^+ =0. a) Assuming that the pH remains constant during aeration, will the precipitate continue to form after the measurement on the tenth day? Assume ideal conditions. b) What should the Mn^{2+} concentration be (in moles/L) at equilibrium, assuming that pH and presence of dissolved oxygen are the same as in part "A"? Assume ideal conditions. c) What should the Mn^{2+} concentration (in moles/L) be at equilibrium if 2 x 10^{-3} moles/liter of NaCl are added to the solution and the pH is adjusted to 2? (problem based on Snoeyink and Jenkins, 1980).

Solution:

a) Convert concentration to moles/L

$$9.2\frac{mg}{L}O_2 \times \frac{gm}{1000mg} \times \frac{1mole}{32gm} = 2.87 \times 10^{-4}M$$

$$0.6\frac{mg}{L}Mn \times \frac{gm}{1000mg} \times \frac{1mole}{55\ gm} = 1.09 \times 10^{-5}M$$

$$0.4\frac{mg}{L}Mn \times \frac{gm}{1000mg} \times \frac{1mole}{55\ gm} = 1.09 \times 10^{-5}M$$

Use the Gibbs free energy equation (3.4).

$$\Delta G = \Delta G° + RTln(Q)$$

$$\Delta G = \Delta G° + RTln\left[\frac{[H^+]^2[MnO_2]}{[Mn^{2+}][O_{2aq}]^{\frac{1}{2}}[H_2O]}\right]$$

$$(note: MnO_2\ is\ a\ solid\ and\ H_2O\ is\ a\ liquid\ so\ they\ go\ to\ 1)$$

$$\Delta G° = \sum products - \sum reactants = [-111 + 2(0)] - \left[-54.4 + \left(\frac{1}{2}\right)(3.93) + -56.69\right] = -1.875\ kcal$$

$$\Delta G = -1.87kcal + \left(1.987 * 10^{-3}\frac{kcal}{molK}\right)(298K)ln\left[\frac{[10^{-8.5}]^2}{[7.27 * 10^{-6}][2.87 * 10^{-4}]^{\frac{1}{2}}}\right] = -15.6\ kcal$$

$\therefore$ Mn^{2+}is still being oxidzed and precipitate still forms

b) At equilibrium $\Delta G = 0 \therefore 0 = \Delta G° + RTln(Q)$

At equilibrium the reaction quotient, Q, is the equilibrium constant, K. and in this case, Henry's constant. Solving for h in the free energy equation:

$$K_{eq} = e^{-\Delta G°/RT} = e^{-\frac{-1.875}{1.987*10^{-3}kcal/molK*(25+273K)}} = 23.7$$

Solve the equilibrium equation for Mn^{2+}

$$23.7 = \left[\frac{[10^{-8.5}]^2}{[Mn^{2+}][2.87*10^{-4}]^{\frac{1}{2}}}\right] \therefore \boldsymbol{[Mn^{2+}] = 2.5 \times 10^{-17} moles/L}$$

c)

$$\mu = \frac{1}{2}[0.02(1)^2 + 0.02(-1)^2 + 10^{-2} + 10^{-14} = 0.025$$

$$-log_{10}\gamma_{H^+} = \frac{0.5(1)^2\sqrt{0.025}}{1+\sqrt{0.025}} \therefore \gamma_{H^+} = 0.85$$

$$-log_{10}\gamma_{Mn^{2+}} = \frac{0.5(2)^2\sqrt{0.025}}{1+\sqrt{0.025}} \therefore \gamma_{Mn^{2+}} = 0.53$$

$$log_{10}\gamma_{O_2} = 0.132(0.025) \therefore \gamma_{O_2} = 1.008$$

Solve the equilibrium equation for Mn^{2+}

$$23.7 = \left[\frac{0.85^2[10^{-2}]^2}{0.53[Mn^{2+}][1.008]^{\frac{1}{2}}[2.87*10^{-4}]^{\frac{1}{2}}}\right] \therefore \boldsymbol{[Mn^{2+}] = 3.3 \times 10^{-4} moles/L}$$

3.6 Phosphate ion reacts in water to form monohydrogen phosphate according to the following reaction:

$PO_4^{3-} + H_2O = HPO_4^{2-} + OH^-$

The equilibrium constant for this reaction is $10^{-1.97}$. a) Given that this is a dilute system (so you can assume ideal conditions), temperature is 298°K and the total combined phosphate/monohydrogen phosphate is 10^{-4} M, what percentage of the total concentration is in the phosphate ion form at pH= 11? b) Will the reaction proceed as written at pH=9 when $[PO_4^{3-}]=10^{-6.8}$ and $[HPO_4^{2-}]=10^{-4}$ M? And if not, which direction will the reaction proceed?

Solution:

a) The equilibrium equation for the reaction is:

$$Kb = \frac{[OH^-][HPO_4{}^{2-}]}{[PO_4{}^{3-}]}$$

Filling in with the given problem information:

$$10^{-1.97} = \frac{[10^{-3}][HPO_4{}^{2-}]}{[PO_4{}^{3-}]}$$

Solve this equation for $HPO_4{}^{2-}$:

$$[HPO_4{}^{2-}] = 10.72\left[PO_4{}^{3-}\right]$$

The problem also states that the total combined phosphate/monohydrogen phosphate is 10^{-4} M:

$$\left[PO_4{}^{3-}\right] + [HPO_4{}^{2-}] = 10^{-4}$$

Plug in the equation for $HPO_4{}^{2-}$ into this equation:

$$\left[PO_4{}^{3-}\right] + 10.72\left[PO_4{}^{3-}\right] = 10^{-4} \ \therefore\ \left[PO_4{}^{3-}\right] = 8.53 * 10^{-6} mol/L$$

Now to solve for the percentage of the total concentration that is in the phosphate ion form:

$$\%\, Total\ Concentration\ in\ the\ phosphate\ ion = \frac{[PO_4{}^{3-}]}{\left[PO_4{}^{3-}\right] + [HPO_4{}^{2-}]} * 100\%$$

$$= \frac{[8.5 * 10^{-6} mol/L]}{[10^{-4}]} * 100\% = \mathbf{8.5}\%$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

b) To find off if the reaction will proceed, you must calculate the equilibrium constant:

$$Q = \frac{[OH^-][HPO_4{}^{2-}]}{[PO_4{}^{3-}]} = \frac{[10^{-5}][10^{-4}]}{[10^{-6.8}]} = 0.00631$$

$$Keq\ was\ given\ as\ 10^{-1.97} = 0.0107$$

$$0.0063 < 0.0107\ (Q < Qact) \therefore \boldsymbol{The\ reaction\ will\ proceed}$$

3.7 The chemical 1,4-dichlorobenzene (1,4-DCB) is sometimes used as a disinfectant in public lavatories. At 20°C (68°F) the vapor pressure is 5.3×10^{-4} atm. (a) What would be the concentration in the air in units of g/m^3? The molecular weight of l,4-DCB is 147 g/mole. (b) An alternative disinfectant is 1-bromo-4-chlorobenzene (l,4-CB). The boiling point of l,4-CB is 196°C, whereas the boiling point of l,4-DCB is 180°C. Which compound would cause the highest concentrations in the air in lavatories? (Explain your answer.)

Solution:

a) Ideal Gas Law: n/V=P/RT

The concentration can go no higher than the saturated vapor pressure (i.e., the equilibrium concentration). Hence, we must merely convert units from atm to g/m^3.

$$\frac{\left(5.3\times10^{-4}\,atm\right)}{\left(0.08205\dfrac{L\cdot atm}{mole\cdot K}\right)\left(293K\right)}=2.2\times10^{-5}\,\frac{mole}{L}$$

Now we must convert from mole/L to g/m^3:

$$\left(2.2\times10^{-5}\,\frac{mole}{L}\right)\left(\frac{147g}{mole}\right)\left(\frac{10^3\,L}{m^3}\right)=\boxed{3.2\,\frac{g}{m^3}}$$

b) <u>1,4-DCB, because a higher boiling point means a lower vapor pressure</u>. The chemical with the highest air concentration would have the highest vapor pressure and the lowest boiling point.

3.8 The boiling temperatures of chloroform (an anesthetic), carbon tetrachloride (commonly used in the past for dry cleaning), and tetrachloroethylene (previously used as a degreasing agent) are 61.7°C, 76.5°C, and 121°C. *The vapor pressure of a chemical is directly proportional to the inverse of the chemical's boiling point.* If a large quantity of these compounds were spilled in the environment, which compound would you predict to have higher concentrations in the air above the site? (Explain your answer.)

Solution:

Since the vapor pressure of a chemical is directly proportional to the inverse of the chemical's boiling point, *chloroform* will have the higher gaseous concentration because it has the lowest boiling point and higher vapor pressure.

3.9 What would be the saturation concentration (mole/L) of oxygen (O_2) in a river in winter when the air temperature is 0°C if the Henry's law constant at this temperature is 2.28×10^{-3} mole/L-atm? What would the answer be in units of mg/L?

Solution:

$$P_{O_2} = 0.21\, atm$$

$$K_H = 2.28 \times 10^{-3}\ \frac{mole}{L - atm}$$

$$(2.28 \times 10^{-3}\ \frac{mole}{L - atm}) \times (0.21\, atm) = 4.79 \times 10^{-4}\, mole\ O_2\ /\ L$$

$$\frac{4.79 \times 10^{-4}\, mole\ O_2}{L} \times \frac{32\ g\ O_2}{1\, mole\ O_2} \times \frac{1000\ mg}{1g} = \boxed{15.3\, mg\ /\ L}$$

3.10 The log Henry constant (units of L-atm/mole and measured at 25°C) for trichloroethylene (TCE) is 1.03; for tetrachloroethylene (PCE) it is 1.44; for 1,2-dimethylbenzene it is 0.71; and for parathion it is -3.42. (a) What are the dimensionless Henry's law constants for each of these chemicals? (b) Rank the chemicals in order of ease of stripping from water to air.

Solution:

Note that in this problem, the Henry's constants are reported as log Henry's constant.

a)

$$H[\frac{L_{H2O}}{L_{Air}}] = \frac{H(L-atm/mole)}{RT}$$

$$H_{trichlor} = \frac{10^{1.03}\,L-atm/mole}{0.08205(L-atm/mole-K)(298K)} = \boxed{0.44}$$

$$H_{tetrachlor} = \frac{10^{1.44}\,L-atm/mole}{0.08205(L-atm/mole-K)(298K)} = \boxed{1.1}$$

$$H_{\dim ethyl} = \frac{10^{0.71}\,L-atm/mole}{0.08205(L-atm/mole-K)(298K)} = \boxed{0.21}$$

$$H_{parathion} = \frac{10^{-3.42}\,L-atm/mole}{0.08205(L-atm/mole-K)(298K)} = \boxed{1.6\times10^{-5}}$$

b) tetrachloroethene, trichloroethene, 1,2-dimethylbenzene, parathion

3.11 The dimensionless Henry's law constant for trichloroethylene (TCE) at 25°C is 0.4. A sealed glass vial is prepared that has an air volume of 4 mL overlying an aqueous volume of 36 mL. TCE is added to the aqueous phase so that initially it has an aqueous phase concentration of 100 ppb. After the system equilibrates, what will be the concentration (in units of µg/L) of TCE in the aqueous phase?

Solution:

Set up a mass balance on the glass vial, assume no chemical or biological loss. Then solve for the TCE equilibrium concentration in the aqueous phase using the dimensionless Henry's constant to substitute for the concentration of TCE in the air phase.

$$M_{total} = M_{H2O} + M_{AIR}$$

$$\{\frac{100\ \mu g}{1\ L} \times \frac{1\ L}{1000\ mL} \times 36\ mL\} = \{C_{eq-H2O}\frac{L}{1000\ mL} \times 36\ mL\} + \{C_{eq-AIR}\frac{L}{1000\ mL} \times 4\ mL\}$$

$$K_H = 0.4 = \frac{[C_{eq-AIR}]}{[C_{eq-H2O}]}$$

Substituted $C_{eq\text{-}AIR} = C_{eq\text{-}H2O} \times 0.4$ and then solve for $C_{eq\text{-}H2O}$.

3.6 µg=$C_{eq\text{-}H2O}$[0.036 L + 0.0016 L]

$\boxed{C_{eq\text{-}H2O} = 96\ \mu g/L}$

3.12 The Henry's law constant for H_2S is 0.1 moles/L-atm and

$$H_2S_{(aq)} \rightleftharpoons HS^- + H^+, \qquad K_a = 10^{-7}$$

If you bubble pure H_2S gas into a beaker of water, what is the concentration of HS^- at a pH of 5 in (a) moles/L; (b) mg/L; (c) ppm_m?

Solution:

a) Because pure H_2S gas is bubbled in the beaker, the aqueous H_2S concentration is fixed and equals $K_H \times P_{H2S}$ (pure gas so P_{H2S}=1atm).

$$K = 10^{-7} = \frac{[HS^-][H^+]}{[H_2S_{aq}]} = \frac{[HS^-][10^{-5}]}{[0.1\,mole/L-atm \times 1\,atm]}$$

$$\boxed{[HS^-] = 0.001\,mole/L}$$

b) In water, mg/L = ppm

$$\frac{0.001\,mole\ HS^-}{L} \times \frac{33.1\,g\ HS^-}{1\,mole\ HS^-} \times \frac{1000\,mg}{1g} = \boxed{33\,mg\ HS^-/L}$$

c)

$$\frac{33.1\,mg\ HS^-}{L} \times \frac{1\,L}{1\,kg} = \boxed{33\ ppm}$$

3.13 Determine the equilibrium pH of aqueous solutions of the following strong acids or bases: (a) 15 mg/L of HSO_4^-; (b) 10 mM NaOH; (c) 2,500 μg/L of HNO_3.

Solution:

Because this problem states that these are strong acids and strong bases, we can assume that they will dissociate 100% of their H^+ and OH^- when added to water (we can also see this assumption by observing the magnitude of the pK_a and pK_b for these compounds.

a)

$$\frac{15\ mg\ HSO_4^-}{L}\times\frac{1\ g}{1000\ mg}\times\frac{1\ mole\ HSO_4^-}{97\ g\ HSO_4^-}\times\frac{1\ mole\ H^+}{1\ mole\ HSO_4^-}=1.6\times10^{-4}\ mole\ H^+$$

$$\boxed{pH=3.8}$$

b)

$$\frac{10\ mmole\ NaOH}{L}\times\frac{1\ mole}{1,000\ mmole}\times\frac{1\ mole\ OH^-}{1\ mole\ NaOH}=0.01\ mole\ OH^-$$

$$[OH^-]=10^{-2}\qquad so\quad [H^+]=10^{-12}$$

$$\boxed{pH=12}$$

c)

$$\frac{2,500\ \mu g\ HNO_3}{L}\times\frac{1g}{10^6\ \mu g}\times\frac{1\ mole\ HNO_3}{63\ g\ HNO_3}\times\frac{1\ mole\ H^+}{1\ mole\ HNO_3}=3.97\times10^{-5}\ moles\ H^+$$

$$\boxed{pH=4.4}$$

3.14 What would be the pH if 10^{-2} moles of hydrofluoric acid (HF) were added to 1 L pure water? The pK_a of HF is 3.2.

Solution:

When HF is added to water, it can either remain as the acid, HF, or dissociate to the base, F^-. Thus, in water we have four unknown species (H^+, OH^-, HF, F^-). Water is not an unknown because we assume its activity is 1. Thus, in order to solve this problem we require 4 independent equations to solve for the 4 unknowns. The 4 equations are:

one mass balance: 10^{-2} moles/L = [HF] + {F^-]

two equilibrium expressions: $10^{-14} = [H^+][OH^-]$ and

$$10^{-3.2} = [H^+][F^-]/[HF]$$

and one expression showing that charge neutrality is maintained in the solution

$$[H^+] = [OH^-] + [F^-]$$

You can solve these expressions simultaneously or make some assumptions to reduce the number of unknowns.

Assumption 1: to reduce the mass balance expression, assume [HF]> [F^-]. This should make sense. We added a lot of a relatively strong acid so we assume that the equilibrium pH is < pK_a. The mass balance then reduces to $[HF]=10^{-2}$ M.

Assumption 2: to reduce the electroneutrality expression, assume $[F^-]>[OH^-]$. This should also make sense. We added a lot of an acid so the pH should be below 7 where the concentration of OH^- becomes very small. Thus, this expression reduces to $[H^+]=[F^-]$.

Substitute these two items into the equilibrium expression for HF.

$$10^{-3.2} = \frac{[H^+][H^+]}{10^{-2}} \Rightarrow [H^+]^2 = 6.3\times10^{-6} \Rightarrow [H^+] = 2.5\times10^{-3}$$

$$\boxed{pH = 2.6}$$

Lastly, we must check our assumptions to make sure they are correct. First we solve for the rest of the unknowns. From the equilibrium expression for HF we can determine that $[F^-]=2.5x10^{-3}$ and from the equilibrium expression for the dissociation of water, $[OH]=4x10^{-12}$. Both assumption are valid, therefore our "approximate" answer is correct.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.15 When Cl_2 gas is added to water during the disinfection of drinking water, it hydrolyzes with the water to form HOCl. The disinfection power of the acid HOCl is 88 times better than its conjugate base, OCl^-. The pK_a for HOCl is 7.5. (a) What % of the total disinfection power (i.e., HOCl + OCl^-) exists in the acid form at a pH = 6? (b) At pH = 7?

Solution:

a) The problem is requesting

$$\frac{[HOCl]}{[HOCl]+[OCl^-]}\times 100\%$$

This requires an additional equation (the equilibrium expression) because we have two unknowns above.

$$K = 10^{-7.5} = \frac{[OCl^-][H^+]}{[HOCl]} = \frac{[OCl^-][10^{-6}]}{[HOCl]}$$

$$[OCl^-] = 0.032\,[HOCl]$$

$$\frac{[HOCl]}{[HOCl]+0.032\,[HOCl]}\times 100\%$$

$$= \boxed{97\%}$$

b) Similarly, when the pH = 7,

$$K = 10^{-7.5} = \frac{[OCl^-][H^+]}{[HOCl]} = \frac{[OCl^-][10^{-7}]}{[HOCl]}$$

$$[OCl^-] = 0.32\,[HOCl]$$

$$\frac{[HOCl]}{[HOCl]+0.32\,[HOCl]}\times 100\%$$

$$= \boxed{76\%}$$

3.16 A 1-liter aqueous solution is prepared at 25°C with 10^{-4} moles of hydrocyanic acid (HCN) and 10^{-3} moles of disodium carbonate (Na_2CO_3) and reaches equilibrium. a) List the eight unknown chemical species here (water is not unknown). b) List (do not solve) all four equilibrium expressions that describe this system making sure to include the value for the equilibrium constants.

Solution:

a) Write the chemical half equilibrium equations of hydrocyanic acid and disodium carbonate.

$$Na_2CO_3 \ + \ H_20 \leftrightarrow Na^{2+} \ + HCO_3{}^{-} + \ H_2CO_3 + CO_3{}^{2-}$$

$$HCN + \ H_20 \leftrightarrow H^{+} + CN^{-} + OH^{-}$$

Combine these for the full chemical equation:

$$HCN + Na_2CO_3 \ + \ H_20 \leftrightarrow H^{+} + CN^{-} + \ Na^{+} \ + HCO_3{}^{-} + \ H_2CO_3 + CO_3{}^{2-} + OH^{-}$$

Here are the eight unknowns:

$$[\boldsymbol{H^{+}}], [\boldsymbol{CN^{-}}], [\boldsymbol{Na^{+}}], [\boldsymbol{HCO_3{}^{-}}], [\boldsymbol{H_2CO_3}], \left[\boldsymbol{CO_3{}^{2-}}\right], [\boldsymbol{OH^{-}}], [\boldsymbol{HCN}]$$

b)

$$k_{a_1} = \frac{[H^{+}][CN^{-}]}{[HCN]} = 10^{-9.2}$$

$$k_W = [H^{+}][OH^{-}] = 10^{-14}$$

$$k_{a_2} = \frac{[H^{+}][HCO_3{}^{-}]}{[H_2CO_3{}^{-}]} = 10^{-6.3}$$

$$k_{a_3} = \frac{[H^{+}]\left[CO_3{}^{2-}\right]}{[H_2CO_3{}^{-}]} = 10^{-7.7}$$

3.17 For the endothermic reaction, $SO_{2(g)} = S_{(s)} + O_2$ will an increase in temperature increase, decrease, or have no effect on the reaction's equilibrium constant?

Solution:

To answer this question, refer to the Vant Hoff relationship from box 3.1, equation 3.9:

$$\text{In}\left[\frac{K_2}{K_1}\right] = \frac{\Delta H^0}{R} \times \left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

An increase in temperature will **<u>increase the equilibrium constant</u>** and drive the reaction to the products.

3.18 What pH is required to reduce a high concentration of a dissolved Mg^{2+} to 25 mg/L? The solubility product for the following reaction is $10^{-11.16}$.

Solution:

$Mg(OH)_{2\,(s)} = Mg^{2+} + 2OH^-$

This problem is similar to example 3.8.

First convert the concentration of Mg^{2+} from mg/L to moles/L:

$$[Mg^{2+}] = 25\frac{mg}{L} \times \frac{1g}{1000mg} \times \frac{1mol}{24g} = 0.00104\frac{mol}{L}$$

The equilibrium expression is written as:

$$10^{-11.16} = \frac{[\mathrm{Mg}^{2+}]\times[\mathrm{OH}^-]^2}{[\mathrm{Mg(OH)}_{2(s)}]}$$

$Mg(OH)_{2(s)}$ is a solid and the concentration is one. Solve the equation of the concentration of OH^-:

$$[OH^-] = \sqrt{\frac{10^{-11.16}}{[Mg^{2+}]}} = \sqrt{\frac{10^{-11.16}}{[0.00104mol/L]}} \;=\; 4.91 \times 10^{-5} mol/L$$

$$\log\left(4.91 \times 10^{-5}\frac{mol}{L}\right) = -4.3 + 14 = \mathbf{9.7}$$

3.19 (a) What is the solubility (in moles/L) of CaF_2 in pure water at 25°C?
(b) What is the solubility of CaF_2 if the temperature is raised 10°C?
(c) Does the solubility of CaF_2 increase, decrease, or remain the same if the ionic strength is raised? (Explain your answer.)

Solution:
a) The reaction is $CaF_{2(s)} = Ca^{2+} + 2F^-$
First, determine the equilibrium constant, K_{so}, for the reaction. Because it is not given it can be determined by setting ΔG to zero and solving for K.

$$\Delta G = \Delta G^\circ + RT \ln K_{so} = 0$$

$$\Delta G = \{(-554) + 2(-279)\} - \{(-1203)\} + 8.314 \times 10^{-3} \times (298) \ln K_{so}$$

$$\ln K_{so} = -36.7 \Rightarrow K_{so} = 1.1 \times 10^{-16} = 10^{-15.95}$$

Now determine the solubility. Let "s" equal the solubility of $CaF_{2(s)}$. And for every mole of $CaF_{2(s)}$ which dissolved, 1 mole of Ca^{2+} and 2 moles of F^- are produced.

$$K_{so} = 10^{-15.95} = [Ca^{2+}][F^-]^2 = [s][2s]^2 = 4s^3$$

$$\boxed{s = 3.0 \times 10^{-6} M}$$

This is the number of moles of calcium fluoride which can be dissolved in one liter of water before a precipitate would begin to form.

b) Determine the equilibrium constant at the new temperature. Then solve problem as in part a).

$$\Delta H^\circ = \sum \Delta H_f^{\,o}\text{products} - \sum \Delta H_f^{\,o}\text{reac tan ts}$$

$$\Delta H^\circ = \left[(-543) + 2(-333)\right] - (-1{,}107) = -102 \text{ kJ / mole}$$

$$\ln \frac{K_2}{K_1} = \frac{\Delta H^o}{R}[\frac{1}{T_1} - \frac{1}{T_2}] = \ln \frac{K_{so,35}}{K_{so,25}} = \frac{-102}{8.314 \times 10^{-3}}\left[\frac{1}{298} - \frac{1}{308}\right]$$

$$\ln K_{so,35} = \ln K_{so,25} - 1.34 = -36.73 - 1.34$$

$$\ln K_{so,35} = -38.07$$

$$K_{so} @ 35^o C = e^{(-38.07)} = 2.93 \times 10^{-17} = [s][2s]^2$$

$$\boxed{s = 1.54 \times 10^{-6} M}$$

Note that in this case, the solubility increased as the temperature increased.

c) $K_{so} = \gamma_{Ca^{2+}} [Ca^{2+}] \quad \gamma^2_{F^-} [F^-]^2$

Because activity coefficients for electrolytes are < 1, the K_{so} will increase, thus, the solubility will increase.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.20 At a wastewater-treatment plant $FeCl_{3(s)}$ is added to remove excess phosphate from the effluent. Assume that the reactions that occur are

$$FeCl_{3(s)} \rightleftharpoons Fe^{3+} + 3Cl^{-}$$
$$Fe^{3+} + PO_4^{3-} \rightleftharpoons FePO_{4(s)}$$

The equilibrium constant for the second reaction is $10^{26.4}$. What concentration of Fe^{3+} would be needed to maintain the phosphate concentration below the limit of 1 mg P/L?

Solution:

Assume all P as PO_4^{3-}

$$[PO_4^{3-}] = \frac{1\,mg\ P}{L} \times \frac{1\,g}{1{,}000\,mg} \times \frac{1\,mole\ P}{31\,g\ P} \times \frac{mole\ PO_4^{3-}}{mole\ P} = 3.2\times10^{-5}\,mole/L$$

$$K = 10^{26.4} = \frac{[FePO_{4(s)}]}{[Fe^{3+}][PO_4^{3-}]} = \frac{1}{[Fe^{3+}][3.2\times10^{-5}]}$$

$$\boxed{[Fe^{3+}] = 1.2\times10^{-22}\ moles/L}$$

3.21 One method to remove metals from water is to raise the pH and cause them to precipitate as their metal hydroxides. (a) For the following reaction, compute the standard free energy of reaction:

$$Cd^{2+} + 2OH^{-} \rightleftharpoons Cd(OH)_{2(s)}$$

(b) The pH of water was initially 6.8 and was then raised to 8.0. Is the dissolved cadmium concentration reduced to below 100 mg/L at the final pH? Assume the temperature of the water is 25°C.

Solution:

a)

$$\Delta G^\circ = \Delta G_f{}^\circ(products) - \Delta G_f{}^\circ(reac\tan ts)$$

$$\Delta G^\circ = -470.0 - [-77.6 + 2(-157)]$$

$$\boxed{\Delta G^\circ = -78.4\ kJ\ /\ mole}$$

b) Calculate the equilibrium concentration of Cd^{2+} and compare to 100 mg/L. At pH = 8, $[OH^-] = 10^{-6}$ M.

$$\Delta G = 0 = \Delta G^\circ + RT \ln K$$

$$0 = -78.4 kJ\ /\ mole + [8.314 \times 10^{-3} kJ - K\ /\ mole \times 298 K \times \ln K]$$

$$K = 5.5 \times 10^{13}$$

$$K = \frac{1}{[Cd^{2+}][OH^-]^2}$$

$$5.5 \times 10^{13} = \frac{1}{[Cd^{2+}][10^{-6}]^2} = 1.8 \times 10^{-2} moles\ /\ L$$

$$[Cd^{2+}] = \frac{1.8 \times 10^{-2} moles}{L} \times \frac{112\ g\ Cd}{1\ mole\ Cd} \times \frac{10^3 mg}{g} = \boxed{2.0 \times 10^3 mg\ /\ L}$$

<u>No, the pH must be raised higher to increase the OH- concentration.</u>

3.22 Naphthalene has a log K_{ow} of 3.33. Estimate its soil-water partition coefficient normalized to organic carbon and also the 95% confidence interval of your estimate.

Solution:

The correlation of Baker et al. (1997) is valid for naphthalene.

$$\log K_{OC} = 0.903 \log K_{OW} + 0.094$$
$$\log K_{OC} = 0.903 \times (3.33) + 0.094$$
$$\log K_{OC} = 3.10 \Rightarrow Koc = 1.26x10^3\ cm^3 / g\ oc$$
$$95\%\ CI\ \ for \log Koc = \pm 0.66\left(\frac{138 + (\log K_{OW} - 3.92)^2}{136}\right)^{1/2}$$
$$\boxed{95\%\ CI = \pm 0.67\ cm^3 / g\ oc}$$

3.23 Atrazine is an herbicide widely used for corn and is a common groundwater pollutant in the corn-producing regions of the United States. The log K_{ow} for atrazine is 2.65. Calculate the fraction of total atrazine that will be adsorbed to the soil given that the soil has an organic carbon content of 2.5%. The bulk density of the soil is 1.25 g/cm^3; this means that each cubic centimeter of soil (soil plus water) contains 1.25 g of soil particles. The porosity of the soil is 0.4.

Solution:

Assume that the correlation of Baker et al. (1997) is valid for atrazine.

$$\log K_{oc} = 0.903 (\log K_{ow}) + 0.094$$

$$\log K_{oc} = 0.903 (2.65) + 0.094$$

$$\log K_{oc} = 2.49 \text{ so } K_{oc} = 309 \text{ cm}^3/\text{g oc}$$

$$K = K_{oc} \times f_{oc} = 309 \text{ cm}^3/\text{g oc} \times 0.025 = 7.73 \text{ cm}^3/\text{g soil}$$

Assume a total of 1 cm^3 of soil. From the porosity, it will have 0.6 cm^3 of soil and 0.4 cm^3 of void space (which is assumed to be filled with water). From the bulk density we can determine that the mass of soil is 0.75 grams (1.25 g/cm^3 x 0.6 cm^3). Set up a mass balance on atrazine in water and sorbed to soil. Use the soil-water partition coefficient to substitute for the sorbed phase concentration in terms of aqueous phase concentration.

$$\begin{aligned}\text{Total atrazine} &= \text{sorbed atrazine} + \text{aqueous atrazine}\\ &= M_{soil} \times C_{sorbed} + Vol \times C_{aqueous}\\ &= \{0.75\text{g} \times (7.73 \text{ cm}^3/\text{g soil}) \times (C_{aqueous})\}+\{0.4 \text{ cm}^3 \times C_{aqueous}\}\\ &=C_{aqueous} [5.80 \text{ cm}^3+0.4 \text{ cm}^3]\end{aligned}$$

Note that in this problem the mass of atrazine sorbed to soil is large relatively to the mass in the aqueous phase. If we knew the total amount of atrazine initially added to the system, we could solve for the equilibrium aqueous phase concentration, then use the soil-water partition coefficient to determine the sorbed phase concentration.

Fraction of total atrazine adsorbed to soil =

$$\left(1-\frac{0.4\ cm^3}{0.4\ cm^3+5.80\ cm^3}\right)\times 100\% = \boxed{94\%}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.24 Mercury concentrations in San Francisco Bay were measured to be 8 ng/L in rain water, 1.25 ng/L dissolved in the Bay water, and 250 ng/gm dry weight of sediment. Using the information provided and assuming equilibrium, what is the sediment-water partition coefficient for mercury in the sediments (units of cm^3 per gram dry weight of sediment)?

Solution:

Use equation 3.32:

$$K = \frac{q}{c} = \frac{250\ ng/g}{1.25\ ng/L} = 200\frac{L}{g} \times \frac{1\ m^3}{1000\ L} \times \frac{(100)^3 cm}{1\ m^3} = \mathbf{2.0} \ \times \mathbf{10^5}\, \frac{\boldsymbol{cm^3}}{\boldsymbol{g}}$$

3.25 Given the following general reaction:

A + 2B + 3C → P + 4Q

Show how the change in concentration of C with time is related to the change in concentration of A, B, P, and Q with time.

Solution:

$$\frac{d[C]}{dt} = \frac{d[A]}{3dt} = \left(\frac{2}{3}\right)\frac{d[B]}{dt} = -\frac{d[P]}{dt} = -\frac{d[Q]}{4dt}$$

3.26 Which of the following statements about the study of chemical kinetics is true ? (a) temperature has no effect on the rate of a reaction, (b) changes in reactant concentration do not affect the rate at which a reaction occurs, (c) the addition of a catalyst to a reaction will speed up the reaction but it will not ultimately result in a larger mass of product, (d) for the same reactants, the larger the surface area, the slower a reaction will occur (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/).

Solution:

(d) For the same reactants, the larger the surface area, the slower a reaction will occur
D is true since smaller particle sizes provide a greater surface area which increases the chances of particle collisions and, thus, the reaction rate increases.

3.27 Peridisulfate ($S_2O_8^{2-}$) reacts with thiosulfate ($S_2O_3^{2-}$) according to the following reaction:

$S_2O_8^{2-} + 2\ S_2O_3^{2-} \rightarrow 2SO_4^{2-} + S_4O_6^{2-}$

a) Show how the change in perdisulfate concentration with time is related to the change in concentration with time of the other three species. b) If the reaction is elementary and irreversible, what is the overall order of the reaction?

Solution:

a)

$$\frac{\boldsymbol{d[S_2O_8{}^{2-}]}}{\boldsymbol{dt}} = \left(\frac{\mathbf{1}}{\mathbf{2}}\right)\frac{\boldsymbol{d\left[S_2O_3{}^{2-}\right]}}{\boldsymbol{3dt}} = -\left(\frac{\mathbf{1}}{\mathbf{2}}\right)\frac{\boldsymbol{d[SO_4{}^{2-}]}}{\boldsymbol{dt}} = -\frac{\boldsymbol{d[S_4O_6{}^{2-}]}}{\boldsymbol{4dt}}$$

b) An irreversible and elementary reaction means that the concentration of products did not influence the rate of the forward reaction. Using equation 3.36:

$$R = k[A]^a[B]^b = k\left[S_2O_8{}^{2-}\right]^1[S_2O_3{}^{2-}]^2$$

Overall order = a + b= 1+2= **3rd order**

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.28 A first-order reaction that results in the destruction of a pollutant has a rate constant of 0.l/day. (a) How many days will it take for 90% of the chemical to be destroyed? (b) How long will it take for 99% of the chemical to be destroyed? (c) How long will it take for 99.9% of the chemical to be destroyed?

Solution:

First Order Reaction: $A = A_o \times e^{-kt}$

$$0.10 = 1.00 \times e^{-(0.1/day)\times t}$$

a) 90% destroyed so 10% of initial concentration remains.

$$t = \frac{\ln\left(\frac{0.10}{1.00}\right)}{-0.1/day} = \boxed{23\ days}$$

b) Same as part a) except 99% destroyed so 0.1% of initial concentration remains

$$t = \frac{\ln\left(\frac{0.01}{1.00}\right)}{-0.1/day} = \boxed{46\ days}$$

c) Same as part a), except 99.9% destroyed so 0.1% of initial concentration remains

$$t = \frac{\ln\left(\frac{0.001}{1.00}\right)}{-0.1/day} = \boxed{69\ days}$$

3.29 A strain of bacteria has been isolated that can cometabolize tetrachloroethane (TCA). This strain of bacteria can be used for the bioremediation of hazardous-waste sites contaminated with TCA. Assume that the biodegradation rate is independent of TCA concentration (i.e., the reaction is zero order). In a bioreactor it is observed that the rate for TCA removal was 1 μg/L-min. What water retention time would be required to reduce the concentration from 1 mg/L in the influent to 1 μg/L in the effluent of a reactor? Assume the reactor is completely mixed.

Solution:

Zero Order Reaction: $A = A_o - kt$ and 1 mg/L = 1,000 μg/L

$$1\mu g / L = 1{,}000\mu g / L - (1\mu g / L - \min)(t)$$

$$\boxed{t = 999\min = 0.7\ days}$$

3.30 Assume that PO_4^{3-} is removed from municipal wastewater through precipitation with Fe^{3+} according to the following reaction: $PO_4^{3-} + Fe^{3+} \longrightarrow FePO_{4(s)}$.
The rate law for this reaction is

$$\frac{d\left[\mathrm{PO}_4^{3-}\right]}{dt} = -k\left[\mathrm{Fe}^{3+}\right]\left[\mathrm{PO}_4^{3-}\right]$$

(a) What is the reaction order with respect to PO_4^{3-}?
(b) What order is this reaction overall?

Solution:

a) **First**

b) **Second**

3.31 Obtain the World Health Organization (WHO) report on "Urine diversion: Hygienic risks and microbial guidelines for reuse." Review Figure 2 in Chapter 1 (Introduction). (a) How many grams of N, P, and K are excreted every day in a Swedish person's urine?

Solution:

This report can be found at:

http://www.who.int/water_sanitation_health/wastewater/urineguidelines.pdf

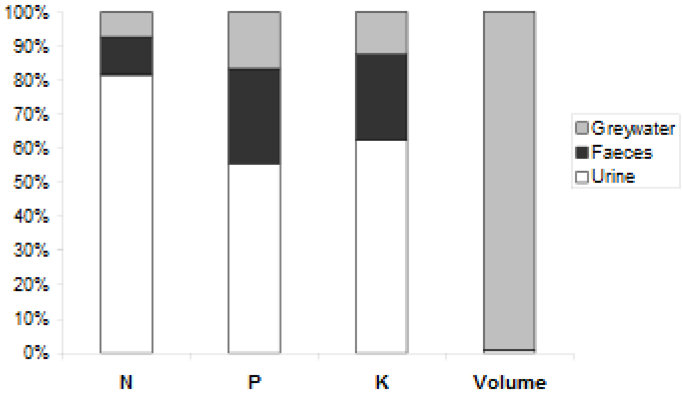


Figure 2. *Content of major plant nutrients and volume in Swedish domestic wastewater. The daily mean excretion per person and day is: 14 g N, 2 g P and 4 g K in a volume of 150-200 litre.*

According to the figure **14 g N, 2g P, and 4g K are excreted every day in a Swedish person's urine.**

3.32 Obtain the World Health Organization (WHO) report on "Urine diversion: Hygienic risks and microbial guidelines for reuse." Read Chapter 4, (Pathogenic microorganisms in urine). Answer the following questions. (a) Is the urine in a healthy individual's bladder sterile or nonsterile? (b) What concentration of dermal bacteria are picked up during urination (bacteria/mL)? (c) What percent of urinary track infections are caused by *E. coli*?

Solution:

This report can be found at:
http://www.who.int/water_sanitation_health/wastewater/urineguidelines.pdf

a) On page 11, the report states "…in a health individual the urine is **sterile** in the bladder."

b) Also on page 11, the report states "…freshly excreted urine normally contains **<10,000 bacteria per mL**"

c) The report states on page 11 that "By urinary tract infections, which in more than **80%** of cases are caused by *E. coli*."

3.33 Ammonia, NH_3, is a common constituent of many natural waters and wastewaters. In treating water containing ammonia at a water-treatment plant, the ammonia reacts with the disinfectant hypochlorous acid, HOCl, in solution to form monochloroamine, NH_2Cl as follows:

$$NH_3 + HOCl \longrightarrow NH_2Cl + H_2O$$

The rate law for this reaction is

$$\frac{d[NH_3]}{dt} = -k[HOCl][NH_3]$$

(a) What is the reaction order with respect to NH_3?
(b) What order is this reaction overall?
(c) If the HOCl concentration is held constant and equals 10^{-4} M, and the rate constant equals 5.1×10^6 L/mole-s, calculate the time required to reduce the concentration of NH_3 to one-half its original value.

Solution:

a) **First**

b) **Second**

c) since [HOCl} remains constant, k×[HOCl] = constant, and the rate expression reduces to a pseudo first order reaction. Also, since 50% reaction, $[NH_3] = 0.5[NH_3]_{initial}$

$$0.5 \times [NH_3]_o = [NH_3]_o \times e^{-k't}$$

$$\frac{d[NH_3]}{dt} = -k[HOCl][NH_3] = -5.1\times10^6\ L/mole - s \times \left[10^{-4}\ mole/L\right] \times [NH_3]$$

$$\boxed{t = 1.4\times10^{-3}\ s}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.34 Nitrogen dioxide (NO_2) concentrations are measured in an air-quality study and decrease from 5 ppm_v to 2 ppm_v in 4 min with a particular light intensity. (a) What is the first-order rate constant for this reaction? (b) What is the half-life of NO_2 during this study? (c) What would the rate constant need to be changed to in order to decrease the time required to lower the NO_2 concentration from 5 ppm_v to 2 ppm_v in 1.5 min?

Solution:

a) $[NO_2] = [NO_2]_o\, e^{-kt}$

$$2 \text{ ppm} = 5 \text{ ppm } e^{-k\,(4\text{ min})}$$

$$-\ln\frac{2}{5} = k(4)$$

$$\boxed{k = 0.23/\min}$$

b) $t_{1/2} = 0.693/k$

$$t_{1/2} = \frac{0.693}{0.23/\min} = \boxed{3.0\min}$$

c)

$$-\ln\frac{2}{5} = k(1.5)$$

$$\boxed{k = 0.61/\min}$$

3.35 Assume that municipal solid waste is 30% organic carbon by wet weight. The organic carbon in the solid waste decays by first order kinetics after placed in a landfill with reported rate constants for a dry climate (0.02/yr), moderate climate (0.038/yr), and wet climate (0.057/yr). Dry climate is defined as precipitation plus recirculated leachate being less than 20 inches/year; moderate climate as precipitation plus recirculated leachate ranges from 20 to 40 inches/year; and, a wet climate having precipitation plus recirculated leachate greater than 40 inches/year. Estimate the time it takes for 20 and 90 percent of the organic carbon contained in a municipal solid waste landfill to decay in the three different climates. In practice, this will be the period when greenhouse gases should be captured from the landfill).

Solution:

Use the first order rate equation to calculate the time it takes for 20 and 90 percent of the organic carbon in the landfill to decay:

$$[C] = [C_o]e^{-kt}$$

For 20%: $C = C_o - 0.2C_o = 0.8C_o$ and we plug that into our first order rate equation:

$$0.8C_o = C_o e^{-kt}$$

C_o's cancel and the equation can be solved for time:

$$t = \frac{\ln(0.8)}{-k}$$

A similar expression can be derived for 90%: $C = C_o - 0.9C_o = 0.1C_o$ and the first order rate equation can be solved for time:

$$t = \frac{\ln(0.1)}{-k}$$

The dry climate has a rate constant of 0.02/yr

$$t_{20\%\ of\ organic\ carbon} = \frac{\ln(0.8)}{-0.02/yr} = 11.2\ years$$

$$t_{80\%\ of\ organic\ carbon} = \frac{\ln(0.1)}{-0.02/yr} = 115\ years$$

The decay times for moderate and wet climates can be calculated in the same way and are displayed in the table below:

Climate	Rate constant (yr^{-1})	time for 20% or organic carbon to decay (years)	time for 80% of organic carbon to decay (years)
Dry	0.02	**11.2**	**115**
Moderate	0.038	**5.87**	**60.6**
Wet	0.057	**3.91**	**40.4**

3.36 On March 11, 2011, a massive earthquake and tsunami triggered a major disaster at Japan's Fukushima nuclear plant. A plume extending to the northwest of the site deposited significant amounts of iodine-131, cesium-134, and cesium-137 up to 30 miles away. Iodine-131 has an 8-day half-life and cesium-137 has a 3-year half-life. Determine how long it will take 99% of the iodine-131 and 99% of the cesium-137 to naturally decay (you can learn about "U.S. Nuclear Power Safety One Year after Fukushima" by reading the report written by D. Lochbaum and E. Lyman, located on the web site of the Union of Concerned Scientists, http://www.ucsusa.org/publications/publications-nuclear-power.html)

Solution:

Use equation 3.53 for the half-life of a first-order relationship to calculate the rate constants for iodine and cesium:

$$t_{1/2} = \frac{0.693}{k}$$

$$k_{iodine} = \frac{0.693}{t_{1/2}} = \frac{0.693}{8\ days} = 0.0866/day$$

$$k_{cesium} = \frac{0.693}{t_{1/2}} = \frac{0.693}{3\ years} = \frac{0.231}{year} \times \frac{1\ year}{365\ days} = 6.3 * 10^{-4}/day$$

Cesium will be the limiting chemical to decay as it has a much slower rate constant. Use the first order rate equation (3.44) to calculate the time it takes 99% of the cesium to naturally decay.

$$[C] = [C]_0 e^{-kt} \text{ where } [C] = (1 - .99)[C]_o = 0.01[C]_o$$

$$0.01[C]_o = [C]_o e^{-kt}$$

The initial concentrations cancel so that you can solve for the decay time since the rate constant has already been calculated.

$$0.01[C]_o = [C]_o e^{-kt}$$

$$t_{cesium} = \frac{\ln(0.01)}{-0.231/year} = \boldsymbol{20\ years}$$

Though not shown, using this same calculation method it takes only 53 days for 99% of the iodine to decay.

3.37 After the Chernobyl nuclear accident, the concentration of ^{137}Cs in milk was proportional to the concentration of ^{137}Cs in the grass that cows consumed. The concentration in the grass was, in turn, proportional to the concentration in the soil. Assume that the only reaction by which ^{137}Cs was lost from the soil was through radioactive decay and the half-life for this isotope is 3 years. Calculate the concentration of ^{137}Cs in cow's milk after 5 years (units of Bq/L) if the concentration in milk shortly after the accident was 12,000 Bequerels (Bq) per liter (a Bequerel is a measure of radioactivity; 1 bequerel equals 1 radioactive disintegration per second).

Solution:

Use equation 3.53 for the half-life of a first-order relationship to calculate the rate constant for cesium:

$$t_{1/2} = \frac{0.693}{k}$$

$$k_{cesium} = \frac{0.693}{t_{1/2}} = \frac{0.693}{3\ years} = \frac{0.231}{year}$$

Use the first order rate equation (3.44) to solve for the concentration of cesium in the cows milk after 5 years:

$$[C]=[C]_0 e^{-kt}$$

$$[Cs] = [12{,}000\ Bg/L]_o e^{-\frac{0.231}{year}\times 5yr} = \mathbf{3,780\ Bq/L}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.38 In the next chapter, Figure 4.14 shows the annual mean growth rate (units of ppm CO_2/year) measured at Mauna Loa (Hawaii). The annual mean rate of growth of CO_2 in a given year is the difference in concentration between the end of December and the start of January of that year. The National Oceanic and Atmospheric Administration (NOAA) reports that the annual growth rate is similar to the global growth rate of CO_2 in the atmosphere (Dr. Pieter Tans, NOAA/ESRL, http://www.esrl.noaa.gov/gmd/ccgg/trends/, and Dr. Ralph Keeling, Scripps Institution of Oceangraphy, scrippsco2.ucsd.edu/).

Yr	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969
ppm/yr	0.94	0.54	0.95	0.64	0.71	0.28	1.02	1.24	0.74	1.03	1.31
Yr	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
ppm/yr	1.06	0.85	1.69	1.22	0.78	1.13	0.84	2.1	1.3	1.75	1.73

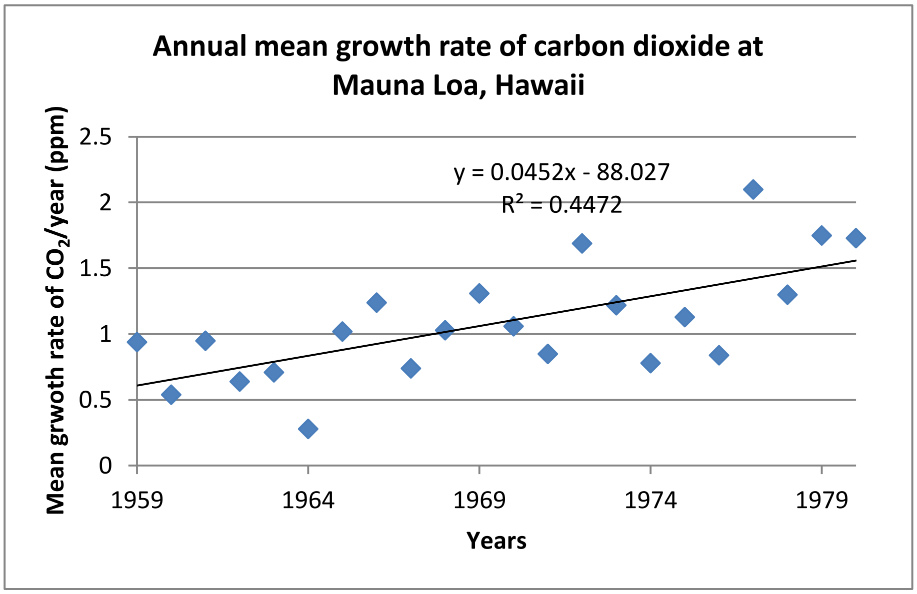
(a) What is the average growth rate of CO_2 in the atmosphere over this 20-year period (ppm CO_2/year)? (b) Review the shape of the figure showing the atmospheric CO_2 measurements made at Mauna Loa over the past 50 years (Figure 4.14 of the next chapter or the web site referred to above). Does the data follow a first order or zero order reactor order? Explain your answer. (c)_ Assume that the 1959 monthly mean concentration of CO_2 measured at Mauna Loa was 315 ppm. Using the average growth rate you determined in part (a) over the 20-year period and the appropriate reactor order, what atmospheric CO_2 concentration would you estimate for the year 1980, 2012, and 2050?

Solution

a) Start by graphing the data given in table 3.13 with the mean growth rate of CO_2/year on the y-axis as the dependent variable and the years on the x-axis. Use linear regression to add a trendline to the data.

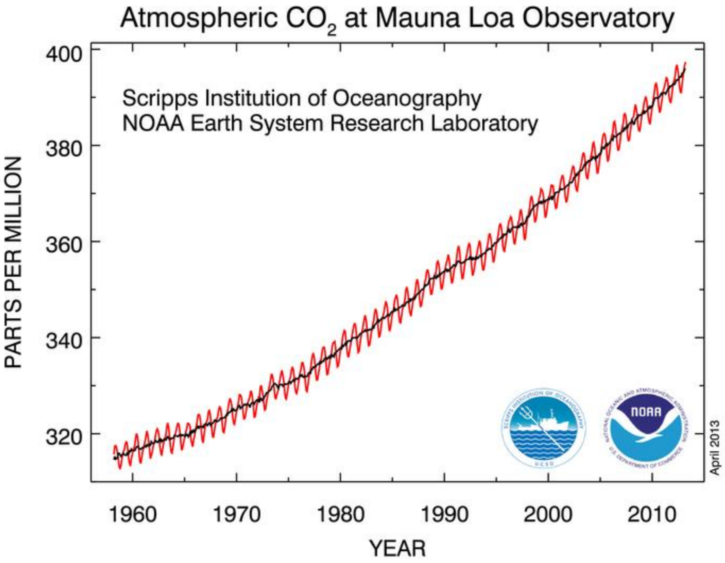
The slope of this trendline is the growth rate of CO_2 in the atmosphere.

$$\boldsymbol{k = 0.0452\ ppmCO_2/year}$$



b) From this website (http://www.esrl.noaa.gov/gmd/ccgg/trends/) or figure 4.14 in the textbook, you can obtain this graph showing the atmospheric CO_2 measurements made at Mauna Loa over the past 50 years.

Figure 3.12 summarizes first and zero order rate expressions. This particular figure appears to be linear like the zero order plot of concentration over time, not exponential like that for the first order reaction. Thus, the **data follows a zero reaction order**.



c) Use the zero-order reaction equation to estimate the atmospheric CO2 concentration in 1980, 2012, and 2050.

$$[C]=[C]_0-kt$$

$$[C]_{1980} = 315 + 0.0452\frac{ppmCO_2}{yr}(1980-1959) = \mathbf{316ppm}$$

$$[C]_{2012} = 315 + 0.0452\frac{ppmCO_2}{yr}(2012-1959) = \mathbf{317ppm}$$

$$[C]_{2050} = 315 + 0.0452\frac{ppmCO_2}{yr}(2050-1959) = \mathbf{319ppm}$$

3.39 If the rate constant for the degradation of biochemical oxygen demand (BOD) at 20°C is 0.23/day, what is the value of the BOD rate constant at 5°C and 25°C? Assume that Θ equals 1.1.

Solution:

Use equation 3.55 to determine the BOD rate constant at 5°C and 25°C.

$$k_{T_2} = k_{T_1} \times \Theta^{(T_2 - T_1)}$$

$$K_{25} = 0.23/day \times 1.1^{25-20} = \mathbf{0.37/}\boldsymbol{day}$$

$$K_5 = 0.23/day \times 1.1^{5-20} = \mathbf{0.055/}\boldsymbol{day}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

3.40 Excess nitrogen inputs to estuaries have been scientifically linked to poor water quality and degradation of ecosystem habitat. The nitrogen loading to Narragansett Bay was estimated to be 8,444,631 kg N/year and to Chesapeake Bay is 147,839,494 kg N/year. The watershed area for Narragansett Bay is 310,464 ha and for Chesapeake Bay is 10,951,074 ha. The nitrogen loading rates are estimated for Galveston Bay to be 16.5 kg N per ha per year, 26.9 kg N per ha per year for Tampa Bay, 49.0 kg N per ha per year for Massachusetts Bay, and 20.2 kg N per ha per year for Delaware Bay. (a) Rank the loading rates from lowest to highest for these six estuaries.

Solution:

You need to calculate the loading rates for Narragansett and Chesapeake Bay. These are simple unit conversions. The rest of the nitrogen loading rates can be found in the problem statement and ranked from lowest to highest in the final table below.

$$Narragansett\ Bay\ nitrogen\ loading\colon \frac{8{,}444{,}631\,\frac{kgN}{yr}}{310{,}464\ ha} = 27.2\,\frac{kgN}{ha\ yr}$$

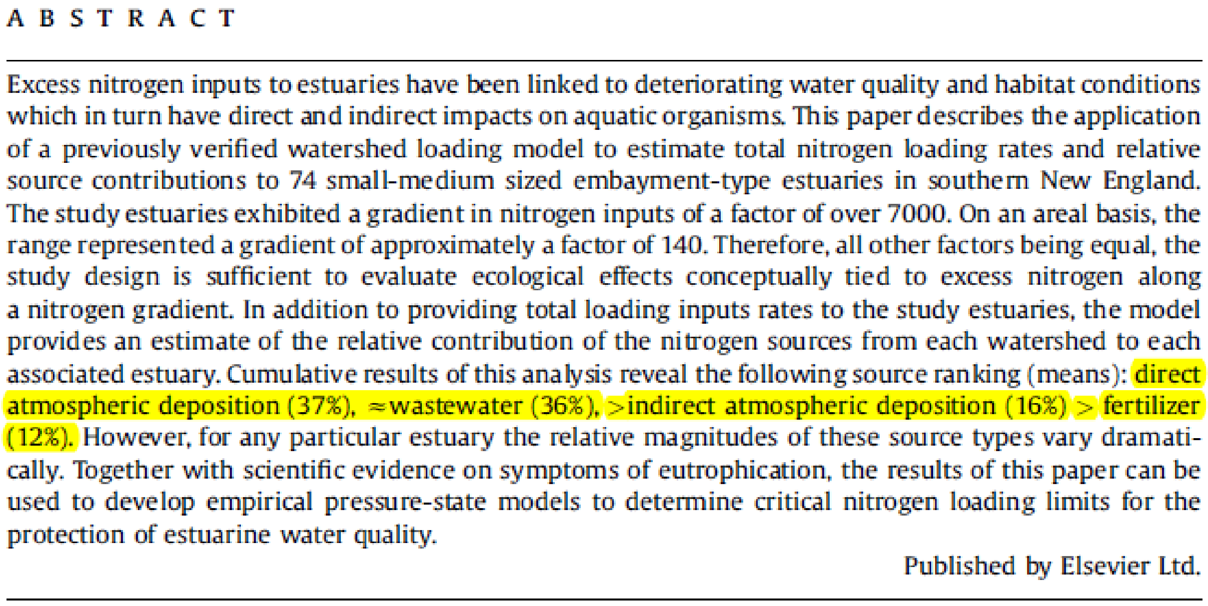
$$Chesapeake\ Bay\ nitrogen\ loading\colon \frac{147{,}839{,}949\,\frac{kgN}{yr}}{10{,}951{,}074\ ha} = 13.5\,\frac{kgN}{ha\ yr}$$

Ranking	**Estuary**	**Nitrogen Loading** $\frac{kgN}{ha\ yr}$
1	Chesapeake Bay	13.5
2	Galveston Bay	16.5
3	Delaware Bay	20.2
4	Tampa Bay	26.9
5	Narragansett Bay	27.2
6	Massachusetts Bay	49.0

3.41 Excess nitrogen inputs to estuaries have been scientifically linked to poor water quality and degradation of ecosystem habitat. Perform a library search for the paper title "Nitrogen inputs to seventy-four southern New England estuaries: Application of a watershed nitrogen model (J.S. Latimer and M.A. Charpentier, *Estuarine, Coastal and Shelf Science*, 89:125-136, 2010). Based on this article, what is the percent contribution of the following four sources of nitrogen to the watershed of the New England estuaries? i) Direct atmospheric deposition to the estuaries, ii) wastewater, iii) indirect atmospheric deposition to the watershed of the estuary, iv) fertilizer runoff from lawns, golf courses, and agriculture.

Solution:

After performing a library search for the paper, the percent contribution of nitrogen based on the source in New England estuaries is in the abstract:



ABSTRACT

Excess nitrogen inputs to estuaries have been linked to deteriorating water quality and habitat conditions which in turn have direct and indirect impacts on aquatic organisms. This paper describes the application of a previously verified watershed loading model to estimate total nitrogen loading rates and relative source contributions to 74 small-medium sized embayment-type estuaries in southern New England. The study estuaries exhibited a gradient in nitrogen inputs of a factor of over 7000. On an areal basis, the range represented a gradient of approximately a factor of 140. Therefore, all other factors being equal, the study design is sufficient to evaluate ecological effects conceptually tied to excess nitrogen along a nitrogen gradient. In addition to providing total loading inputs rates to the study estuaries, the model provides an estimate of the relative contribution of the nitrogen sources from each watershed to each associated estuary. Cumulative results of this analysis reveal the following source ranking (means): direct atmospheric deposition (37%), ≈wastewater (36%), >indirect atmospheric deposition (16%) > fertilizer (12%). However, for any particular estuary the relative magnitudes of these source types vary dramatically. Together with scientific evidence on symptoms of eutrophication, the results of this paper can be used to develop empirical pressure-state models to determine critical nitrogen loading limits for the protection of estuarine water quality.

Published by Elsevier Ltd.

i. Direct atmostpheric deposition (**37%**)
ii. Wastewater (**36%**)
iii. Indirect atmostpheric deposition to the watershed estuary (**16%**)
iv. Fertilizer runoff from lawns, golf courses and agriculture (**12%**)

Chapter 4. Physical Processes

4.1 A waste stabilization pond is used to treat a dilute municipal wastewater before the liquid is discharged into a river. The inflow to the pond has a flow rate of Q = 4,000 m^3/day and a BOD concentration of C_{in} = 25 mg/L. The volume of the pond is 20,000 m^3. The purpose of the pond is to allow time for the decay of BOD to occur before discharge into the environment. BOD decays in the pond with a first-order rate constant equal to 0.25/day. What is the BOD concentration at the outflow of the pond, in units of mg/L?

Solution:

$$\frac{dm}{dt} = m_{in} - m_{out} \pm m_{rxn}$$

$$0 = QC_{in} - QC_{out} - VkC_{out}$$

$$0 = 4000\frac{m^3}{day} \times 25\frac{mg}{L} - 4000\frac{m^3}{day} \times (C_{out}) - (20,000\ m^3) \times (0.25\frac{1}{day}) \times (C_{out})$$

$$\boxed{C_{out} = 11\frac{mg}{L}}$$

4.2 A mixture of two gas flows is used to calibrate an air pollution measurement instrument. The calibration system is shown in Figure 4-23. If the calibration gas concentration C_{cal} is 4.90 ppm_v, the calibration gas flow rate Q_{cal} is 0.010 L/min, and the total gas flow rate Q_{total} is 1.000 L/ min, what is the concentration of calibration gas after mixing (C_d)? Assume that the concentration upstream of the mixing point is zero.

Solution:

$$Q_{cal} \times C_{cal} = Q_{total} \times C_d$$

$$(1{,}000\ L/\min - 0.010\ \ L/\min)(0) + (0.010\ L/\min)(4.90\ ppm_v) = (1.000\ L/\min)\ (C_d)$$

$$C_d = 0.0494\ ppm_v = \mathbf{49.0\ ppb_v}$$

4.3 Consider a house into which radon is emitted through cracks in the basement. The total volume of the house is 650 m^3 (assume that the volume is well mixed throughout). The radon source emits 250 pCi/s (A picoCurie [pCi] is a unit proportional to the amount of radon gas and indicates the amount of radioactivity of the gas). Air inflow and outflow can be modeled as a flow of clean air into the house of 722 m^3/h and an equal air flow out. Radon can be considered to be conservative in this problem. (a) What is the retention time of the house? (b) What is the steady-state concentration of radon in the house (units of pCi/L)?

Solution:

a)

$$\theta = \frac{V}{Q} = \frac{650\ m^3}{722\,\frac{m^3}{h}} = \boxed{0.90\,h}$$

b)

$$0 = \frac{dm}{dt} = m_{in} - m_{out} \pm m_{rxn}$$
$$0 = QC_{in} + E - QC \pm 0$$
$$because\ m_{rxn} = 0 \quad and \quad QC_{in} = 0$$
$$C = \frac{E}{Q} = \frac{(250\,\frac{pCi}{s})(3600\,\frac{s}{h})}{722\,\frac{m^3}{h}} = 1.25\times10^3\,\frac{pCi}{m^3}\times\frac{m^3}{1{,}000L} = \boxed{1.25\,\frac{pCi}{L}}$$

4.4 You are in an old spy movie, and have been locked into a small room (volume 1,000 ft^3). You suddenly realize that a poison gas has just started entering the room through a ventilation duct. You are safe as long as the concentration is less than 100 mg/m^3. If the ventilation air flow rate in the room is 100 ft^3/min and the incoming gas concentration is 200 mg/m^3, how long do you have to escape?

Solution:

Assume the gas is conservative

$$V\frac{dC}{dt} = Q_{in}C_{in} - Q_{out}C_{out} \pm 0$$

integrate to solve for t

$$\frac{dC}{dt} = -\frac{Q}{V}(C - C_{in})$$

$$let \quad y = C - C_{in}$$

$$\text{then,} \quad \frac{dy}{dt} = \frac{dC}{dt} - \frac{d(C_{in})}{dt}$$

$$\mathrm{C_{in}}\ \text{is a constant,} \quad \text{therefore}\ \frac{dC_{in}}{dt} = 0$$

$$so\ \frac{dy}{dt} = \frac{dC}{dt}$$

now integrate

$$C = C_{in} \times (1 - e^{-\frac{Q}{V}(t)})$$

$$100\frac{mg}{m^3} = 200\frac{mg}{m^3} \times (1 - e^{-\frac{100\frac{ft^3}{\min}}{1000\ ft^3}(t)})$$

$$\boxed{t = 6.9\min}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.5 In the simplified depiction of an ice rink with an ice resurfacing machine operating (shown in Figure 4-24), points 1 and 3 represent the ventilation air intake and exhaust for the entire ice rink, and point 2 is the resurfacing machine's exhaust. Conditions at each point are (C indicates the concentration of carbon monoxide, CO): point 1: Q_1=3.0 m^3/s, C_1=10 mg/m^3; point 2: emission rate = 8 mg/s of nonreactive CO; point 3: Q_3, C_3 unknown. The ice rink volume (V) is 5.0 x 10^4 m^3. (a) Define a control volume as the interior of the ice rink. What is the mass flux of CO into the control volume, in units of mg/s*?* (b) Assume that the resurfacing machine has been operating for a very long time, and that the air within the ice rink is well mixed. What is the concentration of CO within the ice rink, in units of mg/m^3*?*

Solution:

a) From the Figure, note that CO enters the C.V. through the flow at point 1 and by direct emission at point 2. The Zamboni emission must be considered in a mass balance on CO in the rink air since it adds CO to the air.

$$m_{in} = (Q_1 C_1) + (Emission @ 2)$$

$$m_{in} = (3.0\frac{m^3}{s} \times 10\frac{mg}{m^3}) + 8\frac{mg}{s} = \boxed{38\frac{mg}{s}}$$

b) Assume steady state and m_{rxn}=0 (since CO non-reactive). Q_3 must equal Q_1 since there are no other airflows.

$$\frac{dm}{dt} = 0 = m_{in} - m_{out} + m_{rxn}$$

$$0 = 38\frac{mg}{s} - Q_3 C_3 \Rightarrow Q_3 C_3 = 38\frac{mg}{s}$$

$$C_3 = \frac{38\frac{mg}{s}}{Q_3} = \frac{38\frac{mg}{s}}{Q_1} = \frac{38\frac{mg}{s}}{3.0\frac{m^3}{s}} = \boxed{13\frac{mg}{m^3}}$$

4.6 Poorly treated municipal wastewater is discharged to a stream. The river flow rate upstream of the discharge point is $Q_{u/s} = 8.7$ m^3/s. The discharge occurs at a flow of $Q_d = 0.9$ m^3/s and has a BOD concentration of 50.0 mg/L. Assuming that the upstream BOD concentration is negligible. (a) What is the BOD concentration just downstream of the discharge point? (b) If the stream has a cross-sectional area of 10 m^2, what would the BOD concentration be 50 km downstream? (BOD is removed with a first-order decay rate constant equal to 0.20/day.)

Solution:

a)

$$Q_{u/s}\ (0) + Q_d\ (C_d) = Q_{total}\ C_{down}$$

$$0.9\frac{m^3}{s} \times 50\frac{mg}{L} = \left(8.7\frac{m^3}{s} + 0.9\frac{m^3}{s}\right) \times C_{down}$$

$$\boxed{C_{down} = 4.7\frac{mg}{L}}$$

b) first order decay

$$C_t = C_o e^{-kt}$$

$$t = \frac{\text{distance}}{\text{velocity}} = \frac{50,000\ m}{\dfrac{9.6\dfrac{m^3}{s}}{10\ m^2}} = 52,083\ s \times \frac{1\ day}{86,400\ s} = 0.6\ days$$

$$C_t = 4.7e^{-\left[\left(0.20\frac{1}{day}\right)(0.6\,days)\right]}$$

$$\boxed{C_t = 4.2\frac{mg}{L}}$$

4.7 As shown in Figure 4.25, during an air emission test, the inlet gas stream to a fabric filter is 100,000 actual ft^3/min (ACFM) and the particulate loading is 2 grains/actual cubic feet (ACF). The outlet gas stream from the fabric filter is 109,000 actual ft^3/min and the particulate loading is 0.025 grains/ actual ft^3/min. What is the maximum quantity of ash that will have to be removed per hour from the fabric filter hopper based on these test results? Assume that 7,000 grains of particles equals 1 lb. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

Solution:

Write a mass balance equation for the problem and then solve for the unknown quantity of ash.

$$\dot{m}_{out} = \dot{m}_{inlet} - \dot{m}_{ash}$$

$$Q_{out}C_{out} = Q_{inlet}C_{inlet} - Q_{ash}C_{ash}$$

$$Q_{ash}C_{ash} = Q_{inlet}C_{inlet} - Q_{out}C_{out}$$

$$Q_{ash}C_{ash} = \left(100{,}000\,\frac{ft^3}{min}\right)\left(2\,\frac{gr}{ft^3}\right) - \left(109{,}000\,\frac{ft^3}{min}\right)\left(0.025\,\frac{gr}{ft^3}\right) = 197275\,\frac{gr}{min}$$

$$197275\,\frac{gr}{min} \times \frac{1\,lb}{7{,}000\,gr} = 28.18\,\frac{lb}{min} \times \frac{60\,min}{hr} = \mathbf{1691\,\frac{lb}{hr}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.8 Two towns, located directly across from each other, operate municipal wastewater-treatment plants that are situated along a river. The river flow is 50 million gallons per day (50 MGD). Coliform counts are used as a measure to determine a water's ability to transmit disease to humans. The coliform count in the river upstream of the two treatment plants is 3 coliforms/l00 mL. Town 1 discharges 3 MGD of wastewater with a coliform count of 50 coliforms/100 mL, and town 2 discharges 10 MGD of wastewater with a coliform count of 20 coliforms/100 mL. Assume that the state requires that the downstream coliform count not exceed 5 coliforms/ 100 mL. (a) Is the state water-quality standard being met downstream? (Assume that coliforms do not die by the time they are measured downstream.) (b) If the state standard downstream is not met, the state has informed town 1 that they must treat their sewage further so the downstream standard is met. Use a mass-balance approach to show that the state's request is unfeasible.

Solution:

a) The concentration of coliforms downstream equals:

$$\frac{(3\ col/100\ mL \times 50\times10^6\ gpd) + (50\ col/100\ mL \times 3\times10^6\ gpd) + (20\ col/100\ mL \times 10\times10^6\ gpd)}{[50\times10^6\ gpd + 3\times10^6\ gpd + 10\times10^6\ gpd]}$$

$$= \boxed{7.9\ col/100\ mL}$$

<u>No</u>, the state water quality is not being met downstream since 7.9 > 5.0.

b)

$$\frac{(3\ col/100\ mL \times 50\times10^6\ gpd) + (X\ \ col/100\ mL \times 3\times10^6\ gpd) + (20\ col/100\ mL \times 10\times10^6\ gpd)}{50\times10^6\ gpd + 3\times10^6\ gpd + 10\times10^6\ gpd}$$

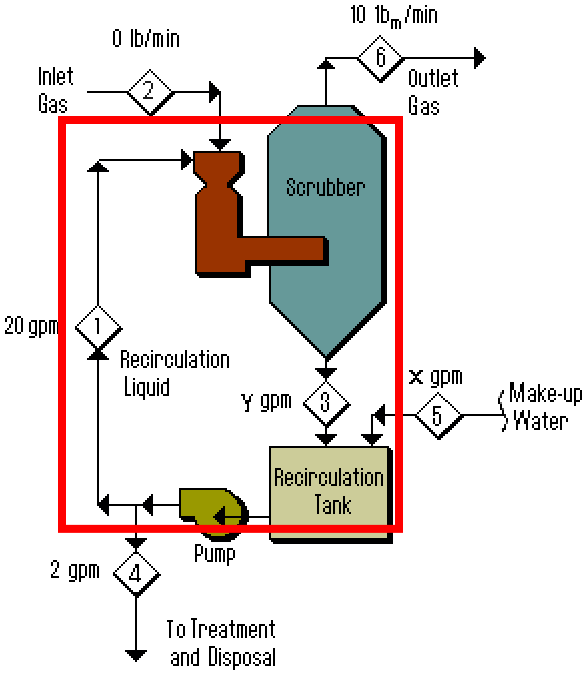
$$= 5.0\ col/100\ mL\ (or\ less)$$

$$X = \boxed{-12\ col/100\ mL}$$

<u>The combined coliform levels from the upstream flow and town 2 exceed the limit no matter what town 1 does.</u> Note that this town has an impossible task. It would have to discharge treated wastewater with a negative number of coliforms to allow the state to meet its downstream water quality standard.

4.9 How much water must be continually added to the wet scrubber shown in Figure 4.26 in order to keep the unit running? Each of the streams is identified by a number located in a diamond symbol. Stream 1 is the recirculation liquid flow stream back to the scrubber and it is 20 gallons per minute (gpm). The liquid being withdrawn for treatment and disposal (stream 4) is 2 gpm. Assume that inlet gas stream (number 2) is completely dry and that the outlet stream (number 6) has 10 lb_m/min of moisture evaporated in the scrubber. The water being added to the scrubber is stream number 5. 1 gallon of water weighs 8.34 lbs. (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

Solution:



First, draw the system boundary. The problem asks for the water that must be continually added to the wet scrubber to keep it running so what matters is what is added or taken away from the system, not the recirculation liquid which should remain constant.

Next, write a mass balance equation for the wet scrubber process.

$$Qin = Qout$$

$$Q_5 + Q_2 = Q_4 + Q_6$$

From the figure, $Q_2 = 0\ \frac{lb}{min}$. Solve for Q_5 which is the amount of water added to the wet scrubber to keep it running (make-up water in the figure):

$$Q_5 = Q_4 + Q_6$$

$$Q_5 = 2\ gpm + 10\ \frac{lbm}{min} \times \frac{1\ gallon}{8.34\ lbs}$$

$$Q_5 = \mathbf{3.2\ gpm}$$

4.10 In the winter, a stream flows at 10 m^3/s and receives discharge from a pipe that contains road runoff. The pipe has a flow of 5 m^3/s. The stream's chloride concentration just upstream of the pipe's discharge is 12 mg/L, and the runoff pipe's discharge has a chloride concentration of 40 mg/L. Chloride is a conservative substance. (a) Does wintertime salt usage on the road elevate the downstream chloride concentration above 20 mg/L? (b) What is the maximum daily mass of chloride (metric tons/day) that can be discharged through the road runoff pipe without exceeding the water quality standard?

Solution:

a) The downstream chloride concentration equals:

$$\frac{(12\,\frac{mg}{L}\times 10\,\frac{m^3}{s})+(40\,\frac{mg}{L}\times 5\,\frac{m^3}{s})}{10\,\frac{m^3}{s}+5\,\frac{m^3}{s}}=\boxed{21\,\frac{mg}{L}}$$

<u>Yes, this is above the 20 mg/L standard.</u>

b)

$$\frac{(12\,\frac{mg}{L}\times 10\,\frac{m^3}{s})+(X\,\frac{mg}{L}\times 5\,\frac{m^3}{s})}{10\,\frac{m^3}{s}+5\,\frac{m^3}{s}}=20\,\frac{mg}{L}\qquad\rightarrow\qquad X=36\,\frac{mg}{L}$$

$$Max\ daily\ mass=\frac{36\ mg}{L}\times\frac{5\ m^3}{s}\times\frac{86,400\ s}{day}\times\frac{1,000\ L}{1m^3}\times\frac{1\ g}{10^3\,mg}\times\frac{1\ ton}{10^6\ g}=\boxed{16\ \frac{tons}{day}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.11 A wet scrubbing system has three separate inlet streams (Figure 4.27). The mass flow rates in these inlet streams are 100 lb_m/min, 58 lb_m/min, and 74 lb_m/min. The water spray into the scrubber is 60 lb_m/min and some of this spray evaporates and leaves with the gas stream. The water stream leaving the scrubber is 49 lb_m/min. What is the mass of the gas stream leaving the scrubber? (problem from EPA Air Pollution Training Institute, http://www.epa.gov/apti/bces/)

Solution:

Write a mass balance equation for the wet scrubbing system then solve for the outlet gas stream:

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

$$\dot{m}_{inlet\ gas\ streams} + \dot{m}_{water} = \dot{m}_{outlet\ liquid\ stream} + \dot{m}_{outlet\ gas\ stream}$$

$$\dot{m}_{outlet\ gas\ stream} = \dot{m}_{inlet\ gas\ streams} + \dot{m}_{water} - \dot{m}_{outlet\ liquid\ stream}$$

$$\dot{m}_{outlet\ gas\ stream} = \left(100\ \frac{lb_m}{min} + 58\ \frac{lb_m}{min} + 74\ \frac{lb_m}{min}\right) + 60\ \frac{lb_m}{min} - 49\ \frac{lb_m}{min}$$

$$\dot{m}_{outlet\ gas\ stream} = \mathbf{243\ \frac{lb_m}{min}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
*Environmental Engineering: Fundamentals, Sustainability, Design,*2nd *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.12 Calculate the hydraulic residence times (the retention time) for Lake Superior and for Lake Erie using data in Table 4.3.

Solution:

Using information provided in Table 4.3.

$$\theta = \frac{V}{Q} \Rightarrow (for\ Superior) = \frac{12,000 \times 10^9 m^3}{67 \times 10^9 \frac{m^3}{yr}} = \boxed{180\ yr}$$

$$(for\ Erie) = \frac{468 \times 10^9 m^3}{182 \times 10^9 \frac{m^3}{yr}} = \boxed{2.6\ yr}$$

4.13 The total flow at a wastewater-treatment plant is 600 m^3/day. Two biological aeration basins are used to remove BOD from the wastewater and are operated in parallel. They each have a volume of 25,000 L. In hours, what is the aeration period of each tank?

Solution:

The aeration period equals the hydraulic residence time. Therefore the aeration period is

$$\frac{V}{Q}=\frac{2\times(25{,}000\ L)\left(\dfrac{m^3}{1{,}000\ L}\right)}{600\ \dfrac{m^3}{day}}\times\frac{24\ h}{day}=\boxed{2\ h}$$

4.14 You are designing a reactor that uses chlorine in a PFR or CMFR to destroy pathogens in water. A minimum contact time of 30 min is required to reduce the pathogen concentration from 100 pathogens/L to below 1 pathogen/L through a first-order decay process. You plan on treating water at a rate of 1,000 gal/min. (a) What is the first-order decay rate constant? (b) What is the minimum size (in gallons) of the reactor required for a plug flow reactor? (c) What size (in gallons) of CMFR would be required to reach the same outlet concentration? (d) Which type of reactor would you select if your treatment objective stated that "no discharge can ever be greater than 1 pathogen/L"? Explain your reasoning. (e) If the desired chlorine residual in the treated water after it leaves the reactor is 0.20 mg/L and the chlorine demand used during treatment is 0.15 mg/L, what must be the daily mass of chlorine added to the reactor (in grams)?

Solution:

For this PFR, θ = 30 min, C_{in}=100 pathogens/L, C_{out}=1 pathogen/L, and Q = 1,000gal/min.

a) For first-order decay in a plug flow reactor

$$\frac{C_t}{C_o} = e^{-kt}$$

$$\frac{1\ pathogen/L}{100\ pathogens/L} = e^{-k(30\,\text{min})} \qquad \Rightarrow \qquad \boxed{k = 0.15/\text{min}}$$

b) The hydraulic residence time equals 30 min; therefore,

$$\theta = \frac{\text{V}}{\text{Q}} = 30\,\text{min} = \frac{\text{V}}{1{,}000\ \text{gal}/\text{min}} \Rightarrow \boxed{\text{V} = 30{,}000\ \text{gal}}$$

c) For a CMFR

$$C_{out} = \frac{C_{in}}{1 + \dfrac{kV}{Q}}$$

$$1 pathogen/L = \frac{100\,pathogens/L}{1 + \dfrac{0.15/\text{min} \times V}{1{,}000 gal/\text{min}}} \Rightarrow \boxed{V = 660{,}000 gal}$$

d) The CMFR should be better handling if your concern is handling variable loadings.

e) The chlorine residual=0.20mg/L and the chlorine demand=0.15mg/L. Therefore, the total chlorine added equals,

$$(0.20\frac{mg}{L} + 0.15\frac{mg}{L}) \times \frac{1{,}000\ gal}{\text{min}} \times \frac{3.78L}{gal} \times \frac{g}{10^3 mg} \times \frac{60\,\text{min}}{h} \times \frac{24h}{day} = \boxed{1.9 \times 10^3\ \frac{g}{day}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.15 The concentration of BOD in a river just downstream of a wastewater treatment plant's effluent pipe is 75 mg/L. If the BOD is destroyed through a first-order reaction with a rate constant equal to 0.05/day, what is the BOD concentration 50 km downstream? The velocity of the river is 15 km/day.

Solution:

$$C_t = C_o \times e^{-kt}$$

$$t = \frac{V}{Q} = \frac{\text{distance}}{\text{velocity}} = \frac{50km}{15\frac{km}{d}} = 3.3\ days$$

$$C_t = 75\frac{mg}{L} \times e^{-(0.05/day)(3.3days)} = \boxed{64\frac{mg}{L}}$$

4.16 A 1.0×10^6 gallon reactor is used in a water reclamation plant. The influent concentration is 100 mg/L, the effluent concentration is 25 mg/L, and the flow rate through the reactor is 500 gal/min. (a) What is the first-order rate constant for decay of BOD in the reactor? Assume the reactor can be modeled as a CMFR. Report your answer in units per hour. (b) Assume the reactor should be modeled as a PFR with first-order decay, *not* as a CMFR. In that case, what must be the first-order decay rate constant within the PFR reactor? (c) It has been determined that the outlet concentration is too high, so the residence time in the reactor must be doubled. Assuming all other variables remain constant, what must be the volume of the new CMFR?

Solution:

a) $V = 1.0 \times 10^6$ gal, $C_{in} = 100$ mg/L, $C_{out} = 25$ mg/L, Q = 500 gal/min. The mass balance on BOD in the CMFR is given as follows, assuming steady state conditions.

$$\frac{dm}{dt} = m_{in} - m_{out} - m_{rxn}$$

$$0 = QC_{in} - QC_{out} - VkC$$

$$C = C_{out}$$

$$k = \frac{QC_{in} - QC_{out}}{VC_{out}} = \frac{Q\,(C_{in} - C_{out})}{VC_{out}} = \frac{(500\ gal/\min)(100\ mg/L - 25mg/L)}{(1.0\times10^6\ gal)(25\ mg/L)} \times 60\,\frac{\min}{h}$$

$$\boxed{k = 0.090/h}$$

b)

$$C_t = C_{in} \times e^{-kt}$$

$$\frac{dC}{dt} = -k\,C$$

$$C_{out} = C_{in} \times e^{-k\theta}$$

$$\theta = \frac{V}{Q} = \frac{1.0\times10^6\ gal}{500\ gal/\min} = 2\times10^3 \min$$

$$25mg/L = 100mg/L \times e^{-k(2\times10^3 \min)}$$

$$k = 6.93\times10^{-4}/\min \times 60\ \min/h = \boxed{0.042/h}$$

c)

θ = V/Q, so if θ doubles and Q remains constant, V must double.

$2 \times (1.0 \times 10^6\ \text{gal}) = \boxed{2 \times 10^6\ \text{gal}}$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.17 You are to design a reactor for removal of reduced iron (Fe^{2+}) from water. The influent water has an iron concentration of 10 mg/L and this must be reduced to 0.1 mg/L. The water has a pH of 6.5 and the plan is to oxidize the iron to Fe^{3+} using pure oxygen gas, then remove the resulting particulate matter in a sedimentation basin. It has been found that the reduction in Fe^{2+} concentration over time equals $K_{apparent} \times [Fe^{2+}]$ where $K_{apparent}$ equals: $8 \times 10^{13} \times$[partial pressure of 0_2] $\times Kw^2/[H^+]^2$. The units of $K_{apparent}$ determined from this expression are min^{-1} and the partial pressure of oxygen is 0.21 atm and the dissociation constant for water, K_w, equals 10^{-14}. Determine the volume (m^3) of a plug flow reactor to treat 1 MGD of water.

Solution:

First, solve for Kapp from the equation given in the problem:

$$Kapp = 8 * 10^{13} \times [partial\ pressure\ of\ O_2] \times \frac{{K_w}^2}{[H^+]^2}$$

$$Kapp = 8 * 10^{13} \times [0.21 atm] \times \frac{{10^{-14}}^2}{[10^{-6.5}]^2} = 0.0168/min$$

Use equation 4.18 to solve for t:

$$\frac{C_t}{C_0} = \exp(-kt)$$

$$t = \frac{\ln\left(\frac{Ct}{Co}\right)}{-k} = \frac{\ln\left(\frac{0.1\ mg/L}{10\ mg/L}\right)}{-0.0168} = 274\ min$$

Remember that residence time is equal to volume over flow rate, thus we can solve for volume:

$$t = \frac{V}{Q} \therefore V = Qt = 1 \times 10^6 \frac{gallons}{day} \times \frac{1\ day}{24\ hrs} \times \frac{1hr}{60\ min} \times 274\ min = 190{,}278\ gallons$$

Convert this volume to cubic meters for the final answer:

$$V = 190{,}278\ gallons \times \frac{1\ m^3}{264.172\ gallons} = \mathbf{720\ m^3}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.18 How many watts of power would it take to heat 1 L of water (weighing 1.0 kg) by 10°C in 1.0 h? Assume that no heat losses occur, so all of the energy expended goes into heating the water.

Solution:

Perform an energy balance using the 1 liter volume of water as the control volume. dE/dt is given by the required rate of heating, -E_{out} is assumed to be zero, E_{in} is the required energy flux, or power.

$$\frac{dE}{dt} = E_{in} - E_{out}$$

$$\frac{\Delta E}{\Delta T} = E_{in}$$

$$\frac{c \times mass \times \Delta T}{\Delta\ time} = E_{in}$$

$$\frac{\frac{4{,}184\ J}{Kg-^{o}\ C} \times (1\ L \times 1\frac{kg}{L}) \times 10^{o}C}{1\ hr \times 3{,}600\ \frac{s}{h}} = E_{in} = 11.6\frac{J}{s} \approx \boxed{12\ W}$$

4.19 Your house has a 40 gal. electric water heater that heats water to a temperature of 110°F. Several friends are visiting you over the weekend and they are taking consecutive showers. Assume that at the maximum heating level, the heater uses 5 kW of electricity. The water use rate is a continuous 2 gpm with the new water saving showerhead you recently installed. Your very old showerhead had used 5 gpm! You replaced the showerhead because you learned that heating water was the second highest energy use in your home. What is the temperature of the water exiting the heater (a) using the old showerhead and (b) the new efficient showerhead? Assume the system is at steady state so all of the energy used heats the water.

Solution:

a) Use the energy balance equation, 4.22, to solve this problem:

$$\frac{dE}{dt} = 0 = \dot{E}_{in} - \dot{E}_{out}$$

For the energy expression, use equation 4.21:

$$\dot{E}_{in} = \dot{m}_{H_2O} \times C \times T_{out}$$

$$0 = \left(\dot{m}_{H_2O} \times C \times T_{in} + 5kW\right) - \left(\dot{m}_{H_2O} \times C \times T_{out}\right)$$

$$0 = \left(5\,\frac{gal\ H_2O}{min} \times 3.785\frac{L}{gal} \times 1.0\frac{kg}{L} \times 4{,}184\ \frac{J}{kg\ °C} + 5kW\right)(T_{in} - T_{out}) + 5000\frac{J}{s} \times \frac{60s}{min}$$

$$0 = 7.91 * 10^4\ \frac{J}{min\ °C}\ (T_{in} - T_{out})\ + 3.0 * 10^5\frac{J}{min}$$

We must convert 110°F to $°C$:

$$\left(\frac{9}{5}\right)°C + 32 = °F$$

$$°C = \left(\frac{5}{9}\right)(110 - 32) = 43.3\ °C$$

Now solve the energy balance equation you derived for T_{out}:

$$T_{out} = \frac{3.0 * 10^5 J/min}{7.91 * 10^4 J/\min °C} + \ T_{in} = 3.79℃ + 43.3℃ = \mathbf{47}℃$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
*Environmental Engineering: Fundamentals, Sustainability, Design,*2*nd Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

b) The same method is used to solve for the old shower head as the more efficient showerhead except the water use rate is 2 gpm instead of 5 gpm:

$$0 = \left(2\,\frac{gal\ H_2O}{min} \times 3.785\frac{L}{gal} \times 1.0\frac{kg}{L} \times 4{,}184\ \frac{J}{kg\ °C} + 5kW\right)(T_{in} - T_{out}) + 5000\frac{J}{s} \times \frac{60s}{min}$$

$$0 = 3.16 * 10^4\ \frac{J}{min\ °C}\ (T_{in} - T_{out})\ + 3.0 * 10^5\frac{J}{min}$$

$$T_{out} = \frac{3.0 * 10^5 J/min}{3.16 * 10^4 J/\min °C} + \ T_{in} = 9.49℃ + 43.3℃ = \mathbf{53}℃$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

4.20 (a) Determine the heat loss (in Btu / °F-day and Btu/degree-day) through a 120 sq. ft. insulated wall described in the following table. (b) Determine the heat loss through the same wall when a 3 ft. by 7 ft. door (R factor = 4.4) is inserted into the wall.

Component of Wall	**R Factor**
2 in. Styrofoam board insulation on outside of wall under siding	10
Old cedar log wall	20
Fiberglass insulation on inside of wall	11
½ in. drywall on inside of wall	0.45
Inside air film along inside of wall	0.68
Outside air film along outside of wall	0.17

Solution:

a) The combined R value for the insulated wall is

$$10 + 20 + 11 + 0.45 + 0.68 + 0.17 = 42\,\frac{Btu}{ft^2 - °\mathrm{F} - hr}$$

$$Heat\ loss = \frac{1}{R} \times A \times t$$

$$Heat\ loss = \frac{1}{42}\,\frac{Btu}{ft^2 - °\mathrm{F} - hr} \times 120\ ft^2 \times 24\,\frac{hr}{day} = \mathbf{68}\,\frac{\mathbf{Btu}}{°\mathrm{F} - \mathbf{day}} = \mathbf{68}\,\frac{\mathbf{Btu}}{\mathbf{degree\ day}}$$

b) $Wall\ area = 120\ ft^2 - (3\ ft\ \times 7\ ft) = 99\ ft^2$

$$Heat\ loss = \left(\frac{1}{42.3}\frac{Btu}{ft^2 - °\mathrm{F} - hr} \times 99\ ft^2 \times \frac{24\ h}{day}\right) + (\frac{1}{4.4}\frac{Btu}{ft^2 - °\mathrm{F} - hr} \times 21 ft^2 \times \frac{24\ h}{day})$$

$$Heat\ loss = \mathbf{171}\frac{\boldsymbol{Btu}}{°\mathrm{F} - \boldsymbol{day}} = \mathbf{171}\frac{\boldsymbol{Btu}}{\boldsymbol{degree\ day}}$$

4.21 Look up (a) the total degree-days for heating and (b) the total degree-days for cooling for your university town or city (or hometown).

Solution:

Students' responses will vary.

The following two URLs provide a method to look up degree day by city and/or zipcode
http://www.cpc.noaa.gov/products/analysis_monitoring/cdus/degree_days/ &
http://www.degreedays.net/

4.22 In Section 14.7, we worked out a problem where the combined heat loss from a hypothetical 3,000 sq. ft. building was 1,053 Btu/degree-days. Determine the total energy requirements (in Btu) to heat that hypothetical building for the locations in the following table.

Location	**Heating Degree-Days**
Anchorage, AK.	541
Winslow, AZ.	70
Yuma, AZ.	0
Rochester, NY.	237
Pittsburgh, PA.	106
Rapid City, SD.	193

Solution:

Once the total heat loss (in units of Btu/^{o}F-day) is determined, that value can be multiplied by the total number of degree days for heating in a particular location for the period of time of interest (day, month, year).

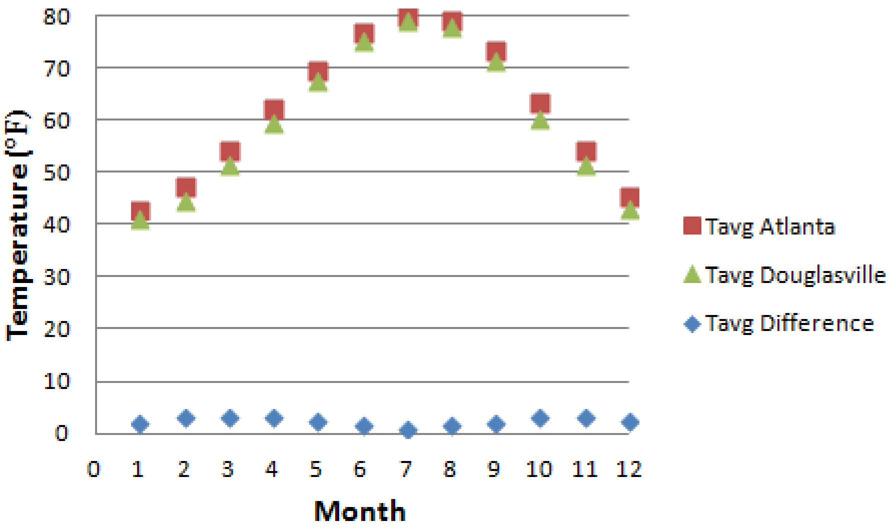
Location	Heating degree days in May 2007	Total energy requirements Btu
Anchorage, Alaska	541	569,673
Winslow, Arizona	70	73,710
Yuma, Arizona	0	0
Rochester, New York	237	249,561
Pittsburgh, Pennsylvania	106	111,618
Rapid City, South Dakota	193	203,229

4.23 Go to the Weather Channel Web site (www .weather.com), and look up the monthly average temperature for a major metropolitan area and nearby rural area anywhere in the world over a 12 mo. period. Use the data you looked up to estimate the magnitude of the urban heat island effect for that city. Graph your data in two figures, and determine the temperature differences in each month.

Solution:

Students' answers may vary depending on the areas they selected. Though the problem asks for the data to be graphed in two figures, it can also be displayed in one as in this solution. Below is a graph of Atlanta, Georgia for the major metropolitan area and Douglasville, Georgia, a nearby rural area. According to section 4.23, the urban heat island is the difference in temperature between urban (u) and rural (r) monitoring stations (the value show is averaged over the 12 month period):

$$\Delta T_{u-r} = 62.6 - 60.3 = \mathbf{2.3}°\text{F}$$



4.24 Identify an urban core of a major metropolitan area that you are familiar with or that is close to your college or university. Calculate the magnitude of the maximum urban heat island impact in the urban core. Provide some detailed alternatives for reducing the urban heat island in this core area, and relate them to specific items in the energy balance performed on the urban canopy.

Solution:

Students' responses will vary. They will need to select an urban core and make some measurements or estimations of the canyon geometry (height of the buildings and width of the street) to determine the maximum change in temperature using Equation 4.33 below.

$$\text{maximum}\,\Delta T_{\text{u-r}} = 7.45 + 3.97 \ln\left(\frac{H}{W}\right)$$

For the second part of the solution, students should review Table 4.6, and update the column on the right for their specific situation.

Features of Urban Environment Related to Terms in the Heat Island Energy Balance Designing and modifying an urban environment to modify climate processes requires an understanding of this balance.

Energy Balance Term	**Feature of an Urban Environment That Alters the Energy Balance Term**	**Engineering Modifications That Reduce Intensity of Urban Heat Island**
Net shortwave and longwave radiation, Q^*	Canyon geometry of the street and building	Canyon geometry influences the way shortwave radiation enters and is absorbed by the built environment and the way longwave radiation is reflected out of the urban canopy.
Heat added by humans (Q_{human})	Emission of waste heat from buildings, factories, and vehicles	Though this is a small term in the overall energy balance, buildings can be designed to reduce the need for mechanical cooling. Cities can be planned so they are dependent on mechanical engines to move people and goods.
Sensible heat flux, Q_{H}	Types of engineering materials	Increasing the surface albedo of paints and roofing materials will limit the surface–air sensible heat flux. Albedo is a measure of the amount of solar energy reflected by the surface.
		Narrow canyon geometry can result in reduced air flow, which decreases the effect of Q_{H}.

Energy Balance Term	**Feature of an Urban Environment That Alters the Energy Balance Term**	**Engineering Modifications That Reduce Intensity of Urban Heat Island**
Latent heat flux, Q_E	Types of engineering materials and storm water management	The latent heat flux out of the system is the result of water evaporation. The energy is carried out in the form of water vapor (in the form of the higher energy in the water molecules in the vapor form). The heat is taken from the vegetation or water. This is the same process as sweat, where one's body is cooled with the heat going away in the form of latent heat.
		Impervious and nonvegetated surfaces hinder evaporative cooling (unless water is sprinkled on them). Low-impact development recognizes that leaving some standing water on the surface is not bad and vegetation such as green roofs and trees are an important feature of the urban built environment.
Increased storage of heat	Different abilities to store heat in different types of construction materials	The thermal conductivity of asphalt and concrete are similar (1.94 versus $2.11 \text{J}/\text{m}^3\text{-K}$, respectively). The thermal admittance of asphalt and concrete results in increased storage of heat.
		Urban surfaces heat up faster than natural and impervious surfaces that retain water.
		Built-environment materials have a high ability to store and release heat. Paved surfaces are thick and in contact with an underlying ground surface. Buildings, though, have a thinner skin that separates indoor and outdoor air.
		Surfaces with higher albedo will reduce the stored heat.

4.25 Assume a small downtown area has two 12 ft. travel lanes with 6 ft. sidewalks on each side. This is all surrounded by buildings that are 25 ft. tall. What is the maximum urban heat island impact that can be expected?

Solution:

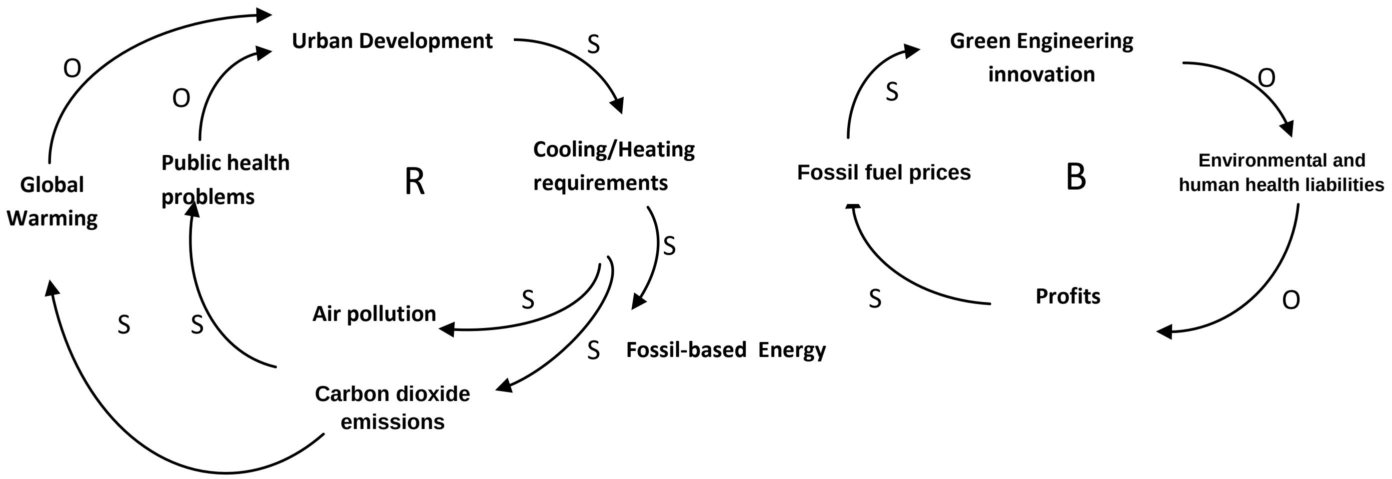
Total street width =2 x 12 ft + 2 x 6 ft = 36 ft

$$\text{Maximum } \Delta T_{u\text{-}r} \text{ (in } ^{o}\text{C)} = 7.45 + 3.97 * \ln(H/W)$$
$$= 7.45 + 3.97 * \ln(25/36) = \boxed{6\ ^{o}\text{C}}$$

4.26 Using the systems thinking approach, draw a systems diagram for urban heat islands, including feedback mechanisms for increased energy demands for cooling and refrigeration, increased air pollution from these increased energy demands, and other effects such as global warming and public health.

Solution:

Students' responses will vary, the following is an example.



4.27 The concentration of a pollutant along a quiescent water-containing tube is shown in Figure 4.28. The diffusion coefficient for this pollutant in water is equal to 10^{-5} cm^2/s. (a) What is the initial pollutant flux density in the *x*-direction at the following locations: *x* = 0.5, 1.5, 2.5, 3.5, and 4.5? (b) If the diameter of the tube is 3 cm, what is the initial flux of pollutant mass in the *x*-direction at the same locations? (c) As time passes, this diffusive flux will change the shape of the concentration profile. Draw a sketch of concentration in the tube versus *x*-axis location showing what the shape at a later time might look like. (It is not necessary to do any calculations to draw this sketch.) Assume that the concentration at *x* = 0 is held at 3 mg/L and the concentration at *x* = 6 is held at 1 mg/L. (d) Describe, in one paragraph, why the concentration profile changed in the way that you sketched in your solution to part (c).

Solution:

a) By looking at Figure 4.21, there is no change in concentration from x=0 to x=1, and no change from x=3 to x=6. This means that the slope = 0 so dC/dx = 0, so J = 0.

At x = 0.5, 3.5, 4.5 cm, the initial pollutant flux density, J = 0
At x = 1.5 and 2.5 cm,

$$x = 1.5cm \Rightarrow J = -D\frac{dC}{dx} = -(10^{-5}\ \frac{cm^2}{s}) \times \frac{2.5\frac{mg}{L} - 3.0\frac{mg}{L}}{1.5\ cm - 1.0\ cm} \times \frac{L}{1{,}000\ cm^3} = 10^{-8}\ \frac{mg}{cm^2 - s}$$

Because the slope (dC/dx) is constant between x = 1 and x = 3, the flux density must also be constant in that region. Thus, at x = 1.5 cm and 2.5 cm, J = 10^{-8} mg/cm^2-s.
(Note that you could also calculate J at every x-location which would yield the same results)

b) If the tube diameter = 3 cm, the initial mass flux at the same locations is:

m = J x A where A = π $d^2/4$ (A = 7.07 cm^2)

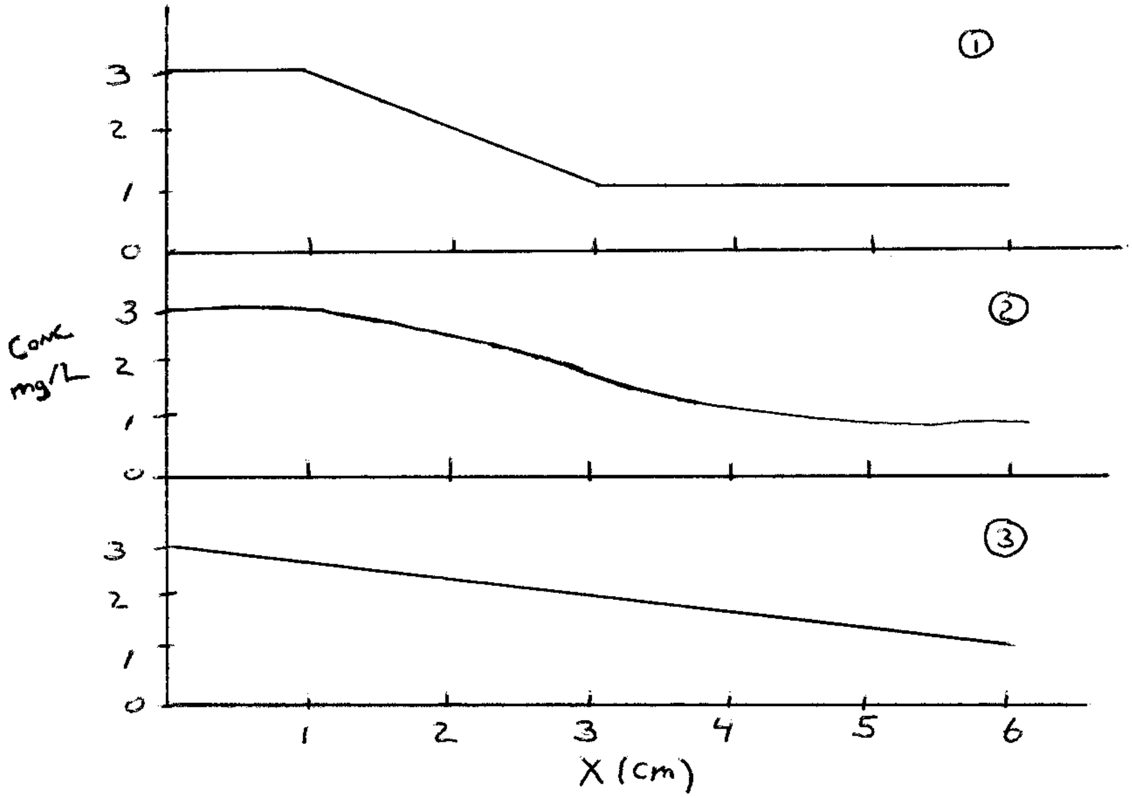
Because J = 0 at x = 0.5, 3.5, and 4.5 cm, then m = 0
Because J = 10^{-8} mg/cm^2-s at x = 1.5 and 2.5 cm,

$$m = J \times A = 10^{-8}\ \frac{mg}{cm^2 - s} \times 7.07\ cm^2 = 7.1 \times 10^{-8}\ \frac{mg}{s}$$

m = 7.1 x 10^{-8} mg/s at x = 1.5 and 2.5 cm

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2^{nd} *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

c) The process occurs over 3 steps. Graph 1 is what occurs initially. Graph 2 shows that as diffusion begins, sharp corners get rounded because mass moves from higher concentration regions to lower concentration regions. Graph 3 shows the eventual profile of the graph.



d) The concentration profile in part (c) is changing due to the random motion of the molecules. The chemical is attempting to reach equilibrium through high concentration areas moving to areas with less concentration.

4.28 The tube in problem 4.22 is connected to a source of flowing water, and water is passed through the tube at a rate of 100 cm^3/s. If the pollutant concentration in the water is constant at 2 mg/L, find: (a) the mass flux density of the pollutant through the tube due to advection; (b) the total mass flux through the tube due to advection.

Solution:

a) The problem is requesting J (flux density) which equals C x v

$$J = C \times v = 2\frac{mg}{L} \times \frac{100\frac{cm^3}{s}}{\pi(\frac{3\ cm}{2})^2} \times \frac{mL}{cm^3} \times \frac{L}{1,000\ mL} = \boxed{0.028\frac{mg}{cm^2 - s}}$$

b) The total mass flux, m = J x A

$$m = J \times A = C \times v \times A = C \times Q$$

$$= 2\frac{mg}{L} \times 100\frac{cm^3}{s} \times \frac{mL}{cm^3} \times \frac{L}{1,000\ mL} = \boxed{0.20\frac{mg}{s}}$$

4.29 The following conditions exist downstream of the point where treated effluent from an advanced wastewater treatment facility has removed the phosphorous concentration to 1 mg P/L. The river characteristics just downstream of the discharge point are cross sectional area equal to 20 m^2 and a volumetric flow rate of 17 m^3/s. Determine the average flux density of phosphorus downstream of the discharge point.

Solution:

Use equation 4.35 to solve this problem which is similar to 4.12:

$J = C \times v$

First, solve for the average river velocity:

$$v = \frac{Q}{A} = \frac{17\ m^3/s}{20\ m^2} = 0.85\frac{m}{s}$$

Now you can solve for the average flux density of phosphorus:

$$J = \left[1\frac{mg}{L} \times \frac{10^3 L}{m^3}\right] \times 0.85\frac{m}{s} = \mathbf{850\frac{mg}{m^2 - s}\ or\ 0.850\frac{g}{m^2 - s}}$$

4.30 Calculate the settling velocity of a particle with 100 μm diameter and a specific gravity of 2.4 in 10°C water ($\mu = 1.308 \times 10^{-3}$ N-s/m^2 and the density of water equals 999.7 kg/m^3).

Solution:

Use the expression for specific gravity, to calculate the density of the particle:

$$SG = \frac{\rho_{particle}}{\rho_{H_2O}}$$

$$\rho_{particle} = \rho_{H_2O} \times SG = 999.7 \frac{kg}{m^3} \times 2.4 = 2399\ kg/m^3$$

Use Stoke's Law, equation 4.54, to calculate the setting velocity of the particle:

$$v_s = \frac{g(\rho_P - \rho_f)}{18\mu} D_P^2$$

$$v_s = \frac{9.81 \frac{m^2}{s} (2399 - 999.7 \frac{kg}{m^3})}{18\ (1.308 * 10^{-3} N - \frac{s}{m^2})} (100\mu m)^2 \times \frac{1\ m^2}{(10^6 \mu m)^2} = 0.005832 \frac{m}{s} = \mathbf{0.58} \frac{\mathbf{cm}}{\mathbf{s}}$$

4.31 Calculate the settling velocity of a particle with 10 µm diameter and a specific gravity of 1.05 in 15°C water. ($\mu = 1.140 \times 10^{-3}$ N-s/m^2 and the density of water equals 999.1 kg/m^3).

Solution:

Use the expression for specific gravity, to calculate the density of the particle:

$$SG = \frac{\rho_{particle}}{\rho_{H_2O}}$$

$$\rho_{particle} = \rho_{H_2O} \times SG = 999.1\frac{kg}{m^3} \times 1.05 = 1049\ kg/m^3$$

Use Stoke's Law, equation 4.54, to calculate the setting velocity of the particle:

$$v_s = \frac{g\left(\rho_P - \rho_f\right)}{18\mu} D_P^2$$

$$v_s = \frac{9.81\frac{m^2}{s}(1049 - 999.1\frac{kg}{m^3})}{18\ (1.140 * 10^{-3}N - \frac{s}{m^2})}\ (10\mu m)^2 \times \frac{1\ m^2}{(10^6\mu m)^2} = 2.4 * 10^{-6}\frac{m}{s} = \mathbf{2.4 * 10^{-4}\ cm/s}$$

4.32 One type of pathogen commonly found in the developing world are helminths (i.e., parasitic intestinal worms). These worm species are generally transmitted in a soil (or biosolids) environment, directly from one human host to another. The eggs of helminths develop into their infective state in a soil environment. (a) Determine the settling velocity for *Ascaris lumbricoides* in a wastewater stabilization lagoon which have a diameter of 50 µm, density of 1.11 g/cm^3 and assumed spherical shape. (b) Determine the settling velocity for hookworm eggs which have a diameter of 60 µm, density of 1.055 g/cm^3 and assumed spherical shape. Assume the wastewater is 15°C. ($\mu = 1.140 \times 10^{-3}$ N-s/m^2 and the density of water equals 999.1 kg/m^3).
Solution:

a) Use Stoke's Law, equation 4.54, to calculate the setting velocity for *Ascaris lumbricoides*:

$$v_s = \frac{g\left(\rho_P - \rho_f\right)}{18\mu} D_P^2$$

$$v_s = \frac{9.81\frac{m^2}{s}(1110 - 999.1\frac{kg}{m^3})}{18\,(1.140 * 10^{-3}N - \frac{s}{m^2})}\,(50\mu m)^2 \times \frac{1\,m^2}{(10^6\mu m)^2} = 1.3 * 10^{-4}\frac{m}{s} = \boldsymbol{0.013\frac{cm}{s}}$$

b) Also, use Stoke's Law, equation 4.54, to calculate the setting velocity for the hookworm eggs:

$$\rho_{particle} = 1.055\frac{g}{cm^3} \times \frac{1\,kg}{1000\,g} \times \frac{(100)^3 cm^3}{1\,m^3} = 1055\,kg/m^3$$

$$v_s = \frac{9.81\frac{m^2}{s}(1055 - 999.1\frac{kg}{m^3})}{18\,(1.140 * 10^{-3}N - \frac{s}{m^2})}\,(60\mu m)^2 \times \frac{1\,m^2}{(10^6\mu m)^2} = 9.6 * 10^{-5}\frac{m}{s} = \boldsymbol{9.6 * 10^{-3}\frac{cm}{s}}$$

Chapter 5. Biology

5.1 The World Health Organization (WHO) reports that diarrhea causes 4% of all deaths worldwide, killing 2.2 million people every year, mostly children in developing countries. Diarrhea is a symptom of infection caused by members of which four organism groups listed in Figure 5.4 which can be spread by contaminated water?

Solution:

Viruses, Bacteria, macroinvertebrates, and protozoa can be spread by contaminated water.

5.2 Figure 5.4 described the major organism groups important to environmental engineering, many which cause water related diseases. Water related diseases include those diseases derived from exposure to microorganisms or chemicals that are found in water humans drink. Other water related diseases include those that have part of their lifecycle in water (e.g., schistosomiasis), diseases like malaria that have water-related vectors due sometimes to improper management of stormwater and solid waste, and other diseases such as legionellosis that is carried by aerosols that contain disease causing organisms. Use Figure 5.4 and research you perform on the World Health Organization's web site on "water related diseases" to answer the following questions: (a) *Giardia intestinalis* and *Cryptosporidium* are members of what group, (b) *Legionella* is a member of what group, (c) Hepatitis A and E are caused by members of what group, (d) Typhoid fever is caused by *Salmonella typhi* and *Salmonella paratyphi* that are part of what group, (e) cholera is caused by *Vibrio cholera* which is a member of what group? (f) Ascariasis is an infection of the small intestine caused by the large roundworm, *Ascaris lumbricoides*, that is a member of what group?

Solution:

a) From this link http://www.who.int/water_sanitation_health/dwq/en/admicrob5.pdf, you will find that *Giardia intestinalis* and *Cryptosporidium* are part of the **protozoa** group.

b) "Legionellosis is a collection of infections that emerged in the second half of the 20th century, and that are caused by Legionella pneumophila and related Legionella bacteria." http://www.who.int/water_sanitation_health/emerging/legionella_rel/en/ Thus, *Legionella* is part of the **bacteria** group.

c) "Hepatitis A and E viruses, while unrelated to one another, are both transmitted via the faecal-oral route, most often through contaminated water and from person to person" http://www.who.int/water_sanitation_health/diseases/hepatitis/en/ Thus, Hepatitis A and E are part of the **virus** group.

d) "Typhoid and paratyphoid fevers are caused by the bacteria Salmonella typhi and Salmonella paratyphi respectively." http://www.who.int/water_sanitation_health/diseases/typhoid/en/ Thus, *Salmonella typhi* and *Salmonella paratyphi* are part of the **bacteria** group.

e) "Cholera is caused by the bacterium Vibrio cholerae." http://www.who.int/water_sanitation_health/diseases/cholera/en/ Thus, *Vibrio cholera* is a member of the **bacteria** group.

f) "Ascariasis is an infection of the small intestine caused by Ascaris lumbricoides, a large roundworm." http://www.who.int/water_sanitation_health/diseases/ascariasis/en/ Thus, *Ascaris lumbricoides* is part of the **macroinverebrates** group.

5.3 Figure 5.4 described the major organism groups important to environmental engineering, many which are used in treatment of domestic, agricultural, and industrial wastes. Identify the major organism groups listed in this figure (e.g., viruses, bacteria, algae, protozoa, rotifers) that: (a) use solar energy to transfer oxygen into wastewater stabilization ponds (i.e., lagoons), (b) are key organisms in the removal of the organic matter that makes up biochemical oxygen demand in wastewater, (c) are single-cell organisms found in biological wastewater treatment and resource recovery systems that feed on bacteria and algae, (d) are multi-cellular organisms found in biological wastewater systems, (e) include the gram-positive organism, *Nocardia*, which is normally found in wastewater treatment plants, but if it experiences excessive growth, can result in foaming and poor settling of solids in the secondary settling reactor (i.e., clarifier).

Solution:

a) **Algae**
b) **Bacteria**
c) **Protozoa**
d) **Rotifers and microcrustaceans**
e) **Bacteria**

5.4 The World Health Organization reports that malaria is the most important parasitic infectious disease. WHO estimates there are 300-500 million cases of malaria globally with the primary burden assumed by those living in Sub-Saharan Africa. Humans contract malaria after being bitten by a malaria-infected mosquito. These mosquitos breed in fresh and sometimes brackish water, which may be because of improper management of irrigation water, stormwater, and solid waste. Malaria is known to be caused by four species of Plasmodium parasites (*P. falciparum*, *P. vivax*, *P. ovale*, *P. malariae*). Are these parasites prokaryotes or eukaryotes?

Solution:

The parasites are **eukaryotes**.

5.5 Mathematical models are used to predict the growth of a population, that is, population size at some future date. The simplest model is that for exponential growth. The calculation requires knowledge of the organism's maximum specific growth rate. A value for this coefficient can be obtained from field observations of population size or from laboratory experiments where population size is monitored as a function of time when growing at high substrate concentrations (i.e., S >> K_s):

Time (d)	Biomass (mg/L)
0	50
1	136
2	369
3	1,004
4	2,730
5	7,421

Calculate μ_{max} for this population assuming exponential growth; include appropriate units.

Solution:

The exponential growth model can be log-linearized. In this case, using all of the data, a plot of ln X_t versus t would yield $\mu_{\max}$ as the slope.

$$ln\ X_t = \mu_{\max} \times t + ln\ X_o$$

This would provide the most accurate value of $\mu_{\max}$. Alternatively, a value for $\mu_{\max}$ may be calculated using the analytical solution to the exponential growth model:

$$X_t = X_0 \times e^{\mu_{\max} \times t}$$

Rearrange and solve for $\mu_{\max}$

$$\mu_{\max} = \frac{ln\left(X_t / X_0\right)}{t}$$

Perform the calculation using any two measures of biomass and the associated time:

$$\mu_{\max} = \frac{ln\left(7,421\frac{mg}{L} / 50\frac{mg}{L}\right)}{5\ days - 0\ days} = \boxed{1.0 / day}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

5.6 Once a value for μ_{max} has been obtained, the model may be used to project population size at a future time. Assuming that exponential growth is sustained, what will the population size in Problem 5-1 be after 10 days?

Solution:

Again, using the exponential growth model and the values for μ_{max} determined in Problem 5-1 with X_o= 50 mg/L, t = 10 days, and μ_{max} = 1/day).

$$X_{10} = 50\frac{mg}{L} \times e^{(1/day \times 10\ days)} = \boxed{1{,}101{,}323\frac{mg}{L}}$$

5.7 Consider a population with an initial biomass (X_0) of 5 mg VSS/L, a maximum specific growth rate (μ_{max}) of 0.9/day, and a respiration rate coefficient of 0.15/day. Determine the biomass concentration (mg VSS/L) at the end of (a) 5 days and (b) 20 days.

Solution:

Use equation 5.7 for exponential growth to solve parts a and b:

$$X_t = X_0 e^{(\mu_{max} - k_d)t}$$

a) $X_{5\ days} = (5\ mgVSS/L) \times\ e^{\left(\frac{0.9}{day} - \frac{0.15}{day}\right)(5)} = \mathbf{213\ mgVSS/L}$

b) $X_{20\ days} = (5\ mgVSS/L) \times\ e^{\left(\frac{0.9}{day} - \frac{0.15}{day}\right)(20)} = \mathbf{1.6 \times 10^7\ mgVSS/L}$

5.8 Consider a population with the following characteristics; initial biomass (X_0) of 200 mg TSS/L, maximum specific growth rate (μ_{max}) of 1/day, and a respiration rate coefficient of 0.05/day. (a) Assume logistic growth. Determine the population's biomass (in units of TSS/L) after 2, 10, 100, and 10,000 days if the carrying capacity (K) is reported to be 5,000 mg TSS/L. (b) Assume exponential growth. Determine the population's biomass (in units of TSS/L) after 2, 10, 100, and 10,000 days.

Solution:

a) Use equation 5.10 for logistic growth to solve part a.

$$X_t = \frac{K}{1+\left[\left(\frac{K-K_0}{X_0}\right)e^{-(\mu_{max}-k_d)t}\right]}$$

$$X_{2\,days} = \frac{5000\,mg\,TSS/L}{1+\left[\left(\frac{5000\,mg\,TSS/L - 200\,mg\,TSS/L}{200\,mg\,TSS/L}\right)e^{-(1/day - 0.05/day)(2days)}\right]} = \boldsymbol{1089\,mg\,TSS/L}$$

Use the same method to solve for 10, 100, and 10,000 days. Check your answers in the table below:

Time (days)	Population biomass (mg TSS/L)
2	1089
10	4991
100	5000*
10,000	5000*

* Notice that carry capacity is reached at 100 days

b) Use equation 5.7 for exponential growth to solve part b:

$$X_t = X_0 e^{(\mu_{max}-k_d)t}$$

$$X_{5\,days} = (5\,mgVSS/L) \times e^{\left(\frac{0.9}{day}-\frac{0.15}{day}\right)(5)} = \boldsymbol{213\,mgVSS/L}$$

Use the same method to solve for 10, 100, and 10,000 days. Check your answers in the table below:

Time (days)	Population biomass (mg TSS/L)
2	1337
10	$2.7{*}10^{6}$
100	$3.6{*}10^{43}$
10,000	∞

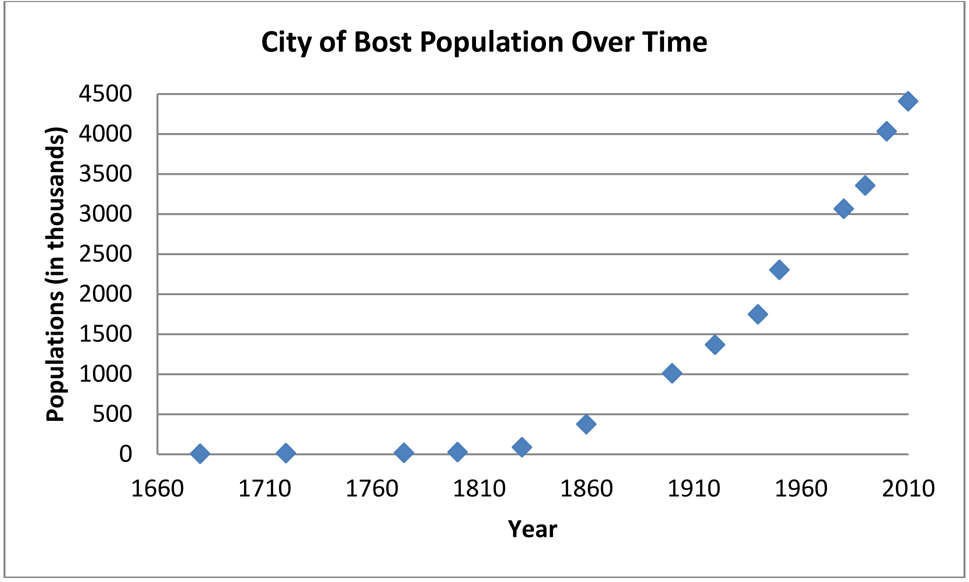
* Notice that carry capacity is reached at 100 days

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

5.9 Table 5.17 provides the U.S. Census Bureau estimate of the population of the city of Boston from 1680 to 2010.
Enter this data into a spreadsheet and make a graph of population over time. (a) Does the population growth follow exponential or logistic growth? (b) How many years did it take for Boston to double its population from 12,000 to 24,000 and from 2 million to 4 million? takes for the population to double to 8.8 million? (c) Using you knowledge of half life from Chapter 3, determine the rate constant for this population growth. Is the rate of growth changing over time? If so, by how much in percent?

Solution:

a) Plot the US Census bureau population data from table 5.17:



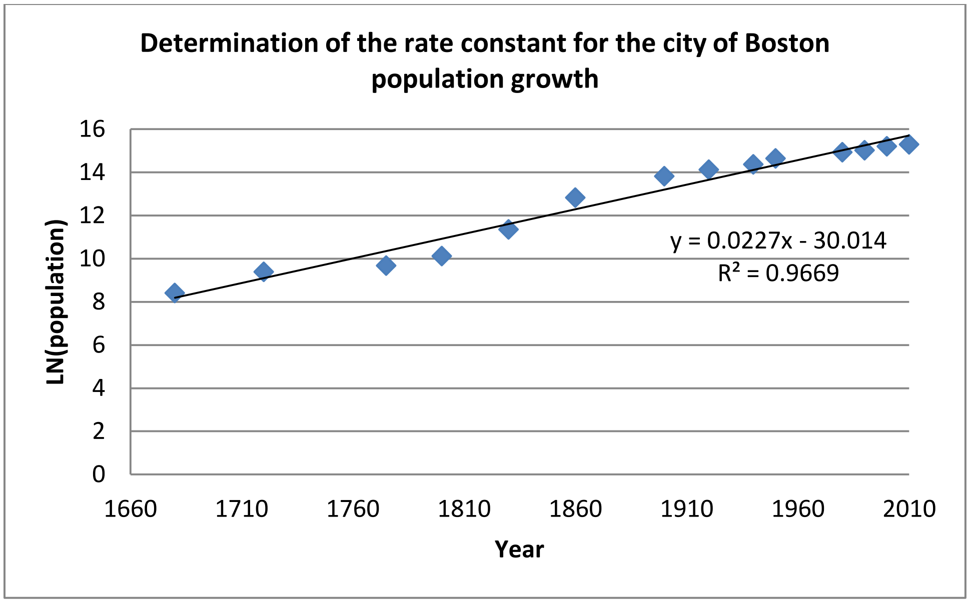
From the graph, it is evident that the population data follows **exponential growth**.

b) From table 5.17, the population is 12,000 in year 1720 and reaches 24,900 in 1800. Thus, it takes **80 years for Boston to double its population from 12,000 to 24,000**.

From table 5.17, the population is 2,301,000 in 1950 and **doubles to 4 million in 50 years** (in the year 2000 the population is 4,032,000).

Looking at the graph, **the population of Boston will double to 8.8 million shortly (less than 30 years**).

c) In figure 3.12, it is shown that the rate constant for exponential decay (or growth) can be determined by graphing the natural log of the concentration/population over time and finding the slope of the line. This method is used to calculate the rate constant for the Boston population data in the figure below.



The rate constant is **0.023**. The rate of growth changes **exponentially** over time.

5.10 This chapter described that in 2007 the average rate growth of the global population was 1.2 percent per year. Determine the doubling time expected for the global population using this information

Solution:

Use the exponential growth equation to determine the doubling time expected for the global population.

$$P_t = P_o e^{kt}$$

Use the relationship that the final population will be twice that of the initial.

$$2P_o = P_o e^{kt}$$

The initial population terms cancel out and the rate constant is 1.2% per year (0.012/year). It is now possible to solve for the one unknown in the equation, time:

$$t = \frac{\ln(2)}{0.012} = \boldsymbol{58\ years}$$

5.11 The rate of increase for the human population in Mexico was 1.5 percent. (a) How long would you expect their population to double from its current level of 116 million people to 232 million in 2058? (b) What might prevent the population from reaching this level?

Solution:

a) Use the exponential growth equation to determine the doubling time expected for the human population in Mexico.

$$P_t = P_o e^{kt}$$

Solve for time.

$$t = \frac{\ln\left(\frac{P_t}{P_o}\right)}{k}$$

The rate of increase is 1.5% per year (0.015/year). Using this and the initial and double population, solve for time.

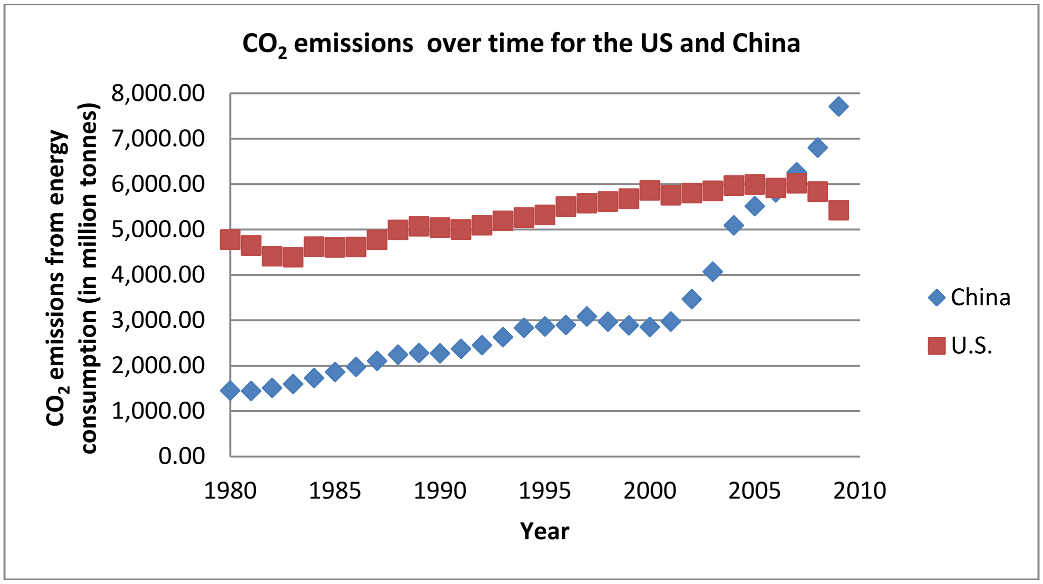
$$t = \frac{\ln\,(232million/116million)}{0.015} = \boldsymbol{46\ years}$$

b) Students' answers may vary but natural disasters, epidemics, governmental policies, carry capacity, economic crisis, etc. may prevent population from reaching this level.

5.12 China and the U.S. were the top two producers of CO_2 emissions associated with energy consumption in 2009. Table 5.18 provides data of CO^2 emissions from energy consumption (in million tonnes) by the U.S. and China from 1980-2009 (data from the Energy Information Administration). (a) Enter this data into a spreadsheet and make a graph of CO_2 emissions from 1980 to 2009 for these two countries. (b) What is the percent increase in emissions for each country since 2000? (c) in a half of page, discuss how technology efficiency, price of fossil fuels, and growth of the economy would have impacted U.S. CO_2 emissions in 2008 and 2009? (d) If the population of China was approximately 1.28 billion and the population of the U.S., was approximately 301 million people, what was their emissions of CO_2 on a tonnes per person basis? Compare your results to the 2009 global value of 4.49 tonnes of CO_2 per person.

Solution:

a) The CO_2 emission data for the US and China was graphed from 1980 and 2009 in excel:



b) Subtract the 2009 CO_2 emission data from that in 2000 for each country and divide by the emission data in 2000 and multiply by 100 to determine the percent increase in emissions for each country since 2000.

$$\%emission\ increase\ in\ China = \frac{7{,}710.50 - 2{,}849.75}{2{,}849.75} \times 100 = \mathbf{171\%}$$

$$\%emission\ increase\ in\ the\ U.S. = \frac{5{,}424.53 - 5{,}861.82}{5{,}861.82} \times 100 = \mathbf{-7.5\%}$$

c) Students' answers may vary

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

d) Divide the CO_2 emission data for each country in 2009 by the population to determine the emissions of CO_2 in a tonnes per person

$$\mathrm{CO_2}\ emissions\ per\ person\ in\ China = \frac{7.710.50 * 10^6 tonnes}{1.28\ billion\ people} = \mathbf{6.02}\,\frac{\boldsymbol{tonnes}}{\boldsymbol{peson}}$$

$$\mathrm{CO_2}\ emissions\ per\ person\ in\ the\ US = \frac{5{,}424.53 * 10^6 tonnes}{301\ billion\ people} = \mathbf{18}\,\frac{\boldsymbol{tonnes}}{\boldsymbol{peson}}$$

The per capita CO_2 emissions for both the U.S. and China exceed the global per capita value of 4.49 tonnes. In particular, the U.S. per capita emissions are extremely high (four times the global value and triple the per capita emissions in China).

5.13 Exponential growth cannot be sustained forever because of constraints placed on the organism by its environment, that is, the system's carrying capacity. This phenomenon is described using the logistic growth model. (a) Calculate the size of the population in Problem 5-1 after 10 days, assuming that logistic growth is followed and that the carrying capacity is 100,000 mg/L. (b) What percentage of the exponentially growing population size would this be?

Solution:

a) The population size after 10 days according to the logistic growth model can be calculated using the analytical solution with K = 100,000 mg/L and X_o and μ_{max} as given in Problem 5-1.

$$X_t = \frac{K}{1+\left(\frac{K-X_o}{X_o}\right)\times e^{-\mu_{max}\times t}}$$

$$X_t = \frac{100{,}000\ \frac{mg}{L}}{1+\left(\frac{100{,}000\frac{mg}{L}-50\frac{mg}{L}}{50\frac{mg}{L}}\right)\times e^{-1/day\ \times 10\ day}} = \boxed{91{,}680\ \frac{mg}{L}}$$

b) Problem 5-2 provided the estimated population at 10 days. This value needs compared to the carrying capacity value determined in part (a) of this problem.

$$\% = \frac{91{,}680}{1{,}101{,}323}\times 100\% = \boxed{8\ \%}$$

5.14 As reported by Mihelcic et al. (2009) “water demand is a function of the design population, minimum personal water requirements, and factors such as seasonal activities and infrastructural demands (e.g., from schools, churches, and clinics). Design population (P_N) is the projected population in the last year of the design life.” It can be calculated as follows:

for populations < 2,000 $$P_N = P_O\left(1+\frac{r\times N}{100}\right)$$

or

for populations > 2,000 $$P_N = P_O\left(1+\frac{r}{100}\right)^N$$

Assume two rural communities in Honduras have initial populations of 1,500 and 2,200 respectively. If you are designing a water system with an expected life of 15 years (N), and the percentage rate of growth is expected to be 3%, what is the community size you would design for in 15 years for each community?

Solution:

For the rural community in Honduras with an initial population of 1,500, use the first equation in the problem statement for populations < 2,000:

$$P_{15\,years} = 1{,}500\,people\left(1+\frac{3\times 15}{100}\right) = \mathbf{2,175\ people}$$

For the rural community in Honduras with an initial population of 2,200, use the second equation in the problem statement for populations >2,000:

$$P_{15\,years} = 2{,}200\,people\left(1+\frac{3}{100}\right)^{15} = \mathbf{3,428\ people}$$

5.15 Using information provided in Problem 5.14., (a) determine the expected population for the community of 1,500 people after 15 years for estimated population rate of growths of 1, 2.5, and 5 percent. (b) Assume this rural community is losing population at a rate of 1 percent per year because of the global phenomenon of rural migration to urban areas. What is the expected population of the community in 15 years?

Solution:

a) For a community of 1,500 people, use the first equation for populations < 2,000 in problem 5.14:

$$P_{15\ years\ at\ 1\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{1 \times 15}{100}\right) = \mathbf{1,725\ people}$$

$$P_{15\ years\ at\ 2.5\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{2.5 \times 15}{100}\right) = \mathbf{2,063\ people}$$

$$P_{15\ years\ at\ 5\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{5 \times 15}{100}\right) = \mathbf{2,625\ people}$$

b) If the rural community is losing population at a rate of 1 percent per year, subtract this by the growth rate in the equations:

$$P_{15\ years\ at\ 1\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{(1-1) \times 15}{100}\right) = \mathbf{1,500\ people}$$

$$P_{15\ years\ at\ 2.5\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{(2.5-1) \times 15}{100}\right) = \mathbf{1,838\ people}$$

$$P_{15\ years\ at\ 5\%\ growth\ rate} = 1{,}500\ people\left(1 + \frac{(5-1) \times 15}{100}\right) = \mathbf{2,400\ people}$$

5.16 Food limitation of population growth is described using the Monod model. Population growth is characterized by the maximum specific growth rate ($\mu_{\max}$) and the half-saturation constant for growth (K_S). (a) Calculate the specific growth rate (μ) of the population in Problem 5.5 growing at a substrate concentration of 25 mg/L according to Monod kinetics if it has a K_s of 50 mg/L. (b) What percentage of the maximum growth rate for the exponentially growing population size would this be?

Solution:

a) The specific growth rate for a population growing under nutrient limited conditions can be calculated using the Monod model:

$$\mu = \mu_{\max} \times \frac{S}{K_s + S} \quad = \quad 1/day \times \frac{25\frac{mg}{L}}{50\frac{mg}{L} + 25\frac{mg}{L}} = \boxed{0.33/day}$$

b) Problem 5-1 provided the estimated maximum growth rate at 1/day. This value needs compared to the specific growth rate determined in part (a) of this problem.

$$\% = \frac{0.33/day}{1/day} \times 100\% = \boxed{33\%}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

5.17 Laboratory studies have shown that microorganisms produce 10 mg/L of biomass in reducing the concentration of a pollutant by 50 mg/L. Calculate the yield coefficient, specifying the units of expression.

Solution:

Remember that by definition,

$$Y = \frac{dX / dt}{dS / dt} = \frac{10\ mg\ biomass / L}{50\ mg\ substrate / L} = \boxed{0.2\ \frac{mg\ biomass}{mg\ substrate}}$$

5.18 An pilot scale facility maintained under aerobic conditions has monitored the rate of removal of pollutant as 10 mg/L-hour. What is the rate of growth of the microorganisms oxidizing the pollutant (mg cells/L-hour) if their yield coefficient is reported to equal 0.40 lb cells/lb substrate?

Solution:

This problem is similar to example 5.4. The yield coefficient *Y* relates the rate of substrate (in this case, organic matter) disappearance to the rate of cell growth. This relationship (Equation 5.14) is written in a batch reactor as follows:

$$\frac{dS}{dt} = -\frac{1}{Y}\frac{dX}{dt}$$

Therefore,

$$Y\frac{dS}{dt} = -\frac{dX}{dt}$$

Substitute the given values for *Y* and the rate of substrate depletion:

*note that 0.4 lb cells/lb substrate is equivalent to 0.4 mg cells/mg substrate (unit conversions cancel out).

$$\frac{0.4\, mg\ cells}{mg\ substrate} \times \frac{10\, mg}{L-hr} = \boldsymbol{\frac{4\, mg\ cells}{L-hr}}$$

5.19 When food supplies have been exhausted, populations die away. This exponential decay is described by a simple modification of the exponential-growth model. Engineers use this model to calculate the length of time that a swimming beach must remain closed following pollution with fecal material. For a population of bacteria with an initial biomass of 100 mg/L and a $k_d = 0.4/\text{day}$, calculate the time necessary to reduce the population size to 10 mg/L.

Solution:

Under conditions of exhausted food supplies (S=0), the overall population growth model is used

$$\frac{dX}{dt} = \left[\mu_{\max} \times \left(1 - \frac{X}{K}\right) \times \left(\frac{S}{K_s + S}\right) - k_d\right] \times X$$

However, because S equals zero, the above expression reduces to a first order decay

$$\frac{dX}{dT} = -k_d \times X$$

The above expression can be solved

$$X_t = X_o \times e^{(-k_d \times t)}$$

And this expression can be solved for time, t. Then given values can be substituted as follows:
X_o = 100 mg/L, X_t = 10 mg/L, and k_d= 0.4/day.

$$t = \frac{-\ln\left(\frac{X_t}{X_o}\right)}{k_d} = \frac{-\ln\frac{10\ mg/L}{100\ mg/L}}{0.4/day} = \boxed{5.8\ days}$$

5.20 A population having a biomass of 2 mg/L at $t = 0$ days reaches a biomass of 139 at $t = 10$ days. Assuming exponential growth, calculate the value of the specific growth coefficient.

Solution:

$$X_t = X_o \times e^{\mu \times t}$$

$$\ln \frac{X_t}{X_o} = \mu \times t$$

$$\ln \frac{139\ mg / L}{2\ mg / L} = \mu \times 10\ days$$

$$\boxed{\mu = 0.42 / day}$$

5.21 Fecal bacteria occupy the guts of warm-blooded animals and do not grow in the natural environment. Their population dynamics in lakes and rivers—that is, following a discharge of untreated domestic wastewater—can be described as one of exponential decay or death. How many days would it take for a bacteria concentration of 10^6 cell/mL to be reduced to the public health standard of 10^2 cell/mL if the decay coefficient is 2/day?

Solution:

$$X_t = X_o \times e^{-k \times t}$$

$$\frac{-\ln \dfrac{10^2 cells / mL}{10^6 cells / mL}}{2 / day} = \boxed{4.6\ days}$$

5.22 The 2012 Living Planet Report from the World Wildlife Fund (WWF, 2012) reported that in the year 2008, the Earth's total biocapacity was 12.0 billion global hectares, which equates to 1.8 global hectares per person. In contract, humanity's ecological footprint was reported to be 18.2 billion global hectares, which equates to 2.7 global hectares per person. (a) Using these values, how many years would it take the Earth to fully regenerate the renewable resources that humanity consumed in one year. (b) "Ecological Overshoot" is a term that describes when the global ecological footprint is larger than the Earth's biocapacity. What was the "ecological overshoot" in 2008 reported in global hectares per person? (c) Review Chapter 1 of the Living Planet Report, what percent did the the global living planet index decline between 1970 and 2008? What percent did the freshwater index decline over the same time period?

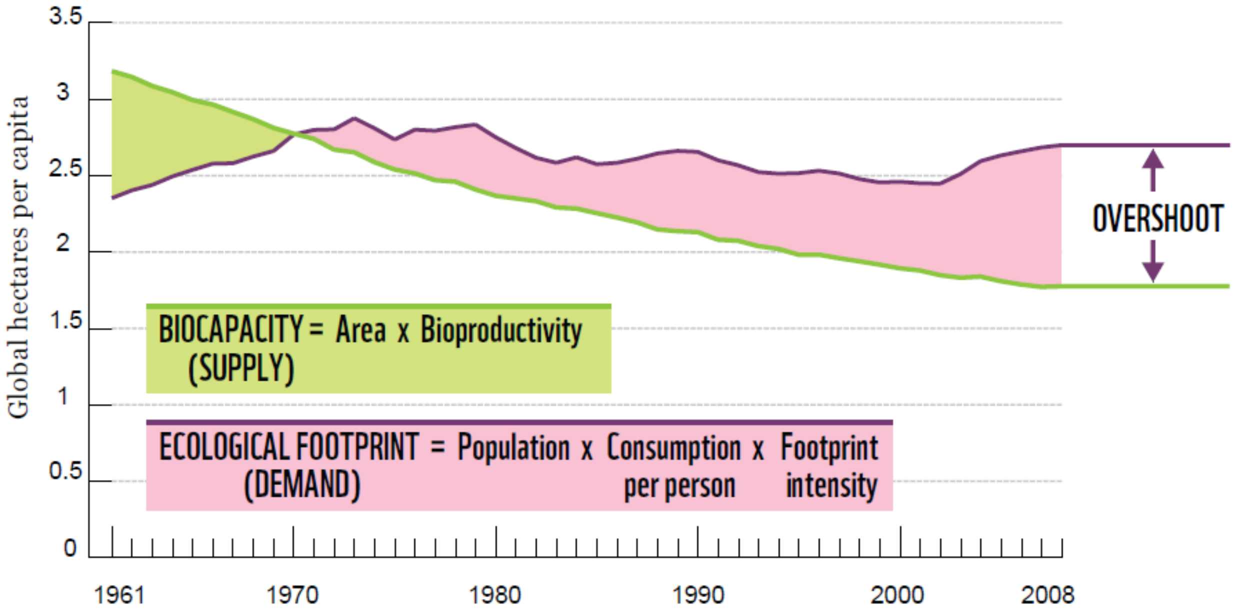
Solution:

a) Divide humanity's ecological footprint by the earth's biocapacity:

$$\#\ of\ years\ for\ Eartht\ o\ fully\ regenerate = \frac{18.2\ billion\ global\ hectares/year}{12.0\ billion\ global\ hectares/year} = 1.5\ years$$

b) "Ecological Overshoot" is described in the 2012 Living Planet Report on pg 40 of the 2012 Living Planet Report

This "ecological overshoot" has continued to grow over the years, reaching a 50 percent deficit in 2008.



The y-axis is in global hectares per capita, ecological overshoot = 2.75-175= **<u>1 global hectare per person</u>**.

c) The Global Living Planet Index is depicted on page 18. The percent decline of the global living planet index was **-28%** from 1970 to 2008.

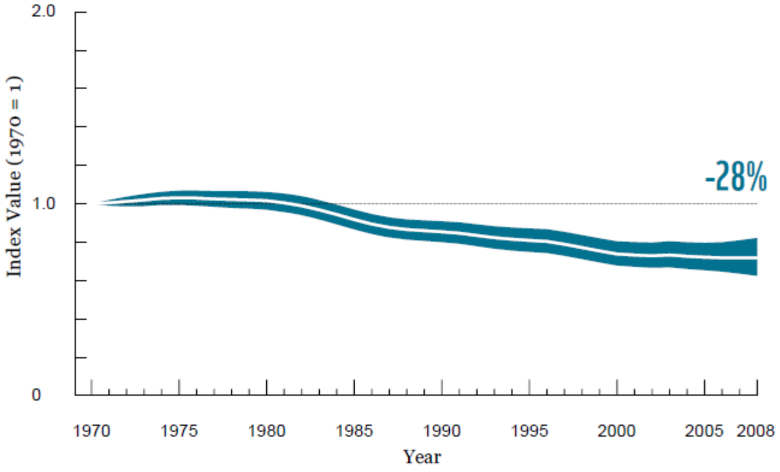


Figure 3: The Global Living Planet Index
The index shows a decline of 28% from 1970 to 2008, based on 9,014 populations of 2,688 species of birds, mammals, amphibians, reptiles and fish. Shading on this, and all Living Planet Index figures represents the 95% confidence limits surrounding the trend; the wider the shading, the more variable the underlying trend (WWF/ZSL, 2012).

Key

- 🟦 Global Living Planet Index
- 🟦 Confidence limits

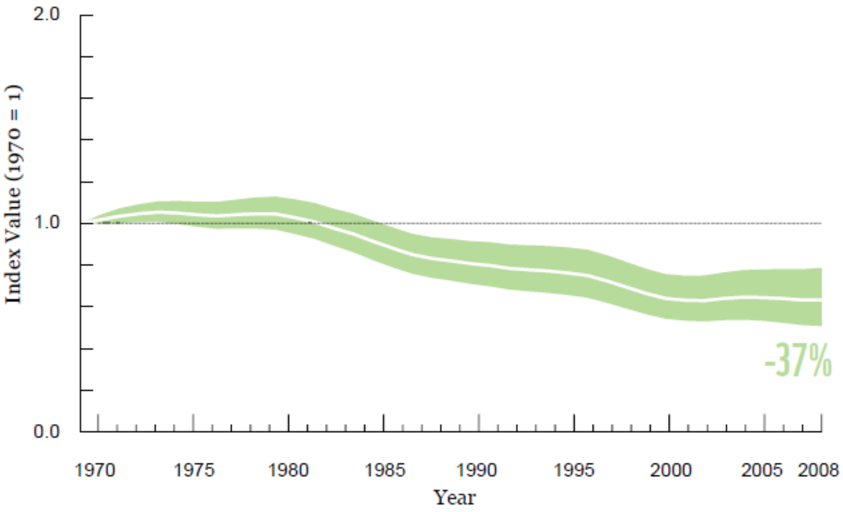
A graph of the freshwater living planet index over time is found on page 25. From 1970-2008, this index declined **37%.**

the biome-based indices – while the temperate freshwater index increased by about 35 per cent (Figure 11b).

Figure 11: The freshwater Living Planet Index
(a) The global freshwater index shows a decline of 37% between 1970 and 2008; (b) The temperate freshwater index shows an increase of about 36%, while the tropical freshwater index shows a decline of around 70% (WWF/ZSL, 2012).

Key 11a

- 🟩 Global freshwater index
- 🟩 Confidence limits



Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

5.23 According to the Web site maintained by Redefining Progress, its latest Footprint Analysis indicates that humans are exceeding their ecological limits by 39 percent. Go to the following Web site, and determine your own ecological footprint. Record your value, and compare it with those for your country and the world. Identify some changes you can make in your current lifestyle, and then rerun the footprint calculator to reflect those changes. Summarize the changes you make and how they affect your ecological footprint. The Web site is www.rprogress.org/ecological_footprint/about_ecological_footprint.htm.

Solution:

Students' answers may vary

5.24 Remediation of toluene in a contaminated groundwater aquifer has been found to have the following biokinetic coefficients for microbial growth. μ_{max} = 1.2/day and K_s = 0.31 mg/L. What is the growth rate of the microorganism (day^{-1}) removing the toluene if the concentration of the pollutant is 1 ppb and 1 ppm?

Solution:

Use the Monod equation 5.11 to solve for the specific growth rate:

$$\mu=\mu_{max}\frac{S}{K_s+S}$$

In water 1 ppm of toluene is equivalent to 1 mg/L of toluene. Similarly 1 ppb of toluene is equivalent to 1.0*10^{-3} mg/L of toluene.

$$\mu_{toluene\ at\ 1ppb} = 1.2/day\left(\frac{1*10^{-3}mg/L}{0.31\ mg/L+\ 1*10^{-3}mg/L}\right) = \mathbf{0.0039/day}$$

$$\mu_{toluene\ at\ 1ppm} = 1.2/day\left(\frac{1mg/L}{0.31mg/L+\ 1mg/L}\right) = \mathbf{0.92/day}$$

5.25 A biological treatment process used to treat wastewater was found to have the following biokinetic coefficients: yield coefficient = 0.52 mg VSS/mg COD, half saturation constant = 60 mg COD/L, and maximum specific growth rate = 0.96/day. What is the growth rate of the organisms (units of day^{-1}) if the organic matter in the reactor is: (a) a low strength wastewater with 125 mg COD/L, (b) a high strength wastewater with COD = 325 mg/L? (c) if the concentration of microorganisms in the biological reactor is 1,000 mg VSS/L, what is the rate of COD utilization?

Solution:

Use the Monod equation 5.11 to solve for the specific growth rate based on the different concentrations of organic matter given in parts a-c:

$$\mu = \mu_{max} \frac{S}{K_s + S}$$

a)

$$\mu_{low\ strength\ WW} = 0.96/day\left(\frac{125\ COD/L}{60\ mg\ COD/L +\ 125\ mg\ COD/L}\right) = \mathbf{0.65/day}$$

b)

$$\mu_{high\ strength\ WW} = 0.96/day\left(\frac{325\ COD/L}{60\ mg\ COD/L +\ 325\ mg\ COD/L}\right) = \mathbf{0.81/day}$$

c)

$$\mu_{1000mg\ VSS/L} = 0.96/day\left(\frac{1{,}000\ mg\ VSS/L}{60\ mg\ COD/L + 1{,}000\ mg\ VSS/L}\right) = \mathbf{0.91/day}$$

5.26 What is the ThOD of the following chemicals? Show the balanced stoichiometric equation with your work: (a) 5 mg/L C_7H_3; (b) 0.5 mg/L C_6Cl_5OH; (c) $C_{12}H_{10}$.

Solution:

a) $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$

$$5\frac{mg}{L}\times\frac{g}{1000\ mg}\times\frac{mole}{92\ g}\times\frac{9\ mole\ O_2}{mole}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{16\frac{mg}{L}}$$

b) $C_6Cl_5OH + 4.5O_2 + 2H_2O \rightarrow 6CO_2 + 5HCl$

$$0.5\frac{mg}{L}\times\frac{g}{1000\ mg}\times\frac{mole}{266.5\ g}\times\frac{4.5\ mole\ O_2}{mole}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{0.3\frac{mg}{L}}$$

c) $C_{12}H_{10} + 14.5O_2 \rightarrow 12CO_2 + 5H_2O$

$$1\frac{mg}{L}\times\frac{g}{1000\ mg}\times\frac{mole}{154\ g}\times\frac{14.5\ mole\ O_2}{mole}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{3\frac{mg}{L}}$$

5.27 A waste contains 100 mg/L ethylene glycol ($C_2H_6O_2$) and 50 mg/L NH_3-N. Determine the theoretical carbonaceous and the theoretical nitrogenous oxygen demand of the waste.

Solution:

First write out and balance the chemical reactions. Note that the ammonia concentration is reported as N.

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$
$$C_2H_6O_2 + 2.5O_2 \rightarrow 2CO_2 + 3H_2O$$

Next, use the reaction stoichiometry to determine the nitrogenous and carbonaceous oxygen demand.

$$50\,\frac{mg\ NH_3-N}{L}\times\frac{g}{1000\ mg}\times\frac{mole\ N}{14\ g}\times\frac{mole\ NH_3}{mole\ N}\times\frac{2\ moles\ O_2}{mole\ NH_3}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{229\,\frac{mg}{L}}$$

$$100\,\frac{mg\ \mathrm{C_2H_6O_2}}{L}\times\frac{g}{1000\ mg}\times\frac{mole\mathrm{C_2H_6O_2}}{62\ g}\times\frac{2.5\ moles\ O_2}{mole\ \mathrm{C_2H_6O_2}}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{129\,\frac{mg}{L}}$$

Total theoretical oxygen demand equals 229 mg/L + 129 mg/L = 358 mg/L

5.28 Calculate the NBOD and ThOD of a waste containing 100 mg/L isopropanol (C_3H_7OH) and 100 mg/L NH_3-N.

Solution:

First write and balance the chemical reactions. Note that all ammonia concentration reported as N.

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$
$$C_3H_7OH + 4.5O_2 \rightarrow 3CO_2 + 4H_2O$$

Next, use the reaction stoichiometry to determine the nitrogenous and carbonaceous oxygen demand.

$$100\,\frac{mg\ NH_3-N}{L}\times\frac{g}{1000\ mg}\times\frac{mole\ N}{14\ g}\times\frac{mole\ NH_3}{mole\ N}\times\frac{2\ moles\ O_2}{mole\ NH_3}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{457\,\frac{mg}{L}}$$

$$100\,\frac{mg\ \mathrm{C_3H_7OH}}{L}\times\frac{g}{1000\ mg}\times\frac{mole\ \mathrm{C_3H_7OH}}{60\ g}\times\frac{4.5\ moles\ O_2}{mole\ \mathrm{C_3H_7OH}}\times\frac{32\ g}{mole\ O_2}\times\frac{1000\ mg}{g}=\boxed{240\,\frac{mg}{L}}$$

<u>Total theoretical oxygen demand equals 457 mg/L + 240 mg/L = 697 mg/L</u>

5.29 A waste contains 100 mg/L acetic acid (CH_3COOH) and 50 mg/L NH_3-N. Determine the theoretical carbonaceous oxygen demand, the theoretical nitrogenous oxygen demand, and the total theoretical oxygen demand of the waste.

Solution:

First write and balance the chemical reactions. Note that all ammonia concentration reported as N.

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$
$$CH_3COOH + 2O_2 \rightarrow 2CO_2 + 2H_2O$$

Next, use the reaction stoichiometry to determine the nitrogenous and carbonaceous oxygen demand.

$$50\ \frac{mg\ NH_3-N}{L} \times \frac{g}{1000\ mg} \times \frac{mole\ N}{14\ g} \times \frac{mole\ NH_3}{mole\ N} \times \frac{2\ moles\ O_2}{mole\ NH_3} \times \frac{32\ g}{mole\ O_2} \times \frac{1000\ mg}{g} = \boxed{228\ \frac{mg}{L}}$$

$$100\ \frac{mg\ \mathrm{CH_3COOH}}{L} \times \frac{g}{1000\ mg} \times \frac{mole\ \mathrm{CH_3COOH}}{60\ g} \times \frac{2\ moles\ O_2}{mole\ \mathrm{CH_3COOH}} \times \frac{32\ g}{mole\ O_2} \times \frac{1000\ mg}{g} = \boxed{107\ \frac{mg}{L}}$$

<u>Total theoretical oxygen demand equals 228 mg/L + 107 mg/L = 335 mg/L</u>

5.30 A waste has an ultimate CBOD of 1,000 mg/L and a k_L of 0.1/day. What is its 5-day CBOD?

Solution:

$$y_5 = L_o \times \left(1 - e^{-k_L \times t}\right)$$

$$y_5 = 1000\,\frac{mg}{L} \times \left(1 - e^{-0.1/day \times 5\ day}\right) = \boxed{393\,\frac{mg}{L}}$$

5.31 A new manufacturing facility is being located in your town It plans to produce 2,000 m^3/day of a wastewater that consists primarily of water and the chemical phenol dissolved in it at a concentration of 5 mg/L. Phenol has a chemical formula of C_6H_5OH.   The company has asked the municipal wastewater treatment to consider treating this industrial waste. Your plant currently treats 30,000 m^3/day with an average influent of 350 mg COD/L.   (a) Estimate the increase in COD loading (kg COD/day) if you accept the industrial waste discharge? (b) Estimate the additional amount of oxygen (in kg O_2/day) needed to oxidize the phenol at the treatment plant.

Solution:

a) Given the flow rate of the industrial wastewater (2,000 m^3/day) and the concentration of phenol (5 mg/L), use unit conversions to estimate the COD loading from the industrial waste discharge to potentially be treated by the municipal wastewater treatment plant.

$$2000\frac{m^3}{day}\times\frac{1000L}{m^3}=2.0*10^6\frac{L}{day}\times\frac{5mg}{L}\times\frac{1\ g}{1000\ mg}\times\frac{1\ kg}{1000g}=\boldsymbol{10\ kg/day}$$

b) Write and balance a chemical equation for phenol and oxygen.

$$C_6H_5OH+6O_2\ \rightarrow 6CO_2+3H_2O$$

Using the molecular weights and molar ratios, first calculate the mass of O_2 needed to oxidize 5 mg/L of phenol.

$$\frac{5\ mgC_6H_5OH}{L}\times\frac{1g}{1000mg}\times\frac{1\ mol}{94\ g/L}\times\frac{6\ molO_2}{1\ mol\ C_6H_5OH}\times\frac{32\ gO_2}{1\ mol}=0.0102\ mgO_2/L$$

Now multiply this amount by the volume of industrial wastewater to get the ***additional*** amount of O_2 needed at the treatment plant.

$$2.0*10^6\frac{L}{day}\times 0.0103\frac{mgO_2}{L}\times\frac{1\ kg}{10^6mg}=\boldsymbol{0.02\ kg\ O_2/day}$$

5.32 Untreated municipal wastewater in Europe may average 600 mg/L for the carbonaceous 5-day BOD while in the U.S. this average value can be as low as 200 mg/L. One reason for this is because the U.S. has a greater water use per capita in the home than in Europe and also has problems associated with the infiltration/inflow of water into their wastewater collection system. (a) If the BOD rate constant for untreated wastewater is 0.35/day, calculate the ultimate BOD of the untreated European and U.S. wastewaters. (b) Assume the dissolved oxygen concentration of oxygen saturated dilution water used in the BOD test is 8 mg/L and you are using a 300-mL BOD bottle. Estimate the volume of sample you would add to the BOD bottle to ensure satisfactory test results for the European and U.S. samples (mL).

Solution:

a) Use equation 5.34 to solve for the ultimate BOD

$$L_0 = \frac{y_t}{(1-e^{-k_L t})}$$

$$L_{o\ europe} = \frac{600\ mg/L}{1-e^{-(0.35/day)(5\ days)}} = \boldsymbol{726\ mgO_2/L}$$

$$L_{o\ USA} = \frac{200\ mg/L}{1-e^{-(0.35/day)(5\ days)}} = \boldsymbol{242\ mgO_2/L}$$

b) This part of the problem is similar to example 5.6 except we want to find the volume of the sample. The 5-day BOD (y_5) is the amount of oxygen consumed over the 5-day period corrected for the dilution of the original sample. This can be written as follows:

$$y_5 = \frac{[DO_{initial} - DO_{final}]}{\left[\frac{mL\ sample}{total\ test\ volume}\right]} = 600\frac{mg}{L}(europe)or\ 200\frac{mg}{L}U.S.$$

Solve the equation for the volume of the sample (mL sample) in the denominator.

$$mL\ sample = \frac{[DO_{initial} - DO_{final}]}{y_5}[total\ test\ volume]$$

$$mL\ sample_{europe} = \frac{[8mg/L - 2\ mg/L]}{600\ mg/L}[300mL] = \boldsymbol{3\ mL}$$

$$mL\ sample_{USA} = \frac{[8mg/L - 2\ mg/L]}{200\ mg/L}[300mL] = \boldsymbol{9\ mL}$$

5.33 (a) Calculate the ultimate BOD of a waste that has a measured 5-day BOD of 20 mg/L, assuming a BOD rate coefficient of 0.15/day measured at 20^{o}C. (b) Estimate the rate coefficient and resulting BOD ultimate if the temperature of the waste is raised to 30^{o}C.

Solution:

a) Use equation 5.34 to solve for the ultimate BOD

$$L_0 = \frac{y_t}{(1-e^{-k_L t})}$$

$$L_o = \frac{20 mg/L}{1 - e^{-(0.15/day)(5\ days)}} = \mathbf{38\ mgO_2/L}$$

b) Use equation 3.55 to calculate the rate coefficient if the temperature is raised to 30°C:

$$k_{T_2} = k_{T_1} \times \Theta^{(T_2 - T_1)}$$

$$k_{30} = 0.15/day \times 1.072^{(30℃ - 20℃)} = \mathbf{0.30/day}$$

Use this rate constant in the ultimate BOD equation

$$L_o = \frac{20 mg/L}{1 - e^{-(0.30/day)(5\ days)}} = \mathbf{26\ mgO_2/L}$$

5.34 A 5 mL wastewater sample is placed in a standard 300 mL BOD bottle, and the bottle is filled with dilution water. The bottle had an initial dissolved-oxygen concentration of 9 mg/L and a final dissolved-oxygen concentration of 3.5 mg/L. A blank (a BOD bottle filled with dilution water) run in parallel showed no change in dissolved oxygen over the 5-day incubation period. The BOD reaction rate coefficient for the waste is 0.3/day. Calculate the 5-day (y_5) and ultimate (L_0) BOD of the wastewater.

Solution:

Use the equation in example 5.7 to calculate the 5-day BOD of the wastewater:

$$y_5 = \frac{[DO_{initial} - DO_{final}]}{\left[\frac{mL\ sample}{total\ test\ volume}\right]} = \frac{[9\ mg/L - 3.5\ mg/L]}{\left[\frac{5\ mL}{300\ mL}\right]} = \mathbf{330\ mg\ O_2/L}$$

Use equation 5.34 to solve for the ultimate BOD:

$$L_0 = \frac{y_t}{(1-e^{-k_L t})} = \frac{330\ mg\ O_2/L}{1-e^{-(0.3/day)(5day)}} = \mathbf{425\ mg\ O_2/L}$$

5.35 A city has a population of 50,000 people, an average household generated wastewater flow of 430 L/day-person, and the average BOD$_5$ of the untreated wastewater in population equivalents is 0.1 kg BOD$_5$/day-person. If the BOD reaction rate coefficient for the wastestream is 0.4/day, determine the ultimate (L_0) BOD of the wastewater.

Solution:

First, calculate the volume of water used by the city population in five days:

$$50{,}000\ people\ \times \frac{430L}{day - person} \times 5days = 1.08 * 10^8 L$$

Second, calculate the mass of BOD$_5$ by the city population in five days:

$$0.1kg \frac{BOD_5}{day - person} \times 50{,}000\ people \times 5\ days = 2.5 * 10^4\ BOD_5$$

Divide the mass of BOD$_5$ by the volume of water to calculate the 5-day BOD of the wastewater

$$y_5 = \frac{2.5 * 10^4\ BOD_5}{1.08 * 10^8 L} \times \frac{1000\ g}{1\ kg} \times \frac{1000mg}{1\ g} = 233\ mgO_2/L$$

Use equation 5.34 to solve for the ultimate BOD:

$$L_0 = \frac{y_t}{(1 - e^{-k_L t})} = \frac{233\ mg\ O_2/L}{1 - e^{-(0.4/day)(5day)}} = \mathbf{269\ mg\ O_2/L}$$

5.36 A 10-mL sample is added to a 300-mL BOD bottle. Dilution water is added to the sample bottle and the initial dissolved oxygen concentration is measured as 8.5 mg/L. After the sample is sealed, the laboratory incorrectly takes a measurement of dissolved oxygen reading on day 6 of 3 mg/L. If the BOD reaction rate coefficient for the sample is 0.30/day, (a) estimate what the 5-day BOD should have been. (b) estimate what the dissolved oxygen reading should have been on day 5. (c) determine the ultimate BOD of this sample.

Solution:

a) Use the equation in example 5.7 to calculate the 5-day BOD of the wastewater:

$$y_5 = \frac{\left[DO_{initial} - DO_{final}\right]}{\left[\frac{mL\ sample}{total\ test\ volume}\right]} = \frac{[8.5\ mg/L - 5\ mg/L]}{\left[\frac{10\ mL}{300\ mL}\right]} = \mathbf{105\ mg\ O_2/L}$$

b) $8.5\frac{mg}{L} - \frac{0.3}{day}(5\ days) = \frac{\mathbf{7\ mg}}{\mathbf{L}}$

c) Use equation 5.34 to solve for the ultimate BOD:

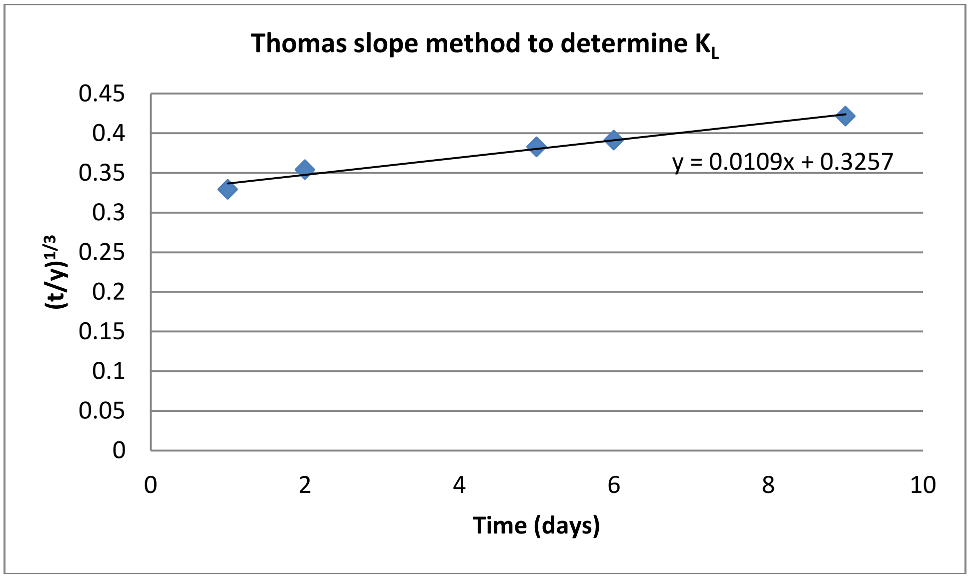
$$L_0 = \frac{y_t}{(1 - e^{-k_L t})} = \frac{105\ mg\ O_2/L}{1 - e^{-(0.3/day)(5day)}} = \mathbf{135\ mg\ O_2/L}$$

5.37 You are provided the following BOD data collected over a 10 day period. Day 1: BOD = 28 mg/L, Day 2: BOD = 45 mg/L; Day 5: BOD = 89 mg/L; Day 6: BOD = 100 mg/L; Day 9: BOD = 120 mg/L. Calculate the BOD rate constant and the ultimate BOD of the sample.

Solution:

Use the Thomas slope method to determine the CBOD reaction-rate coefficient. Plot the parameter $(t/y)^{1/3}$ versus t where y is the CBOD. k_L is determined from the slope and intercept of the trendline fitted to the data using equation 5.35 below:

$$k_L = 6.01\frac{\text{slope}}{\text{intercept}}$$



According to the plot, the slope is 0.0109 and the intercept is 0.326. k_L can now be calculated.

$$k_L = 6.01\frac{0.0109}{0.326} = \mathbf{0.20/day}$$

Use equation 5.34 to solve for the ultimate BOD:

$$L_0 = \frac{y_t}{(1-e^{-k_L t})} = \frac{120\ mg\ O_2/L}{1-e^{-(0.20/day)(9day)}} = \mathbf{144\ mg\ O_2/L}$$

5.38 Suppose the estimated BOD of an influent sample is expected to be 150 mg/L and the dissolved oxygen of oxygen saturated dilution water used in the BOD test is 8.5 mg/L. If you are using a 300-mL BOD bottle, estimate the maximum and minimum amount of sample you would add to the BOD bottle to ensure satisfactory test results.

Solution:

This problem is similar to example 5.8.

Minimum dilution ensures that 2 mg/L of oxygen is depleted.

$$mL\ sample\ added\ to\ the\ BOD\ bottle$$
$$= minimum\ allowable\ oxygen\ depletion\left(\frac{mg}{L}\right) \times \frac{volume\ of\ BOD\ bottle\ (mL)}{estimated\ BOD\ \left(\frac{mg}{L}\right)}$$

$$minimum\ sample(mL) = \left(8.5\frac{mg}{L} - \frac{6.5mg}{L}\right) \times \frac{300\ mL}{150\ mg/L} = \mathbf{4\ mL}$$

Maximum Dilution (ensures that 1 mg/L of oxygen remains in the bottle at the end of the test) is determined as follows.

$$mL\ sample\ added\ to\ the\ BOD\ bottle$$
$$= maximum\ allowable\ oxygen\ depletion\left(\frac{mg}{L}\right) \times \frac{volume\ of\ BOD\ bottle\ (mL)}{estimated\ BOD\ \left(\frac{mg}{L}\right)}$$

$$minimum\ sample(mL) = \left(8.5\frac{mg}{L} - \frac{1\ mg}{L}\right) \times \frac{300\ mL}{150\ mg/L} = \mathbf{15\ mL}$$

5.39 If the BOD rate constant at 20°C is 0.12/day, what is the BOD rate constant at 10°C? What fraction of ultimate BOD would remain in a sample that has been incubated for 3 days (a) at 20°C and (b) at 10°C? (c) Solve for the fraction of ultimate BOD remaining at 20 and 10 °C, but after 6 days of incubation.

Solution:

Use equation 3.55 to calculate the rate coefficient if the temperature is raised to 10℃:

$$k_{T_2} = k_{T_1} \times \Theta^{(T_2 - T_1)}$$

$$k_{30} = 0.12/day \times 1.072^{(10℃ - 20℃)} = \mathbf{0.06/day}$$

For parts a-c, solve for the fraction of ultimate BOD that would remain in the sample in terms of y_t, the CBOD exerted at any time *t*. Use equation 5.33:

$$y_t = L_0(1 - e^{-k_L t})$$

a)

$$y_{3days\,@\,T=20℃} = L_o\left(1 - e^{-\left(\frac{0.12}{day}\right)(3days)}\right) = \mathbf{0.30L_o}$$

b)

$$y_{6\ days\,@\,T=10℃} = L_o\left(1 - e^{-\left(\frac{0.06}{day}\right)(3days)}\right) = \mathbf{0.16L_o}$$

c)

$$y_{6days\,@\,T=20℃} = L_o\left(1 - e^{-\left(\frac{0.12}{day}\right)(6days)}\right) = \mathbf{0.51L_o}$$

$$y_{6days\,@\,T=10℃} = L_o\left(1 - e^{-\left(\frac{0.06}{day}\right)(6days)}\right) = \mathbf{0.30L_o}$$

5.40 The estimated BOD of an influent sample is expected to be 280 mg/L and the dissolved oxygen of oxygen saturated dilution water used in the BOD test is 9 mg/L. If you are using a 250-mL BOD bottle, estimate the maximum and minimum amount of sample you would add to the BOD bottle to ensure satisfactory test results.

Solution:

This problem is similar to example 5.8.

Minimum dilution ensures that 2 mg/L of oxygen is depleted.

$$mL\ sample\ added\ to\ the\ BOD\ bottle$$
$$= minimum\ allowable\ oxygen\ depletion\left(\frac{mg}{L}\right) \times \frac{volume\ of\ BOD\ bottle\ (mL)}{estimated\ BOD\ \left(\frac{mg}{L}\right)}$$

$$minimum\ sample(mL) = \left(9\frac{mg}{L} - 7\frac{mg}{L}\right) \times \frac{250\ mL}{280\ mg/L} = \mathbf{2\ mL}$$

Maximum Dilution (ensures that 1 mg/L of oxygen remains in the bottle at the end of the test) is determined as follows.

$$mL\ sample\ added\ to\ the\ BOD\ bottle$$
$$= maximum\ allowable\ oxygen\ depletion\left(\frac{mg}{L}\right) \times \frac{volume\ of\ BOD\ bottle\ (mL)}{estimated\ BOD\ \left(\frac{mg}{L}\right)}$$

$$maximum\ sample(mL) = \left(9\frac{mg}{L} - \frac{1\ mg}{L}\right) \times \frac{250\ mL}{280\ mg/L} = \mathbf{7\ mL}$$

5.41 Excess nitrogen inputs to estuaries have been scientifically linked to poor water quality and degradation of ecosystem habitat. The nitrogen loading to Narragansett Bay was estimated to be 8,444,631 kg N/year and to Chesapeake Bay is 147,839,494 kg N/year. The watershed area for Narragansett Bay is 310,464 ha and for Chesapeake Bay is 10,951,074 ha. The nitrogen loading rates are estimated for Galveston Bay to be 16.5 kg N per ha per year, 26.9 kg N per ha per year for Tampa Bay, 49.0 kg N per ha per year for Massachusetts Bay, and 20.2 kg N per ha per year for Delaware Bay. (a) Rank the loading rates from lowest to highest for these six estuaries.

Solution:

You need to calculate the loading rates for Narragansett and Chesapeake Bay. These are simple unit conversions. The rest of the nitrogen loading rates can be found in the problem statement and ranked from lowest to highest in the final table below.

$$Narragansett\ Bay\ nitrogen\ loading\colon \frac{8{,}444{,}631\,\frac{kgN}{yr}}{310{,}464\ ha} = 27.2\,\frac{kgN}{ha\ yr}$$

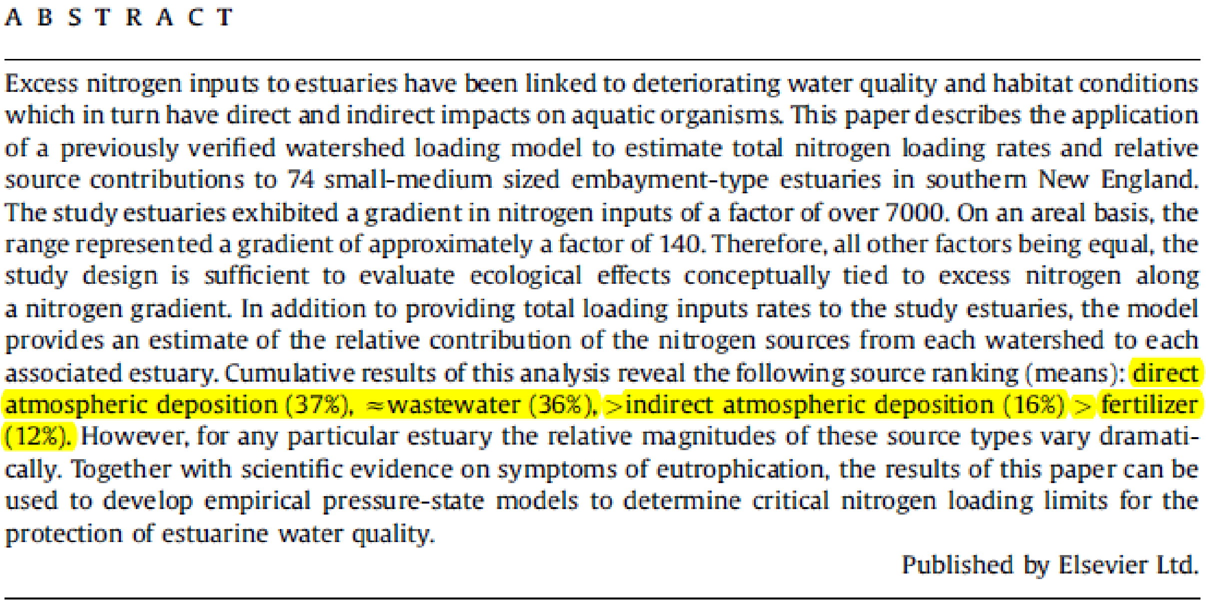
$$Chesapeake\ Bay\ nitrogen\ loading\colon \frac{147{,}839{,}949\,\frac{kgN}{yr}}{10{,}951{,}074\ ha} = 13.5\,\frac{kgN}{ha\ yr}$$

Ranking	**Estuary**	**Nitrogen Loading** $\frac{kgN}{ha\ yr}$
1	Chesapeake Bay	13.5
2	Galveston Bay	16.5
3	Delaware Bay	20.2
4	Tampa Bay	26.9
5	Narragansett Bay	27.2
6	Massachusetts Bay	49.0

5.42 Excess nitrogen inputs to estuaries have been scientifically linked to poor water quality and degradation of ecosystem habitat. Perform a library search for the paper title "Nitrogen inputs to seventy-four southern New England estuaries: Application of a watershed nitrogen model (J.S. Latimer and M.A. Charpentier, *Estuarine, Coastal and Shelf Science*, 89:125-136, 2010). Based on this article, what is the percent contribution of the following four sources of nitrogen to the watershed of the New England estuaries? i) Direct atmospheric deposition to the estuaries, ii) wastewater, iii) indirect atmospheric deposition to the watershed of the estuary, iv) fertilizer runoff from lawns, golf courses, and agriculture.

Solution:

After performing a library search for the paper, the percent contribution of nitrogen based on the source in New England estuaries is in the abstract:



ABSTRACT

Excess nitrogen inputs to estuaries have been linked to deteriorating water quality and habitat conditions which in turn have direct and indirect impacts on aquatic organisms. This paper describes the application of a previously verified watershed loading model to estimate total nitrogen loading rates and relative source contributions to 74 small-medium sized embayment-type estuaries in southern New England. The study estuaries exhibited a gradient in nitrogen inputs of a factor of over 7000. On an areal basis, the range represented a gradient of approximately a factor of 140. Therefore, all other factors being equal, the study design is sufficient to evaluate ecological effects conceptually tied to excess nitrogen along a nitrogen gradient. In addition to providing total loading inputs rates to the study estuaries, the model provides an estimate of the relative contribution of the nitrogen sources from each watershed to each associated estuary. Cumulative results of this analysis reveal the following source ranking (means): direct atmospheric deposition (37%), ≈wastewater (36%), >indirect atmospheric deposition (16%) > fertilizer (12%). However, for any particular estuary the relative magnitudes of these source types vary dramatically. Together with scientific evidence on symptoms of eutrophication, the results of this paper can be used to develop empirical pressure-state models to determine critical nitrogen loading limits for the protection of estuarine water quality.

Published by Elsevier Ltd.

i. Direct atmostpheric deposition (**37%**)
ii. Wastewater (**36%**)
iii. Indirect atmostpheric deposition to the watershed estuary (**16%**)
iv. Fertilizer runoff from lawns, golf courses and agriculture (**12%**)

5.43 Humans produce 0.8 to 1.6 L of urine per day. The annual mass of phosphorus in this urine on a per capita basis ranges from 0.2 to 0.4 kg P. a) what is the maximum concentration of phosphorus in human urine in mg P/L? b) what is the concentration in moles P/L? c) most of this phosphorus is present as HPO_4^{2-}. What is the concentration of phosphorus in mg HPO_4^{2}-/L?

Solution:

a) $[P]_{max} = \frac{0.4\ kg}{year} \times \frac{1000g}{1\ kg} \times \frac{1000\ mg}{1\ g} \times \frac{1day}{0.8\ L} \times \frac{year}{365\ days} = \mathbf{1369}\frac{\boldsymbol{mg}}{\boldsymbol{L}}.$

b) $1369\frac{mg}{L} \times \frac{1\ g}{1000\ mg} \times \frac{1\ mol\ \mathrm{P}}{30.97\ g} = \mathbf{0.04}\ \frac{\boldsymbol{mol}\ \mathbf{P}}{\boldsymbol{L}}$

c) $0.04\ \frac{mol\ \mathrm{P}}{L} \times \frac{1\ mol\ \mathrm{HPO_4}^{2-}}{1\ mol\ \mathrm{P}} \times \frac{95.97\ g}{1\ mol\ \mathrm{HPO_4}^{2-}} \times \frac{1000\ mg}{1\ g} = \mathbf{3838}\frac{\boldsymbol{mg}}{\boldsymbol{L}}$

5.44 Assume 66% of phosphorus in human excrement in found in urine (the remaining 34% is found in feces). Assume humans produce 1 L of urine per day and the annual mass of phosphorus in this urine is 0.3 kg P. If indoor water usage is 80 gallons per capita per day in a single individual apartment, what is the concentration (in mg P/L) in the wastewater that is discharged from the apartment unit? Account for phosphorus in urine and feces.

Solution:

First, solve for x, the total mass of phosphorous in feces and urine.

$$0.66\ \times x\ = 0.3\ kg$$

$$x = \frac{0.3\ kg}{.66} = 0.45\ kg\ \mathrm{P}$$

$$\frac{0.45\ kg\ \mathrm{P}}{(80+1)L} \times \frac{1000\ g}{1\ kg} \times \frac{1000\ mg}{1\ g} = \mathbf{5.5\ \times 10^{3}}\,\frac{\boldsymbol{mg}\ \mathbf{P}}{\boldsymbol{L}}$$

5.45 Fish that reside in the Potomic River Estuary have bioaccumulation factors (BAFs) reported as 26,200,000 (units of L/kg) for largemouth bass and 10,500,000 for white perch. If the concentration of PCB116 dissolved in the water column is 0.064 ng/L, what is the estimated concentration of PCB116 in the fish (ng/kg).

Solution:

$$[PCB116]_{large\ mouth\ bass} = 26{,}200{,}000\,\frac{L}{kg} \times 0.064\,\frac{ng}{L} = \mathbf{1.7 \times 10^{6}}\boldsymbol{ng/kg}$$

$$[PCB116]_{white\ perch} = 10{,}500{,}000\,\frac{L}{kg} \times 0.064\,\frac{ng}{L} = \mathbf{6.7 \times 10^{5}}\boldsymbol{ng/kg}$$

5.46 Concentrations of one particular PCB dissolved in the waters of Lake Washington near Seattle were reported to be 42 pg/L. Estimate the fish-specific BAF (in units of L/kg) for (a) cutthroat with a measured fish concentration of 375 ppb, (b) yellow perch with a measured fish concentration of 191 ppb, and (c) pikeminnows which have a measured fish concentration of 1,000 ppb.

Solution:

The **bioaccumulation factor (BAF)** is defined as "..the ratio of the concentration of a chemical in an organism to that in the surrounding medium…"

a) From chapter two, $375\ ppb_m = \frac{.375\ mg\ PCB}{1.0\ kg\ fish}$

$$BAF = \frac{.375\ mgPCB/kg}{42\ pg/L} \times \frac{10^9\ pg}{mg} = \mathbf{8.9 \times 10^6 L/kg}$$

b)

$$BAF = \frac{.191\ mgPCB/kg}{42\ pg/L} \times \frac{10^9\ pg}{mg} = \mathbf{4.5 \times 10^6 L/kg}$$

c)

$$BAF = \frac{1\ mgPCB/kg}{42\ pg/L} \times \frac{10^9\ pg}{mg} = \mathbf{2.4 \times 10^7 L/kg}$$

5.47 Go to the IPCC Web site (www.ipcc.ch). Choose a specific ecosystem to study, and use information from the Web site to research the impact of climate change on that ecosystem. Write a one-page essay (properly referenced) summarizing your findings.

Solution:

Students' responses will vary.

5.48 Biofuels are being suggested as a method to close the carbon loop. Do a library and Internet search on a particular type of biofuel. Write a one-page essay that addresses the link between biofuels and the global carbon cycle. Also address the impact that your particular biofuel may have on water quality, food supply, biodiversity, and air quality.

Solution:

Students' responses will vary.

5.49 According to the U.S. Environmental Protection Agency, mountain top coal mining consists of removal of mountaintops to expose coal seams and subsequent disposal of the associated mining overburden in adjacent valleys (see http://www.epa.gov/region3/mtntop/). In your own words, discuss the environmental impacts associated with mountain top mining. How does this relate to EPA's Healthy Waters Priority Program and does this method of providing energy fit into a sustainable future that considers social, environmental, and economic balance?

Solution:

Students' responses will vary.

5.50 The U.S. Environmental Protection Agency defines a TMDL as the calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards. The TMDL approach is a way to apply carrying capacity to a particular waterbody. Under section 303(d) of the Clean Water Act, states, territories, and authorized tribes are required to develop lists of impaired waters. Go the following web site (http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/index.cfm) that lists the states which EPA is under court order or agreed in a consent decree to establish TMDLs for. Produce a clear and easy to read map of all 50 states that shows the locations of these states.

Solution:

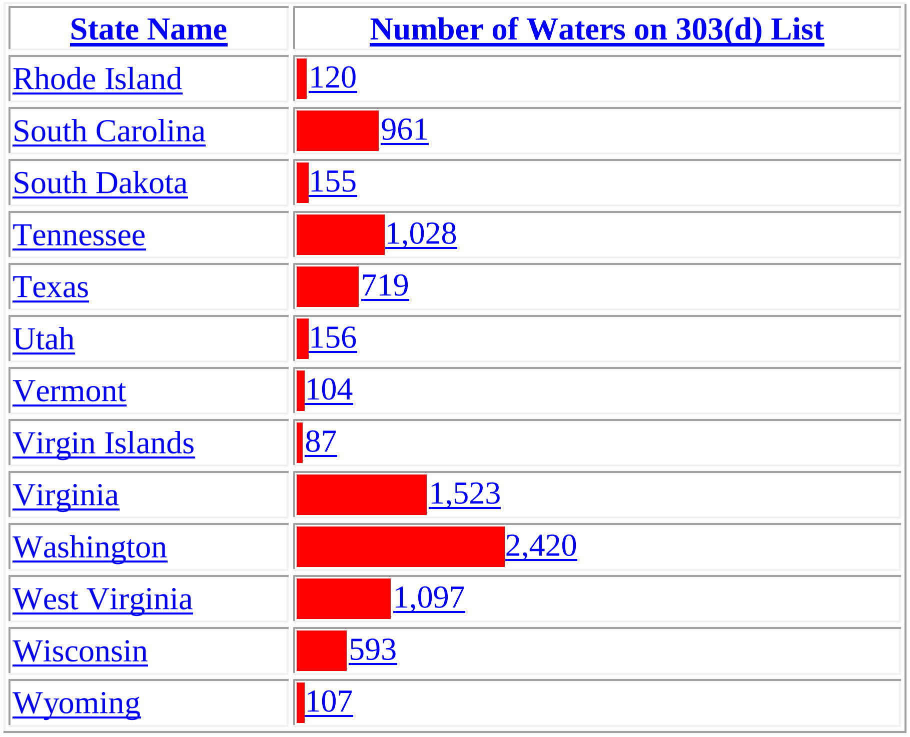
The purpose of this problem is to show students the severity of water impairment in the United States. As of November, 2013 the EPA web site reported the following impaired waters by state. Note that each state has a significant number of impaired waters. Thus the map the students draw of the country will have all 50 states included.

If an instructor wishes, students could be asked to produce the same figure and list the number of impaired water bodies in each state, or break the number of impaired water bodies in groups of < 50, 51-100, 101-250, 251-500, > 501 and then shade in states according to number of impaired water bodies.

Impaired Waters Listed By State (as of November, 2013).

State Name	Number of Waters on 303(d) List
Alabama	209
Alaska	35
American Samoa	44
Arizona	79
Arkansas	225
California	1,021
Colorado	244
Connecticut	425
Delaware	101
District Of Columbia	36
Florida	2,292
Georgia	215
Guam	47

State Name	Number of Waters on 303(d) List
Hawaii	309
Idaho	916
Illinois	1,057
Indiana	1,836
Iowa	480
Kansas	1,330
Kentucky	1,300
Louisiana	274
Maine	114
Maryland	184
Massachusetts	720
Michigan	2,352
Minnesota	1,144
Mississippi	180
Missouri	257
Montana	584
N. Mariana Islands	24
Nebraska	330
Nevada	215
New Hampshire	1,449
New Jersey	716
New Mexico	209
New York	528
North Carolina	1,270
North Dakota	201
Ohio	267
Oklahoma	723
Oregon	1,397
Pennsylvania	6,957
Puerto Rico	165



State Name	**Number of Waters on 303(d) List**
Rhode Island	120
South Carolina	961
South Dakota	155
Tennessee	1,028
Texas	719
Utah	156
Vermont	104
Virgin Islands	87
Virginia	1,523
Washington	2,420
West Virginia	1,097
Wisconsin	593
Wyoming	107

Total: 41,531 impaired waters

Chapter 6 Environmental Risk

6.1 What is the regulatory difference in the RCRA between a hazardous and toxic substance?

Solution:

In regulatory terms according to RCRA, toxicity is a subset of hazardous. A hazardous waste denotes a regulated waste and only certain waste streams are designated as hazardous. Wastes are determined to be hazardous based on: 1) physical characteristics such as reactivity, corrosivity, and ignitability; 2) toxicity; 3) the quantity generated; and, 4) the history of the chemical in terms of environmental damage it may have causes, and the environmental fate. Toxicity is thus a subset of a hazardous waste or chemical.

6.2 Identify several types of risk during your commute to school? Which of these risks would classify as environmental risk?

Solution:

Students' responses will vary. For example, Colleen Naughton is a graduate student at the University of South Florida. She bikes two miles to and from school each day. She is exposed to environmental risk in several ways on her commute. First, she breathes in the exhaust from cars along the road and the air she breathes may also contain biological pathogens. Since she is exercising, she is breathing in more frequently and at higher volumes than sitting. She is also exposed to UV rays from the sun due to ozone depletion. Her skin is also exposed to the polymers on her handle bars and from her helmet. Non environmental risks would include potential accident opportunities between her and the other vehicles as they turn or accidentally ride into the bike lane.

Though there is significant environmental risk associated with biking to campus, there are health benefits compared to cars. Also, with cars, drivers are still exposed to air with biological pathogens and exhaust and have higher exposure to fire retardants and other chemicals in the seats and plastics in their cars.

6.3 Rank these scenarios in order of their environmental risk (low to highest). (a) a factory worker has been provided no protective breathing equipment, and the chemical being emitted has been judged to have zero hazard, (b) a factory worker has been provided protective breathing equipment that removes 99% of a hazardous chemical, (c) a factory worker has been provided protective breathing equipment that removes 100% of a hazardous chemical. (d) a factory worker has been provided protective breathing equipment that removes 100% of a chemical that has been judged to have zero hazard (e) a toxic chemical was identified in a factory's drinking water supply. The worker you are evaluating has a desk job and is not exposed to any of a toxic chemical emitted in the air of the factory manufacturing area. This worker also brings all her water and other beverages from home in reusable containers.

Solution:

Risk is a function of hazard and exposure as seen in equation 6.1:

$$\text{Risk} = f\left(\text{hazard}, \text{exposure}\right)$$

Use this expression to rank the scenarios in the order of their environmental risk (lowest to highest):

1. (e) a toxic chemical was identified in a factory's drinking water supply. The worker you are evaluating has a desk job and is not exposed to any of a toxic chemical emitted in the air of the factory manufacturing area. This worker also brings all her water and other beverages from home in reusable containers.

This assumes that exposure is only from the drinking water and not from other exposure routes like washing his/her hands in the bathroom. The worker brings his/her own water and is, thus, not exposed to the contamination.

2 and 3: (a) a factory worker has been provided no protective breathing equipment and the chemical being emitted has been judged to have zero hazard and **(d)** a factory worker has been provided protective breathing equipment that removes 100% of a chemical that has been judged to have zero hazard.

Both a and d are considered equal risk in this case. In scenario a the worker does not have protective equipment but the chemicals he/she is exposed to are zero hazard. In scenario d, the chemical that the worker is exposed to also has zero hazard and he/she has protective equipment.

4. (c) a factory worker has been provided protective breathing equipment that removes 100% of a hazardous chemical.

Though the worker has breathing equipment that removes 100% of the hazardous chemical, he/she still has the potential to be exposed to the hazardous chemical if, for example, the breathing equipment is not worn correctly. This is a higher risk than both scenarios a and d since the chemicals involved were zero hazard.

5. (b) a factory worker has been provided protective breathing equipment that removes 99% of a hazardous chemical *This has the highest risk of all five scenarios since the protective equipment only removes 99% of a hazardous chemical. In scenario c the protective breathing equipment removes 100% of a hazardous chemical.*

6.4 Rank these three scenarios in order of their environmental risk (low to highest). (a) Customers visit a bar 6 hours per week in a location where the state has passed regulations that prevent customers from smoking inside restaurants and bars. (b) Wait staff are exposed to second hand tobacco smoke 8 hours per day during work. (c) Customers are exposed to second hand tobacco smoke 2 hours per week while dining at the same restaurant as the wait staff in part (b). (d) Wait staff work 8 hours per day in an establishment located in a state that has passed regulations that prevent customers from smoking in restaurants and bars.

Solution:

Risk is a function of hazard and exposure as seen in equation 6.1:

$$\text{Risk} = f\left(\text{hazard}, \text{exposure}\right)$$

Use this expression to rank the scenarios in the order of their environmental risk (lowest to highest):

1 and 2: (a) Customers visit a bar 6 hours per week in a location where the state has passed regulations that prevent customers from smoking inside restaurants and bars. & **(d)** Wait staff work 8 hours per day in an establishment located in a state that has passed regulations that prevent customers from smoking in restaurants and bars.

In this case, scenarios a and b are equal. Though the exposure is longer, there is no hazard as there are regulations against smoking in both scenarios.

3. (c) Customers are exposed to second hand tobacco smoke 2 hours per week while dining at the same restaurant as the wait staff in part (b).

4. (b) Wait staff are exposed to second hand tobacco smoke 8 hours per day during work.

This scenario has the highest risk as it has the longest exposure, 8 hours compared to 2 hours in scenario c to the hazard of second hand smoke.

6.5 What are three considerations besides toxicity that contribute to a chemical being labeled “hazardous”?

Solution:

From section 6.3.1 on Hazardous Waste, four considerations are:

1) Physical characteristics such as reactivity, corrosivity, and ignitability;

2) toxicity;

3) quantity generated; and

4) the **history of the chemical** in terms of environmental damage it caused and the likely environmental fate. Hazardous wastes may or may not exhibit toxicity.

6.6 Identify the top three chemical releases in your hometown or university community using the EPA's Toxic Release Inventory database. What information can you find about the toxicity of these chemicals? Is it easy or difficult to find this information? Is the information consistent, or is it conflicting? Does it vary with source (government versus industry)?

Solution:

Students' responses will vary.

6.7 The EPA released the 2011 Toxic Release Inventory (TRI) National Analysis in January of 2013. Locate this information and fill in Table 6.18 below for toxic chemical disposal and releases (in the year 2011) for the following three large aquatic ecosystems: Long Island Sound, the Gulf of Mexico, and the San Francisco Bay Delta Estuary. All these water bodies of water are recognized as being important for ecological, economic, and social reasons.

Solution:

Go to the EPA Tri website: http://www.epa.gov/tri/ and click on the "National Analysis" link on the left hand side and scroll down and click on the "large aquatic ecosystems link" under a map of the US: http://www.epa.gov/tri/tridata/tri11/nationalanalysis/tri-lae-intro.html. From this web page you can select each of the different large aquatic ecosystems to complete the table.

San Fran: http://www.epa.gov/tri/tridata/tri11/nationalanalysis/tri-lae-san_fran.html

Gulf of Mexico: http://www.epa.gov/tri/tridata/tri11/nationalanalysis/tri-lae-gulf-of-mexico.html

Long Island Sound: http://www.epa.gov/tri/tridata/tri11/nationalanalysis/tri-lae-long-island.html

	San Francisco Bay Delta Estuary	Gulf of Mexico	Long Island Sound
Number of TRI Facilities	437	1,315	47
Area (square miles)	60,000 (watershed)	86,800 (watershed)	17,000
Total On-site and Off-site Disposal or Other Releases	20.6 million lbs	334.7 million lbs	3 million lbs
Total on-site releases to air	3.6 million lbs	104.0 million lbs	1.4 million lbs
Total on-site releases to water	1.3 million lbs	22.3 million lbs	247 thousand lbs
Total on-site releases to land	14.0 million lbs	27.9 million lbs	38 thousand lbs
Underground Injection	9 thousand lbs	151.4 million lbs	None
Top Five Industrial Sectors Contributing to the TRI	Hazardous waste management, petroleum, chemicals, food/beverages/tobacco, primary metals	Chemicals, petroleum, electric utilities, paper, hazardous waste management	Fabricated metals, chemicals, primary metals, plastics and rubber, miscellaneous manufacturing

6.8 Define Pollution Prevention and describe why it is the preferred approach to addressing the challenge of waste.

Solution:

Section 6.3.3 states that **Pollution prevention** is focused on increasing the efficiency of a process to reduce the amount of pollution generated. (section 6.3.3)

According to the EPA: "Pollution prevention is reducing or eliminating waste at the source by modifying production processes, promoting the use of non-toxic or less-toxic substances, implementing conservation techniques, and re-using materials rather than putting them into the waste stream."
(http://www.epa.gov/p2/pubs/p2policy/definitions.htm)

This is the preferred approach to address the challenge of waste since it is less hazardous to the environment and it requires less energy later in clean up and regulation. Though we may be able to remediate sites with hazardous waste, this may take years and 100% removal may never be achieved. Prevention is preferred in this case since clean-up is eliminated in the first place.

6.9 What is the difference between pollution prevention and sustainability?

Solution:

The EPA states that "Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations."

Also according to the EPA: "Pollution prevention is reducing or eliminating waste at the source by modifying production processes, promoting the use of non-toxic or less-toxic substances, implementing conservation techniques, and re-using materials rather than putting them into the waste stream."
(http://www.epa.gov/p2/pubs/p2policy/definitions.htm)

In comparing the two definitions of sustainability and pollution prevention by the EPA, it is evident that sustainability is broader than pollution prevention as it encompasses the social, economic as well as environmental components for future and present generations. Pollution prevention is an important component of sustainability.

6.10 Use the pollution prevention hierarchy to rank the following scenarios from **least to most preferred**. In addition, label each scenario as an example of source reduction, recycling, treatment, or disposal. (a) ammonia nitrogen is transformed to less toxic nitrate nitrogen at the wastewater treatment plant and then discharged to a receiving water body, (b) urine (which contains 75% of the nitrogen excreted by the human body) is collected in the household and applied to a backyard garden as a fertilizer, (c) a homeowner decides to no long place food scraps in a garbage disposal connected to the sink and instead sets up a backyard composting machine, (d) nitrogen in the wastewater is precipitated out and recovered for fertilizer at a centralized treatment plant, as struvite (magnesium ammonium phosphate, $NH_4MgPO_4{\cdot}6H_2O$).

Solution:

Section 6.3.3 defines source reduction, recycling, treatment, and disposal and figure 6.6 depicts the pollution prevention hierarchy.

- **Source reduction**—Waste (hazardous substance, pollutant, or contaminants) should be prevented at the source (prior to recycling, treatment, or disposal).
- **Recycling**—Waste generated should be reused either in the process that created it or in another process.
- **Treatment**—Waste that cannot be recycled should be treated to reduce its hazard.
- **Disposal**—Waste that is not treated should be disposed of in an environmentally safe manner.

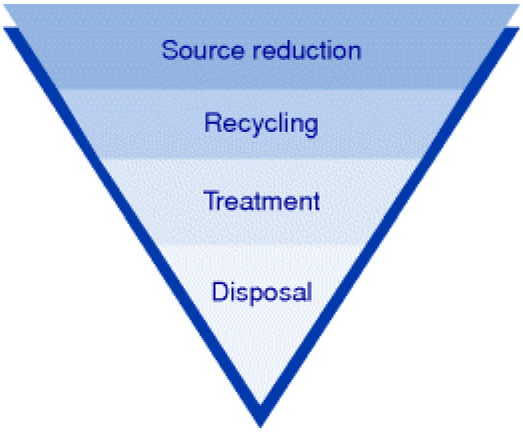


Figure 6.6 Pollution Prevention Hierarchy

When ranking the scenarios, disposal is least preferred and source reduction is most preferred.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

1. (a) ammonia nitrogen is transformed to less toxic nitrate nitrogen at the wastewater treatment plant and then discharged to a receiving water body. **(Disposal** of ammonia nitrogen into a water body even though it is transformed to be less toxic**)**

2. (d) nitrogen in the wastewater is precipitated out and recovered for fertilizer at a centralized treatment plant, as struvite (magnesium ammonium phosphate, $NH_4MgPO_4 \cdot 6H_2O$). (**Recycling** nitrogen in urine as fertilizer)

3 and 4. (c) a homeowner decides to no long place food scraps in a garbage disposal connected to the sink and instead sets up a backyard composting machine, (**Source reduction** as it prevents the food scrap waste from entering the treatment plant. This may also be considered **Recycling** nutrients at the household level)

(b) urine (which contains 75% of the nitrogen excreted by the human body) is collected in the household and applied to a backyard garden as a fertilizer. (**Source reduction** since this urine no longer enters the waste stream that would need to be treated at the waste water treatment plant)

If both scenarios are considered source reduction, scenarios c and b are equal as they are both examples of source reduction.

6.11 Label each scenario as an example of source reduction, recycling, treatment, or disposal. (a) the community collects household solid waste and disposes all the waste in a sanitary landfill. (b) the community implements a yard waste collecdtion program to address this component of the wastestream (assume it makes up 14% of the total wastestream). The yard waste is then composted and reused in the community. (c) the community changes its billing plan from one flat rate charged per household to a new plan that charges households for each bag (or trash can) of solid waste placed on the curb for pickup. Their idea is this will cause homeowners to reduce the amount of waste they produce and discard. (d) a national policy is instituted to reduce the amount of packaging associated with consumer products. (e) households begin to purchase locally grown food from local outlets so the packaging associated with food distribution is reduced. (f) the community solid waste authority requires separation of glass, paper/cardboard, and metal by households in a new curbside recycling program. (g) the community burns solid waste at a high temperature to recover energy, releasing some toxic chemicals into the air and producing an ash product, but reducing the volume of waste that needs to be disposed of in a landfill.

Solution:

Section 6.3.3 defines source reduction, recycling, treatment, and disposal and figure 6.6 depicts the pollution prevention hierarchy.

- **Source reduction**—Waste (hazardous substance, pollutant, or contaminants) should be prevented at the source (prior to recycling, treatment, or disposal).
- **Recycling**—Waste generated should be reused either in the process that created it or in another process.
- **Treatment**—Waste that cannot be recycled should be treated to reduce its hazard.
- **Disposal**—Waste that is not treated should be disposed of in an environmentally safe manner.

(c) the community changes its billing plan from one flat rate charged per household to a new plan that charges households for each bag (or trash can) of solid waste placed on the curb for pickup. Their idea is this will cause homeowners to reduce the amount of waste they produce and discard. (**Source reduction**)

(d) a national policy is instituted to reduce the amount of packaging associated with consumer products. (**Source reduction**)

(e) households begin to purchase locally grown food from local outlets so the packaging associated with food distribution is reduced. (**Source reduction**)

(b) the community implements a yard waste collection program to address this component of the wastestream (assume it makes up 14% of the total wastestream). The yard waste is then composted and reused in the community. (**Recycling**)

(f) the community solid waste authority requires separation of glass, paper/cardboard, and metal by households in a new curbside recycling program. (**Recycling**)

(a) the community collects household solid waste and disposes all the waste in a sanitary landfill. **(Disposal)**

(g) the community burns solid waste at a high temperature to recover energy, releasing some toxic chemicals into the air and producing an ash product, but reducing the volume of waste that needs to be disposed of in a landfill. **(Disposal and Source Reduction)**

6.12 (a) List a different environmental risk associated with an indoor environment in the developed world and developing world. (b) What particular building occupants are at the greatest risk for the items you have identified?

Solution:

Developed World	**Developing World**
Environmental risk is from exposure to chemicals emitting from building materials, paints, floor coverings, and furniture.	Environmental risk is from exposure to smoke associated with burning of solid fuels such as wood.
Group that accepts most of this risk are individuals who occupy the building for a longer period of time. At the home this could be children and a parent or adult who stays home watching the child. At work, this would be employees.	Group that accepts most of this risk are women and children.

6.13 Go to the Web site of the World Health Organization (www.who.org). Based on the information there, write a referenced two-page essay on global environmental risk. How much environmental risk is from factors such as unsafe water and sanitation, indoor air, urban air, and climate?

Solution:

Students' responses will vary however they should reference the Health and Environment Linkages Initiative (HELI) at http://www.who.int/heli/risks/en/. They have identified six major environmental risks that include: (1) unsafe water, poor sanitation and hygiene, responsible for 1.7 million deaths each year (2) indoor smoke which kills 1.6 million people annually, (3) Malaria that kills 1.2 million people each year, (4) urban air pollution which is responsible for 800,000 death annually, (5) unintentional acute poisonings that kill 355,000 people each year, and (6) climate change that cause 150,000 deaths annually. There is a link to each priority risk on the website where the student can obtain more information for their essay.

6.14 Recalling that the Environmental Protection Agency defines environmental justice as the “fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies,” research an issue of environmental justice in your hometown or state. What is the environmental issue? What groups of society are being harmed by the environmental issue? What injustice is taking place?

Solution:

Students’ responses will vary.

6.15 Online at www.scorecard.org, you can search for the location and number of hazardous-waste sites by location. Use it to search for hazardous-waste sites in your hometown or a city close to your university. Comment on whether the number and location of hazardous-waste sites pose any environmental injustice to residents of the community you are investigating.

Solution:

Students' responses will vary based on their university's location. Below is a screen shot of the output from www.scorecard.org for the toxics near University of South Florida. There appear to be three super fund sites located in Hillsborough County.

POLLUTION REPORT CARD

Your Zip Code: 33617 Your Community: HILLSBOROUGH County

TOXICS

Toxic Chemicals Released by Factories, Power Plants and Other Industrial Companies

In 2002, this county ranked among the dirtiest/worst 10% of all counties in the U.S. in terms of total environmental releases.

1. See how your county stacks up against all others in the U.S.
2. Get a list of:
   - the top polluters in your county
   - the top chemicals released in your county
3. Learn more about pollution from industrial facilities in your community.

Lead Hazards

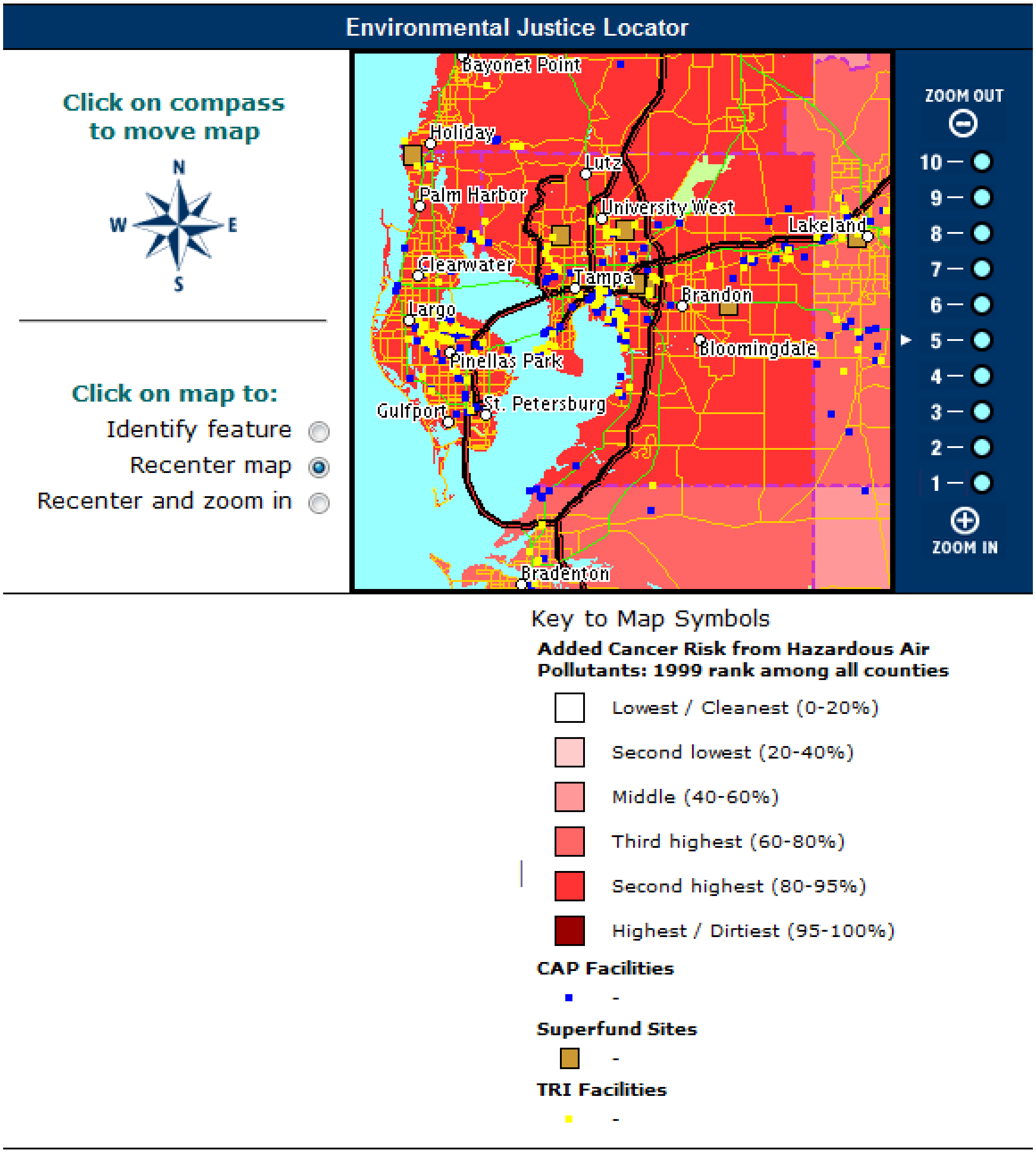
1. 1 percent of houses in HILLSBOROUGH County have a high risk of lead hazards.
2. See how your county stacks up against all others in the U.S.

Worst Toxic Waste Sites (Superfund Sites)

In 2004, this county ranked about the average of all counties in the U.S. in terms of the number of designated Superfund sites.

1. 3 Superfund sites in HILLSBOROUGH County caused contamination of drinking water sources
2. See what Superfund sites are in your community.
3. See how your county stacks up against all others in the U.S.

If you click on the link to "see how your county stacks up", you can view an Environmental Justice Locator. In Hillsborough County, added cancer risk from hazardous air pollutants is ranked the second highest (80-95%) throughout the county (see Figure). It appears that there is environmental injustice caused by the hazardous-waste sites to Hillsborough County.



Click on map to:

Identify feature ○

Recenter map ●

Recenter and zoom in ○

Key to Map Symbols

Added Cancer Risk from Hazardous Air Pollutants: 1999 rank among all counties

☐ Lowest / Cleanest (0-20%)

🟥 Second lowest (20-40%)

🟥 Middle (40-60%)

🟥 Third highest (60-80%)

🟥 Second highest (80-95%)

🟥 Highest / Dirtiest (95-100%)

CAP Facilities

■ -

Superfund Sites

■ -

TRI Facilities

■ -

6.16 List the four components of a complete risk assessment.

Solution:

The four components of a complete risk assessment are: **hazard assessment, dose-response assessment, exposure assessment, and risk characterization.**

6.17 The Integrated Risk Information System (IRIS), an electronic database that identifies human health effects related to exposure to hundreds of chemicals, is available at www.epa.gov/iris. Go to IRIS and determine (a) the weight of evidence descriptor; (b) the reference dose (RfD); and (c) the slope factor if available for the following six chemicals/substances: arsenic, methylmercury, ethylbenzene, methyl ethyl ketone, naphthalene, and diesel engine exhaust.

Solution:

Weight of evidence characterization (obtained from IRIS) that describe the potential for a chemical or substance to cause cancer in humans.

Chemical or substance	**Weight of evidence characterization**	**RfD mg/kg-day**	**Slope factor (mg/kg-day)$^{-1}$**
Arsenic	Human carcinogen	3×10^{-4}	1.5
Methylmercury	Possible human carcinogen	1×10^{-4}	
Ethylbenzene	not classifiable as to human carcinogenicity	0.1	
Methyl ethyl ketone	data are inadequate for an assessment of human carcinogenic potential	0.6	
Naphthalene	Possible human carcinogen	0.02	
Diesel engine exhaust	likely to be carcinogenic to human	exposure is through inhalation, RfC is 5 $\mu g/m^3$	

6.18 Why must children especially be protected from environmental contaminants? Use the term lethal dose (LD) in your answer.

Solution:

In section 6.3.2 on toxicity, median lethal dose (LD50) is defined as “the dose that results in the death of 50 percent of a test organism population.” “The LD50 is typically presented as the mass of contaminant dosed per mass (body weight) of the test organism” in units of mg/kg. It is particularly important to protect children from environmental contaminants since they have a lower body mass. 10 mg of a contaminant will have a higher median lethal dose for a lower body mass (For example, for an average 70kg adult the LD50 would be 0.14mg/kg while for a 10kg child it would be 1 mg/kg).

6.19 A study of the potential of acrylonitrile to produce brain tumors in rats was conducted by administering the carcinogen in drinking water for twenty-four months. The results of the study for female rats are tabulated below.

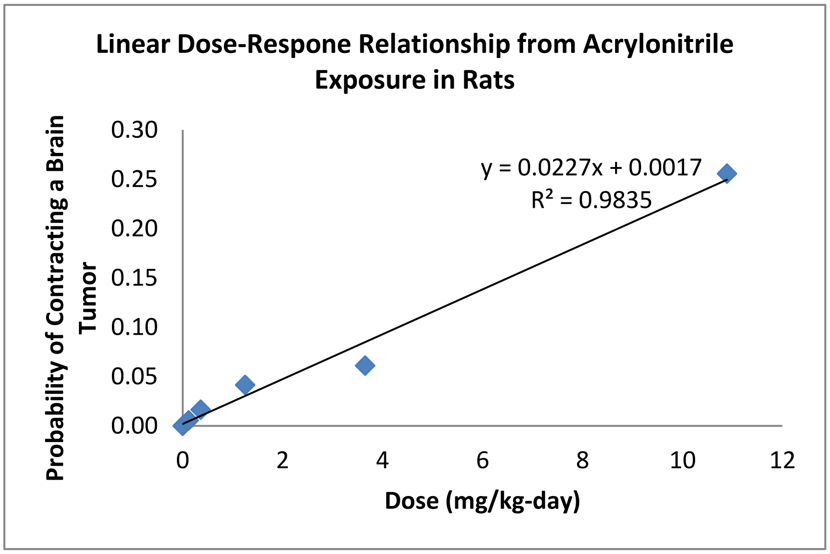
Dose (mg/kg-day)	Brain tumor incidence
0	1/179
0.12	1/90
0.36	2/91
1.25	4/85
3.65	6/90
10.89	23/88

(a) Determine the slope factor (SF) of the dose-response relationship (assume it's linear). (Don't forget to account for the one rat that had a brain tumor even though he wasn't exposed to the chemical). (b) How accurate is the linear model of the data?

Solution:

(a) To account for the one rat that had a brain tumor even though it wasn't exposed to the chemical, subtract the brain tumor incidence at a dose of 0.006 from each row. (See column of the calculated excess risk) Now plot the excess risk vs. the dose to determine the slope factor.

Dose	Brain tumor incidence	Excess Risk
0	0.006	0.000
0.12	0.011	0.006
0.36	0.022	0.016
1.25	0.047	0.041
3.65	0.067	0.061
10.89	0.261	0.256



From the plot, it is evident that the **SF = 0.023 (mg/kg-day)$^{-1}$**

(b) **The linear model of data is accurate** with an R^2 value of 0.98 which is close to one.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

6.20 The EPA maintains a comprehensive site of chemical risk information, called the Integrated Risk Information System (IRIS): http://www.epa.gov/iris/

Visit the page describing the assessment of the Reference Dose (RfD) for Chronic Oral Exposure: http://www.epa.gov/ncea/iris/subst/0209.htm#umforal for the chemical atrazine. Atrazine is a popular herbicide, tens of millions of pounds of atrazine are applied to vegetation in the U.S. annually and it is a widespread drinking water contaminant.

After reading through the brief provided by IRIS, please answer the following: (a) What tests did the EPA/Ciba-Geigy perform in order to assess the toxicity of atrazine? Summarize in tabular format the test subjects, time period, and overall key toxic responses to be observed. (b) What uncertainty factor is used and how was that derived (what are its components)? (c) What are the NOAEL and RfD for atrazine, and to which response do these doses refer?

Solution:

a.

Test subjects	**Time period**	**Toxic responses**
Sprague-Dawley rats	2 years	• Decrease body weight and weight gain, • lower mean red cell count, hemoglobin and hematocrit, • increase in platlet count, • decreased triglyceride and glucose levels, • lower absolute weight of vital organs, • acinar hyperplasia of mammary gland, • epithelial hyperplasia of the prostate, • increased myeloid hyperplasia in the bone marrow of both the femur and sternum, • muscle and retinal degeneration, and • increase in coagulative centrolobular necrosis in the liver.
Groups of 5-month old beagle dogs	1 year	• Cardiopathy syndrome, • cardiac toxicity, • dilation of right and occasionally the left atriums (manifesting as atrophy and myelosis), and • death.
Charles River CD Rats	133-152 days	• Lower body weights and depressed body weight gains, and • reduced food consumption.

Test subjects	**Time period**	**Toxic responses**
Charles River rats	Dosing period: 6-15 days during gestation	• Maternal toxicity, • death, • reduced food consumption, • reduced weight gain, • salivation, • ptosis, • swollen abdomen, • oral/nasal discharge, • bloody vulva, and • delayed ossification.
Rabbit	Dosing period: 7-19 days during gestation	• Maternal toxicity, • decreased body weight gain, • low-food efficiency, • abnormal stool samples, • blood on vulva, • developmental toxicity, • decreased total live fetuses and litter size, • increase post-implantation loss, and • decrease in mean fetal weight.

b. **The uncertainty factor of 100 reflects 10 for interspecies extrapolation and 10 for intraspecies-variability.**

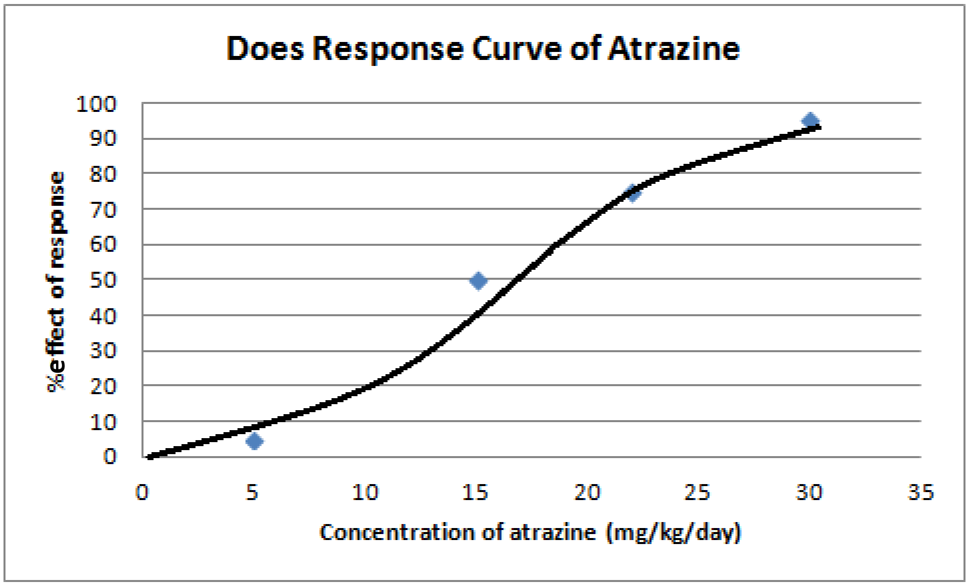
c. **NOAEL is 70ppm (3.5 mg/kg-day) and the RfD is 3.5*10^{-2} mg/kg-day which is based off a 2-year rat feeding study.**

6.21 Visit the page describing the assessment of the Reference Dose (RfD) for Chronic Oral Exposure: http://www.epa.gov/ncea/iris/subst/0209.htm#umforal for the chemical atrazine. Atrazine is a popular herbicide, tens of millions of pounds of atrazine are applied to vegetation in the U.S. annually and is a widespread drinking water contaminant. (a) What are the NOAEL and RfD for atrazine, and to which response do these doses refer? (b) Assume the following additional toxicity data points: LOAEL – 5 mg/kg/day (affects 5% of population); LD50 – 15 mg/kg/day; Other data points – 22 mg/kg/day (affects 75% of population), 30 mg/kg/day (affects 95% of population). Draw a dose-response curve for these data. (c) What is the approximate slope of the curve? (d) Now consider applying atrazine to your lawn and assume that there are babies in the household that like to eat grass. What is the maximum amount of grass that a baby can eat safely in a day? Assume the following conditions: baby weight ~10kg, residual atrazine concentration on grass from one application is ~0.01% (where 1% = 10,000 ppm_m). (e) Given these results from part (d), does spraying your lawn with atrazine present any serious risk in this case? Use the “Hazard Quotient” to make this determination.

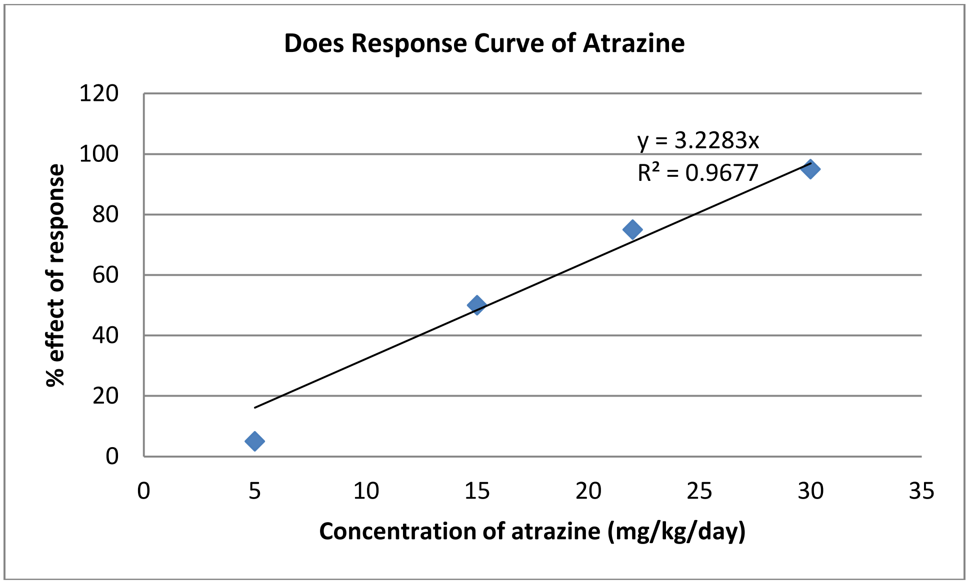
Solution:

a. **NOAEL is 70ppm (3.5 mg/kg-day) and the RfD is $3.5*10^{-2}$ mg/kg-day which is based off a 2-year rat feeding study.**

b. Plot the % effect response vs. the concentration of atrazine in order to draw the dose-response curve as in figure 6.5 in the textbook.



c. Adding a trendline to the % effect of response vs. the concentration of atrazine plot, and setting the intercept to zero, the approximate slope of the curve is **3.2 % effect of response/mg/kg/day.**



d. As given in the problem: 1% = 10,000 ppm_m which, as covered in chapter 2, is equal to 100 mg atrazine/kg grass. From part a, the NOAEL is 3.5 mg/kg-day. Using unit conversions and the weight of an average baby given in the problem as 10kg; the amount of grass a baby can eat per day can be calculated as shown:

$$3.5\frac{mg}{kg-day}\times 10\ kg\times\frac{1\ kg\ grass}{100\ mg\ atrazine}\times\frac{1000g}{1\ kg}=\boldsymbol{350\ grams\ of\ grass}$$

e. The hazard quotient can be calculated using equation 6.6:

$$HQ=\frac{average\_daily\_dose}{RfD}$$

Use the reference dose found from part a and your results from part d as well.

$$HQ=\frac{350\ \frac{mg\ grass}{day}\times\frac{1}{10\ kg}}{3.5*10^{-2}\frac{mg}{kg-day}}=1000$$

Spraying your lawn with atrazine presents a serious risk to babies who eat grass since the hazard quotient is much greater than 1.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

6.22 The sigmoid curve used in a dose-response analysis (and many other engineering applications) has the form:

$$response(x) = \frac{1}{1+e^{LD50-x}}$$, where *x* is the dose in mg/kg/day

(a) Show mathematically that the inflection point of the dose-response curve occurs when $x = LD50$. What does this mean in practical terms? (b) Using the information provided in Question 6.21, provide the dose-response equation for atrazine. What is the dose necessary to produce a lethal response in 90% of the test population?

Solution:

a. Substitute x=LD50 in the sigmoid curve given in the problem:

$$response(x) = \frac{1}{1+e^{LD50-LD50}} = \frac{1}{1+e^{0}} = \frac{1}{1+1} = 1/2$$

This corresponds to the definition of LD50, the median lethal dose, “which is the dose that results in the death of 50% of a test organism population.”

b. LD50 is given in question 6.21 as 15 mg/kg/day. Using this value and setting response(x) equal to 0.90 for a lethal reponse of 90%, solve for the required dose:

$$0.90 = \frac{1}{1+e^{15\frac{mg}{kg-day}-x}}$$

$$1+e^{15\frac{mg}{kg-day}-x} = \frac{1}{0.9}$$

$$e^{15\frac{mg}{kg-day}-x} = \frac{1}{0.9} - 1$$

$$15\frac{mg}{kg-day} - x = \ln\left(\frac{1}{0.9} - 1\right)$$

$$x = 15\frac{mg}{kg-day} - \ln\left(\frac{1}{0.9} - 1\right) = \mathbf{17}\ \boldsymbol{\frac{mg}{kg-day}}$$

6.23 Consider a pharmaceutical product with two dose-response curves, one that shows the effective dose (ED) and the second that shows the lethal dose (LD). Assume that *LD*50 = 2 ×*ED*50 and is equal to 28.27 mg/kg/day. This pharmaceutical company makes money from selling each course of this drug (*D* dollars per *effective* dose) but must pay damages for each death that it causes (1,000*D* dollars per *lethal* dose). (a) Putting aside questions of ethics and market acceptability, what should the company set as its recommended dose in order to maximize profits? Show all your work. Hint: You will need to utilize the equation in problem 6.22.

Solution:

a. First, solve for ED50 from the equation given in the problem.

$$LD50 = 2ED50 = 28.27\ \frac{mg}{kg-day}$$

$$\therefore ED50 = \frac{28.27\ \frac{mg}{kg-day}}{2} = 14.135\ \frac{mg}{kg-day}$$

Second, derive a profit expression:

$$Profit = \frac{D}{1+e^{ED50-x}} - \frac{1000\ D}{1+e^{LD50-x}}$$

Third, take the first derivative to set the equation equal to 0:

$$\frac{dD}{dX} = 0 = \frac{e^{ED50-x}}{(1+e^{ED50-x})^2} - \frac{1000\ e^{LD50-x}}{(1+e^{LD50-x})^2}$$

Fourth, substitute the value of ED50:

$$\frac{dD}{dX} = 0 = \frac{e^{ED50-x}}{(1+e^{ED50-x})^2} - \frac{1000\ e^{LD50-x}}{(1+e^{LD50-x})^2}$$

Fifth, solve for x, the recommended dose in order to maximize profits using excel or a graphing calculator solver tool:

$$x = \mathbf{17.72}\ \boldsymbol{\frac{mg}{kg-day}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

6.24 Visit the following EPA Office of Pesticides webpage that provides information on the state of the U.S. federal scientific debate on atrazine:
http://www.epa.gov/oppsrrd1/reregistration/atrazine/atrazine_update.htm

Write a one-page memo from the perspective of the strategy team at Syngenta, one of the main global manufacturers of atrazine, giving a summary of the EPA activities, findings, and rulings. From a strategy perspective, what overall recommendations would you give, knowing what you do about how the EPA is considering atrazine?

Solution:

Students' answers may vary.

6.25 Assume an adult female who weighs 50 kg drinks 2 L of water every day and the absorption factor for the chemical of concern is 75 percent (so 25 percent of the chemical is excreted). The concentration of the chemical in the drinking water is 55 ppb. Determine the dose in mg/kg-day.

Solution:

From chapter 2, 1 ppb=1μg/L

$$Female\ adult\ dose = \frac{55\ \mu g/L \times \frac{1\ mg}{10^3 \mu g} \times 2L \times 0.75}{50\ kg} = \mathbf{1.7 \times 10^{-3}}\ \frac{\boldsymbol{mg}}{\boldsymbol{kg - day}}$$

6.26 (a) Determine the dose (in mg/kg-day) for a bioaccumulative chemical with BCF = 10^3 that is found in water at a concentration of 0.1 mg/L. Calculate your dose for a 50 kg adult female who drinks 2 L lake water per day and consumes 30 g fish per day that is caught from the lake. (b) What percent of the total dose is from exposure to the water, and what percent is from exposure to the fish?

Solution:

a) In this case, dose is from drinking contaminated water and eating contaminated fish. 30 g of fish equates to 0.030 kg of fish.

$$The\ dose\left(\frac{mg}{kg\text{ - }day}\right)=\frac{\left(2\frac{L}{day}\times 0.1\frac{mg}{L}\right)+\left(0.1\frac{mg}{L}\right)\left(\frac{1000L}{kg}\right)\left(0.03\frac{kg}{day}\right)}{50\ kg}$$

$$=\frac{0.2\frac{mg}{day}+3\frac{mg}{day}}{50\ kg}=\boxed{0.064\frac{mg}{kg\text{ - }day}}$$

b)
Dose from water = 0.2 mg/day / 50 kg (equates to <u>6% of total dose</u>)
Dose from fish = 3 mg/day / 50 kg (equates to <u>94% of total dose</u>)

6.27 Calculate a risk-based groundwater protection standard (in ppb) for the chemical 1,2-dichloroethane for a residential homeowner where the person's well used for drinking water is contaminated with 1,2-dichloroethane. Assume you are determining risk for an average adult who weighs 70 kg. The state where you work has determined that an acceptable risk is 1 cancer occurrence per 10^6 people. Use the values for route of intake, exposure frequency, exposure duration, and averaging time provided for residential use in Table 6.14. Assume an oral slope factor for 1,2-dichloroethane of 9.2×10^{-2} per (mg/kg)/day.

Solution:

Remember that carcinogens have an AT of 70 years. Using exposure data from Table 6-6, the acceptable concentration of 1,2-dichloroethane in the groundwater (assuming the only route of exposure is from drinking contaminated water) is:

$$Conc = \frac{(70\ kg)(10^{-6})(70\ yr)\left(\frac{365\ days}{yr}\right)\left(\frac{1,000\ \mu g}{mg}\right)}{\left(\frac{0.092}{mg/kg\text{-}day}\right)\left(\frac{350\ days}{yr}\right)(30\ yr)\left(2\frac{L}{day}\right)}$$

$$\boxed{= 0.93\frac{\mu g}{L}\ (0.93\ ppb)}$$

6.28 Determine if exposure by oral ingestion to the chemicals xylene, toluene, arsenic, and hexavalent chromium poses a noncarcinogenic health risk. The chemical specific reference doses (mg/kg-day) obtained from IRIS are: xylene (0.2), toluene (0.8), arsenic (0.0003), and hexavalent chromium (0.003) Assume a 70 kg individual consumes 2 liters of water per day with these chemicals dissolved at a concentration of 1 mg/L.

Solution:

Calculate the dose of chemical that the 70kg individual is exposed to and then compare this to the reference dose of each chemical. If the reference dose is smaller than the calculated dose than exposure or ingestion of the chemicals poses a noncarcinogenic health risk.

$$Dose = \frac{1\ mg/L \times 2L/day}{70\ kg} = 0.03\ \frac{mg}{kg - day}$$

$$\boldsymbol{Xylene}\ 0.2 > 0.03 \therefore \boldsymbol{NO}$$

$$\boldsymbol{Toluene}\ 0.8 > 0.03 \therefore \boldsymbol{NO}$$

$$\boldsymbol{Arsenic}\ 0.0003 < 0.03 \therefore \boldsymbol{YES}$$

$$\boldsymbol{Hexavalen\ chromium}\ 0.003 < 0.03 \therefore \boldsymbol{YES}$$

6.29 A commercial area had its own separate groundwater supply system that provided drinking water. Unfortunatately the groundwater was contaminated with arsenic at a concentration of 10 ppb. The property owner placed a deed restriction on accessing the groundwater and also contacted the city to complete a hookup with the city water supply. Determine if exposure by oral ingestion to the chemical arsenic poses a noncarcinogenic health risk for individuals consuming drinking water after the property owner' actions have taken place. Assume a 70 kg individual consumes 2 liters of water per day and the reference dose for arsenic is 0.0003 mg/kg-day.

Solution:

From chapter 2, 1 ppb = 1μg/L

Calculate the dose of arsenic that a 70kg individual is exposed to and then compare this to the reference dose for arsenic. If the reference dose is smaller than or equal to the calculated dose than oral ingestion of arsenic poses a noncarcinogenic health risk.

$$Adult\ dose = \frac{10\frac{\mu g}{L} \times \frac{1\ mg}{10^3 \mu g} \times 2\frac{L}{day}}{70\ kg} = 3.0 \times 10^{-4}\ \frac{mg}{kg - day}$$

$0.0003\frac{mg}{kg-day} = RfD\ of\ Arsenic\ (0.0003\ \frac{mg}{kg-day})\ \therefore$
$\boldsymbol{exposure\ to\ arsenic\ in\ this\ case\ poses\ a\ noncarinogenic\ health\ risk}$

6.30 (a) Calculate a risk-based groundwater protection standard for the chemical benzo(*a*)pyrene. Assume you are determining risk for an average adult female who weighs 50 kg and consumes 2 L water and eats 30 g fish per day. The state has determined that an acceptable risk is 1 cancer occurrence per 10^5 people. Use the values for exposure frequency, exposure duration, and averaging time provided for residential land use. (b) According to EPA's Integrated Risk Information System (IRIS), what type of carcinogen is benzo(*a*)pyrene, using the weight of evidence of human and animal studies? (c) Assuming the chemical is leaching from some contaminated soil, estimate the allowable concentration of benzo(*a*)pyrene in the pore water of contaminated soil.

Solution:

a) IRIS states that this chemical's oral slope factor is 7.3 per (mg/kg)/day.

$$Conc = \frac{(50\ kg)(10^{-5})(70\ yr)\left(\frac{365\ days}{yr}\right)\left(\frac{1{,}000\ \mu g}{mg}\right)}{\left(\frac{7.3}{mg/kg\text{-}day}\right)\left(\frac{350\ days}{yr}\right)(30\ yr)\left(2\frac{L}{day}\right)}$$

$$\boxed{= 0.083\frac{\mu g}{L}\ (0.083\ ppb)}$$

b) As stated in IRIS, the weight-of-evidence judgment of the likelihood that benzo(*a*)pyrene is a probable human carcinogen.

c) The "target soil leachate concentration" is the concentration in the pore water of the contaminated soil. It is defined as the applicable groundwater criteria multiplied by a dilution-attenuation factor. We assumed the DAF was 16 in an example problem.

$$\text{Thus, } 0.083\frac{\mu g}{L} \times 16 = \boxed{1.3\frac{\mu g}{L}}$$

6.31 Is there an unsafe risk associated with a 70 kg adult eating 15 g fish every day that contains 1 mg/kg of methylmercury? Methylmercury has been shown to cause developmental neuropsychological impairment in human beings. The RfD for methylmercury is 1×10^{-4} mg/kg-day.

Solution:

Determine the average daily dose the individual is exposed to and divide this value by the RfD to determine the hazard quotient. The average daily dose is:

$$\frac{\left(1\frac{mg}{kg}\right)\left(15\frac{g}{day}\right)\left(\frac{kg}{1000\ g}\right)}{70\ kg} = 2\times10^{-4}\ \frac{mg}{kg\text{ - }day}$$

Use this value and the RfD to determine the HQ:

$$\text{Hazard Quotient (HQ)} = \frac{2\times10^{-4}\ \frac{mg}{kg\text{ - }day}}{1\times10^{-4}\ \frac{mg}{kg\text{ - }day}} = 2$$

Because the HQ is greater than 1; the risk is not acceptable.

6.32 Is there an unsafe risk associated with a 70 kg adult eating 15 g fish every day that contains 9.8 µg/ kg of Arochlor 1254? Arochlor 1254 can exhibit noncarcinogenic effects in humans. Use the IRIS database to find any other information required to solve this problem.

Solution:

The RfD was not given. IRIS reports that the RfD for Arochlor 1254 is 2 x 10^{-5} mg/kg-day. Determine the average daily dose the individual is exposed to and divide this value by the RfD to determine the hazard quotient. 9.8 µg/kg is equal to 0.0098 mg/kg. The average daily dose is:

$$\frac{\left(0.0098\frac{mg}{kg}\right)\left(15\frac{gm}{day}\right)\left(\frac{kg}{1000\ gm}\right)}{70\ kg} = 2.1\times10^{-6}\ \frac{mg}{kg\text{ - }day}$$

Use this value of the dose and the RfD to determine the HQ:

$$\text{Hazard Quotient (HQ)} = \frac{2.1\times10^{-6}\ \dfrac{mg}{kg\text{ - }day}}{2.0\times10^{-5}\ \dfrac{mg}{kg\text{ - }day}} = 0.1$$

Because the HQ is less than 1; the concentration of the chemical in the fish will not result in adverse noncarcinogenic effects.

6.33 Concentrations of toxaphene in fish may impair human health and fish-eating birds (such as bald eagles) that feed on the fish. (a) If the log of the octanol–water partition coefficient (log K_{ow}) for toxaphene is assumed to equal 4.21, what is the expected concentration of toxaphene in fish? (Assume that the equilibrium aqueous phase toxaphene concentration is 100 ng/L.) (b) If it is assumed that an average person drinks 2 L untreated water daily and consumes 30 g contaminated fish, what route of exposure (drinking water or eating fish) results in the greatest risk from toxaphene in 1 year? (c) What route of exposure is greatest for a higher-risk group that is assumed to consume 100 g fish per day? Support all of your answers with calculations. Assume the following correlation applies to toxaphene and our problem's specific fish:

$$\log \text{BCF} = 0.85 \log K_{\text{ow}} - 0.07$$

Solution:

a) The BCF relates the aqueous concentration to the concentration in fish; BCF = $[\text{toxaphene}_{\text{fish}}]/[\text{toxaphene}_{\text{aq}}]$. The problem did not provide a BCF; therefore, you need to either look one up in a reliable data base or estimate it,

$\log BCF = 0.85(4.21) - 0.07 = 3.5$; therefore, the BCF = $10^{3.5}$

$10^{3.5} = [\text{toxaphene}_{\text{fish}}] / [\text{toxaphene}_{\text{aq}}] = [\text{toxaphene}_{\text{fish}}] / 100$ ppt

$[\text{toxaphene}_{\text{fish}}] = 3.2 \times 10^5$ ppt = 0.32 ppm (or <u>0.32 mg of toxaphene/kg of fish</u>)

b) & c) Determine the mass of toxaphene that an individual is exposed to in 1 year.

A person drinking 2 L untreated water per day is exposed in one year to:

$$\left(2\frac{L}{day}\right)\left(100\frac{ng}{L}\right)\left(\frac{g}{10^9\ ng}\right)\left(365\frac{day}{yr}\right) = 7.3\times10^{-5}\ \frac{g\ toxaphene}{yr}$$

A person consuming 30 g of contaminated fish per day is exposed in one year to:

$$\left(30\frac{g\ fish}{day}\right)\left(22\frac{mg\ of\ toxaphene}{kg\ of\ fish}\right)\left(\frac{g}{1{,}000\ mg}\right)\left(\frac{kg}{1{,}000\ gm}\right)\left(365\frac{day}{yr}\right) = 0.24\ \frac{g\ toxaphene}{yr}$$

The high risk group consumes 100 g of contaminated fish per day:

$$\left(100\frac{g\ fish}{day}\right)\left(22\frac{mg\ of\ toxaphene}{kg\ of\ fish}\right)\left(\frac{g}{1{,}000\ mg}\right)\left(\frac{kg}{1{,}000\ gm}\right)\left(365\frac{day}{yr}\right) = 0.80\ \frac{g\ toxaphene}{yr}$$

Note that because the toxaphene bioconcentrates strongly in the food chain, an individual is exposed to a much greater mass of chemical by ingesting contaminated food versus drinking contaminated water. In this situation, the dose (and risk) increases with an increased in fish consumption. This amount could be much greater for segments of our population which consume more fish than the average person as well as for wildlife which depend upon fish for food. Also note that for chemicals that persist (do not degrade by natural mechanisms) and also bioconcentrate, what seems like a low water concentration may actually turn out to have a great environmental significance. This effect can be even more greatly magnified if the BCF is higher.

6.34 Identify a brownfield in your local community, hometown, or a nearby city. What was specifically done at the site? What are several social, economic, and environmental issues associated with restoring the brownfield site?

Solution:

Students' responses will vary.

6.35 The Code of Federal Regulations (CFR) is the codification of the general and permanent rules published in the Federal Register by the executive departments and agencies of the Federal Government. It can be accessed at http://www.gpoaccess.gov/cfr/. What CFR number is associated with the following sections? (for example, 50 CFR for Wildlife and Fisheries). (a) Protection of Environment; (b) Transportation, (c) Conservation of Power and Water Resources, (d) Public Health, and (e) Highways.

Solution:

a) CFR 40 Protection of Environment
b) CFR 49 Transportation
c) CFR 18 Conservation of Power and Water Resources
d) CFR 42 Public Health
e) CFR 23 Highways

6.36 Research the safety of your personal care and household cleaning products using a web site such as http://lesstoxicguide.ca/index.asp?fetch=personal. Develop a table that lists 7 current personal care or household cleaning products used in your apartment, home, or dormitory. Add a second column that lists a less hazardous alternative for each of the 7 products.

Solution:

Students' responses will vary but an example table is listed below.

Product	**Non-hazardous alternative**
1. Crest toothpaste	1. Arm and Hammer Teeth Whitening Booster Toothpaste
2. Garnier Fructis hair conditioner	2. Dr. Bronner's Magic Organic Citrus Hair Rinse
3. OB non-applicator tampons	3. Diva cup
4. Garnier fructis hair gel	4. Aloe vera gel
5. Oil of Olay Face Cream	5. Shea butter
6. ACT fluoride rinse	6. Tom's of Main Natural Baking Soda Mouthwash
7. Tom's of Main Natural Deodorant	7. Make your own recipe with cornstarch

6.37 Do some background research. Some good places to look for this and related information include EXTOXNET, the National Toxicology Program (NTP), the Agency for Toxic Substances and Disease Registry (ATSDR), and the National Library of Medicine (choose one). (a) Is atrazine bioaccumulative and/or persistent in the environment? Explain your answer. (b) Now consider applying atrazine to your lawn and assume that there are children in the household and they like to eat grass, dirt, and worms while playing on grass. Assume the atrazine is both bioaccumulative and persistent. How does this new information about the partitioning and persistence behavior of atrazine affect your consideration of the potential toxicity of atrazine to humans?

Solution:

a. According to the following links from the Agency for Toxic substances and EXTONET, **atrazine is *not* bioaccumulative but it is persistent in the environment**.

ASDR

http://www.atsdr.cdc.gov/toxguides/toxguide-153.pdf

“Atrazine in the atmosphere can adsorb onto particulates and be transported significant distances away from the nearest application site. Atrazine does not tend to bioaccumulate.”

EXTONET

http://pmep.cce.cornell.edu/profiles/extoxnet/24d-captan/atrazine-ext.html

“Atrazine is only slightly toxic to fish and other pond or stream life. In whitefish, atrazine accumulates in the brain, gall bladder, liver and gut (Arch. Hydrobiol. Suppl. 59(2-3):252-87. 1981). Fish may bioaccumulate atrazine to levels of 11 times the concentration in surrounding water. This is a low level of bioaccumulation. Atrazine is easily broken down.”

http://extoxnet.orst.edu/pips/atrazine.htm

“Atrazine is highly persistent in soil.”

b. **Children are a high risk population since they have lower body mass than adults. A persistent and bioaccumulative chemical applied to grass where children play and may even ingest the grass, would be dangerous to human health.**

Chapter 7 Water: Quantity and Quality

7.1 The average annual rainfall in an area is 60 cm. The average annual evapotranspiration is 35 cm. Thirty percent of the rainfall infiltrates and percolates into the underlying aquifer; the remainder is runoff that moves along or near the ground surface. The underlying aquifer is connected to a stream. Assuming there are no other inputs or outputs of water to the underlying aquifer and the aquifer is at steady state (neither gains nor loses water), what is the amount of baseflow contributed to the stream from the groundwater?

Solution:

$$\text{P} = 60\text{ cm} \quad \text{ET} = 35\text{ cm} \quad \text{I} = 0.3 \times 60\,\text{cm} = 18\text{ cm} \quad \text{R} = 60 - 35 - 18 = 7\text{ cm}$$

$$\text{At steady} - \text{state in the aquifer, In} = \text{Out since } \Delta\text{S} = 0$$

$$\therefore \text{Baseflow} = \text{Infiltration}$$

$$\boxed{\text{The baseflow is 18 cm}}$$

7.2 An agricultural watershed that is managed to minimize runoff consists of 150 acres that has a land slope of 1-2% and sandy soils. The land is planned to be developed into a residential subdivision (30% as a low-density residential area, 30% as a medium-density residential area, and the remaining land preserved as green space. (a) Calculate the peak runoff flowrate (ft^3/min) before and after the development takes place for a storm with rainfall intensity of 0.35 in/hr. (b) Determine the percent change in peak runoff between the two land use scenarios. (c) If the greenspace was equally developed between low- and medium- density development, how does your answer to part (b) change? (d) How do your answers for the peak runoff flow rate in part (a) change if 100% of the land is developed in a high-density residential?

Solutions:

a. Use the rational method (equation 7.1) to determine the peak runoff flow rates before and after development takes place. This problem is similar to example 7.1. Consult table 7.2 for run-off coefficients.

$Q = \sum C_j \, i \, A_j$

$$Q_{pre-development} = 0.08 \times 0.35\frac{in}{hr} \times 150\ acres = 4.2\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{252\ ft^3/min}$$

$$\begin{aligned}Q_{post-development} \\ &= \left(0.14 \times 0.35\frac{in}{hr} \times 150\ acres \times 0.3\right) + \left(0.25 \times 0.35\frac{in}{hr} \times 150\ acres \times 0.3\right) \\ &+ \left(0.05 \times 0.35\frac{in}{hr} \times 150\ acres \times 0.4\right) = 7.2\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{432\ ft^3/min}\end{aligned}$$

b. $Percent\ change = \frac{[post\ development\ run{-}off - predevelopment\ run{-}off]}{pre{-}development\ run{-}off} \times 100\%$

$$Percent\ change = \frac{[432\ ft^3/min - 252\ ft^3/min]}{252\ ft^3/min} \times 100\% = \mathbf{71\%\ increase\ in\ runoff}$$

c. Use the rational method again as in part a and then the equation for percent change in part b.

$$\begin{aligned}Q_{equally\ developed} &= \left(0.14 \times 0.35\frac{in}{hr} \times 75\ acres\right) + \left(0.25 \times 0.35\frac{in}{hr} \times 75\ acres\right) \\ &= 10.24\ \frac{ft^3}{s} \times \frac{60s}{min} = 614\ ft^3/min\end{aligned}$$

$$Percent\ change = \frac{[614\ ft^3/min - 252\ ft^3/min]}{252\ ft^3/min} \times 100\% = \mathbf{144\%\ increase\ in\ runoff}$$

d. Use the same method as in part c.

$$Q_{equally\ developed} = \left(0.47 \times 0.35\frac{in}{hr} \times 150\ acres\right) = 24.7\ \frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{1480\ ft^3/min}$$

$$Percent\ change = \frac{[1480 ft^3/min - 252\ ft^3/min]}{252\ ft^3/min} \times 100\% = \mathbf{488\%\ increase\ in\ runoff}$$

7.3 A rural watershed that is managed to minimize runoff consists of 120 acres of cultivated land that has a gentle land slope (1-2%) and silty/sandy soils. The land is planned to be developed into a residential housing with plans for 25% low-density residential area, 25% for medium-density residential area, and 50% set aside as green space. (a) Estimate the annual mass loading due to runoff for suspended solids (SS), phosphorus (P), and nitrogen (N) (lbs/year). (b) How does your answer to part (a) change if the slope of the land is 3%? (c) How does your answer to part (a) change if the greenspace is developed into commercial development to serve social and economic needs of the community, without leaving any natural areas as open green space?

Solution:

a. This problem is similar to example 7.2. Use equation 7.2 to calculate the annual mass loading of the pollutants. Look up typical values for pollutant export coefficients based on land use in table 7.3.

$L = \sum (A_i\ C_{e,i})$

$$L_{SS} = \left(30\ acres \times 10\ \frac{lbs\ SS}{acre{-}yr}\right) + \left(30\ acres\ \times 250\ \frac{lbs\ SS}{acre{-}yr}\right) + \left(60\ acres\ \times 3\ \frac{lbs\ SS}{acre{-}yr}\right) = \mathbf{7,980}\ \frac{\mathbf{lbs\ SS}}{\mathbf{yr}}$$

$$L_p = \left(30\ acres \times 0.04\ \frac{lbs\ P}{acre{-}yr}\right) + \left(30\ acres\ \times 0.3\ \frac{lbs\ P}{acre{-}yr}\right) + \left(60\ acres\ \times 0.03\ \frac{lbs\ P}{acre{-}yr}\right) = \mathbf{12}\ \frac{\mathbf{lbs\ P}}{\mathbf{yr}}$$

$$L_N = \left(30\ acres \times 0.4\ \frac{lbs\ N}{acre - yr}\right) + \left(30\ acres\ \times 3.9\ \frac{lbs\ N}{acre - yr}\right) + \left(60\ acres\ \times 0\ \frac{lbs\ P}{acre - yr}\right) = \mathbf{129}\ \frac{\mathbf{lbs\ P}}{\mathbf{yr}}$$

b. **Answers to part a do not change** if the slope of the land is 3%. The flow rate would change but the loading would remain the same.

c. Use the same method to calculate the annual mass loading of pollutants as in part a. Use different export coefficients based on commercial development in place of green space.

$$L_{SS} = \left(30\ acres \times 10\ \frac{lbs\ SS}{acre - yr}\right) + \left(30\ acres\ \times 250\ \frac{lbs\ SS}{acre - yr}\right) + \left(60\ acres\ \times 1{,}000\ \frac{lbs\ SS}{acre - yr}\right) = \mathbf{67,800}\ \frac{\mathbf{lbs\ SS}}{\mathbf{yr}}$$

$$L_p = \left(30\ acres \times 0.04\ \frac{lbs\ P}{acre{-}yr}\right) + \left(30\ acres\ \times 0.3\ \frac{lbs\ P}{acre{-}yr}\right) + \left(60\ acres\ \times 1.5\ \frac{lbs\ P}{acre{-}yr}\right) = \mathbf{100}\ \frac{\mathbf{lbs\ P}}{\mathbf{yr}}$$

$$L_N = \left(30\ acres \times 0.4\ \frac{lbs\ N}{acre - yr}\right) + \left(30\ acres\ \times 3.9\ \frac{lbs\ N}{acre - yr}\right) + \left(60\ acres\ \times 9.8\ \frac{lbs\ P}{acre - yr}\right)$$
$$= \mathbf{717}\,\boldsymbol{\frac{lbs\ P}{yr}}$$

$$\%\ change_{LSS}\ = \frac{67{,}800\ \frac{lbs\ SS}{yr} -\ 7{,}980\,\frac{lbs\ SS}{yr}}{7{,}980\,\frac{lbs\ SS}{yr}} \times 100\%\ = \mathbf{750\%}\ \boldsymbol{increase}$$

$$\%\ change_{LP}\ = \frac{100\ \frac{lbs\ P}{yr} -\ 12\,\frac{lbs\ P}{yr}}{12\,\frac{lbs\ P}{yr}} \times 100\%\ = \mathbf{733\%}\ \boldsymbol{increase}$$

$$\%\ change_{LN}\ = \frac{717\ \frac{lbs\ N}{yr} -\ 129\ \frac{lbs\ N}{yr}}{129\ \frac{lbs\ N}{yr}} \times 100\%\ = \mathbf{456\%}\ \boldsymbol{increase}$$

7. 4 Peak rainfall intensities vary by geographical region. Assume the peak rainfall (inches of rain) reported in different states over a 30 minute period are: Florida-2.8; Iowa-1.8; Arizona-1.6; and Montana-0.8. (a) What is the peak runoff flow rate (ft^3/min) for an undisturbed open area of 10 acres with a slope of 1.75% that consists of sandy soil? Perform the same calculations for clayey soils (b) What is the peak runoff flow rate for a similar topography and soil type, but if the 10 acres of open area are commercially developed.

Solution:

a. Use the rational method (equation 7.1) to determine the peak runoff flow rates. This problem is similar to example 7.1. Consult table 7.2 for the run-off coefficient of sandy-soil in an open area at 1.75% slope (0.05).

$Q = \sum C_j\ i\ A_j$

$$Q_{FL} = 0.05 \times \frac{2.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 2.8\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{168\ ft^3/min}$$

$$Q_{Iowa} = 0.05 \times \frac{1.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 1.8\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{108\ ft^3/min}$$

$$Q_{AZ} = 0.05 \times \frac{1.6\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 1.6\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{96\ ft^3/min}$$

$$Q_{MN} = 0.05 \times \frac{0.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 0.8\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{48\ ft^3/min}$$

For clayey soils, the run-off coefficient of 0.16 is used from table 7.2 for clayey soils in an open area with a slope of 1.75%.

$$Q_{FL} = 0.16 \times \frac{2.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 9.0\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{538\ ft^3/min}$$

$$Q_{Iowa} = 0.16 \times \frac{1.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 5.8\frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{346\ ft^3/min}$$

$$Q_{AZ} = 0.16 \times \frac{1.6\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 5.1\ \frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{307\ ft^3/min}$$

$$Q_{MN} = 0.16 \times \frac{0.8\ in}{30\ min} \times \frac{60min}{1\ hr} \times 10\ acres = 2.6\ \frac{ft^3}{s} \times \frac{60s}{min} = \mathbf{154\ ft^3/min}$$

b. Use the rational method as in part a to determine the peak runoff flow rate. In this case the runoff coefficient will be 0.71 for sandy soils at a 1.75% slope in commercial land use.

$$Q_{FL} = 0.71 \times \frac{2.8\ in}{30\ min} \times \frac{60 min}{1\ hr} \times 10\ acres = 40 \frac{ft^3}{s} \times \frac{60 s}{min} = \mathbf{2390\ ft^3/min}$$

$$Q_{Iowa} = 0.71 \times \frac{1.8\ in}{30\ min} \times \frac{60 min}{1\ hr} \times 10\ acres = 26 \frac{ft^3}{s} \times \frac{60 s}{min} = \mathbf{1530\ ft^3/min}$$

$$Q_{AZ} = 0.71 \times \frac{1.6\ in}{30\ min} \times \frac{60 min}{1\ hr} \times 10\ acres = 23 \frac{ft^3}{s} \times \frac{60 s}{min} = \mathbf{1360\ ft^3/min}$$

$$Q_{MN} = 0.71 \times \frac{0.8\ in}{30\ min} \times \frac{60 min}{1\ hr} \times 10\ acres = 11 \frac{ft^3}{s} \times \frac{60 s}{min} = \mathbf{682\ ft^3/min}$$

7.5 Western Australia is expected to see by the year 2030 a 10-20% increase in peak rainfall intensity from the effects of climate change. If the current peak rainfall intensity is 200 mm of rainfall falling over an 18-hr period, what is the peak runoff flowrate you expect for a densely populated urban area of 20 acres on sandy soils with a slope of 1.75%, that consists of one half high-density residential development and one half commercial development? Report your results in cm^3/min and ft^3/min.

Solution:

a. Use the rational method (equation 7.1) to determine the peak runoff flow rates. This problem is similar to example 7.1. Consult table 7.2 for the run-off coefficient of sandy-soil in an open area at 1.75% slope (0.05).

$Q = \sum C_j\, i\, A_j$

First, the rainfall intensity needs to be calculated and converted into inches per hour.

$$i = \frac{200\ mm}{18\ hr} \times \frac{1\ m}{1000 mm} \times \frac{100\ cm}{1\ m} \times \frac{1\ in}{2.54\ cm} = 0.437\ in/hr$$

$$Q\ = \left(0.47 \times 0.437 \frac{in}{hr} \times 10\ acres\right) + \left(0.71 \times 0.437 \frac{in}{hr} \times 10\ acres\right) = 5.16\ \frac{ft^3}{s} \times \frac{60s}{min}$$
$$= \mathbf{310\ ft^3/min}$$

$$Q\ =\ 310 \frac{ft^3}{min} \times \frac{(12\ in)^3}{1\ ft^3} \times \frac{(2.54\ cm)^3}{in^3}\ = \mathbf{8.8 \times 10^6\ cm^3/min}$$

7.6 A small public well is used to supply drinking water to a small residential community located in a 26 square-kilometer watershed. For the month of June, the measured rainfall was 12 cm, the estimated evapotransiration was 7.5 cm and the surface water runoff entered a small stream with an average flow of 0.32 m^3/sec that leaves the watershed. Estimate the average flow (m^3/day) from the public well without depleting the underlying aquifer (neither gains nor loses water). Assume that all water that infiltrates will percolate to the aquifer.

Solution:

First calculate the daily flow rate of the rain, the stream and the daily evapotranspiration in m^3/day using unit conversions from the information provided in the problem.

$$Q_{rain} = \frac{12\ cm}{30\ days} \times \frac{1\ m}{100\ cm} \times 26\ km^2 \times \frac{(1000m)^2}{1\ km^2} = 104{,}000\,\frac{m^3}{day}$$

$$Q_{evapo} = \frac{7.5\ cm}{30\ days} \times \frac{1\ m}{100\ cm} \times 26\ km^2 \times \frac{(1000m)^2}{1\ km^2} = 65{,}000\,\frac{m^3}{day}$$

$$Q_{stream} = 0.32\,\frac{m^3}{s} \times \frac{60\ s}{1\ min} \times \frac{60\ min}{1\ hr} \times \frac{24\ hours}{1\ day} = 27{,}650\,\frac{m^3}{day}$$

Now write a balance of the flow rates

$$Q_{in} = Q_{out}$$

$$Q_{rain} = Q_{evapo} + Q_{stream} + Q_{well}$$

Solve for the average flow of the well.

$$Q_{well} = Q_{rain} - Q_{evapo} - Q_{stream}$$

$$Q_{well} = 104{,}000\,\frac{m^3}{day} - 65{,}000\,\frac{m^3}{day} - 27{,}650\,\frac{m^3}{day} = \mathbf{11,350\ \frac{m^3}{day}}$$

7.7 Go to the United Nations Environment Programme's Global Environment Outlook Web page, http://geodata.grid.unep.ch/. Look up two countries located in different hemispheres. (a) What are their current amounts of water withdrawals and freshwater withdrawals? (b) Are these countries currently experiencing water scarcity or expected to experience water scarcity?

Solution:

The problem statement refers students to a site that does not have sufficient data. Students will need to be guided to different sources of information or track down information on their own. The table below shows examples of locations of country specific data required to solve this problem as of November, 2013. Students will also need to learn that data availability is not collected yearly, so should indicate the relevant year the data was collected.

Parameter	**Source**	**Notes**
Water withdrawals	Water withdrawals by country http://chartsbin.com/view/1455	Note units can be total withdrawal for the country (km3/year) or on a per capita basis (m3/year-capita)
Freshwater withdrawals	CIA factbook provides information on freshwater withdrawals. (https://www.cia.gov/library/publications/the-world-factbook/fields/2202.html) As well as the World bank: http://data.worldbank.org/indicator/ER.H2O.FWTL.K3	Note units can be total withdrawal for the country (km3/year) or on a per capita basis (m3/year-capita)
Country specific data on water scarcity	http://www.un.org/waterforlifedecade/scarcity.shtml	See comment below

http://www.un.org/waterforlifedecade/scarcity.shtml Note from this page on the United Nations defines water scarcity. "Hydrologists typically assess scarcity by looking at the population-water equation. An area is experiencing water stress when annual water supplies drop below 1,700 m3 per person. When annual water supplies drop below 1,000 m3 per person, the population faces water scarcity, and below 500 cubic metres "absolute scarcity". Water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity is a relative concept and can occur at any level of supply or demand. Scarcity may be a social construct (a product of affluence, expectations and customary behavior) or the consequence of altered supply patterns - stemming from climate change for example."

7.8 Go to the Web site of the U.S. Geological Survey (USGS), www.usgs.gov, and navigate to "Water Use in the United States." Look up the total water withdrawals associated with the following uses in your state: thermoelectric, irrigation, public supply, industrial, domestic, livestock, aquaculture, and mining. Place the eight uses in a table in order of greatest to least water withdrawals. Determine the percent of the total water withdrawals associated with each of these uses. Compare these percentages to the national percentages listed in Table 7.6. Discuss how your state compares with the national average.

Solution:

Students' responses will vary depending on state.

For Pennsylvania using year 2000 data:

Use Category	Withdraw in MGD	% of Total
Thermoelectric	6980	70.1
Public Supply	1460	14.7
Industrial	1190	12.0
Mining	182	1.8
Domestic	132	1.3
Irrigation	13.9	0.1
Live Stock	-	-
Aquiculture	-	-
Calculated Total	9958	100

7.9 Go to the Web site of the U.S. Geological Survey (USGS), www.usgs.gov, and navigate to "Water Use in the United States." Look up the total surface water and groundwater withdrawals associated with your state. Determine the percent of surface water and groundwater withdrawals relative to total withdrawals in your state. Compare these percentages with the national distribution of surface water and groundwater use. Discuss how your state compares with the national average.

Solution:

Students' responses will vary depending on state.

For Pennsylvania using year 2000 data:

Use Category	Withdraw in MGD	% of Total
Groundwater	666	6.7
Surface Water	9290	93.3
Calculated Total	9956	100

7.10 Contact your local water or wastewater authority. Ask for the annual water usage rates (average, maximum-day, minimum-day, and so on). For a water authority, ask how much is unaccounted-for water; for a wastewater authority, ask for how much is wet-weather flows. Use these numbers to estimate a demand factor and per capita (or metered connections) water usage rates. Discuss how your local values compare with the expected range of values described in this chapter.

Solution:

Students' responses will vary depending on to water authority.

7.11 (a) Estimate your own actual water use during a typical day. List your water use activities, and estimate the volume of water used for each activity. (b) Compare your water usage rate with that of an average per person rate such as 101 gpdc. (c) Explain why your rate may be more or less than the average rate. (d) How much of your water use do you think was discharged as wastewater? (e) Did you do any water use activity that did not create any collected wastewater?

Solution:

Students' responses will vary.

7.12 Estimate the daily water demand and wastewater generation for a department store that has six floors. On each floor are two sets of men's and women's lavatories. The men's have two toilets, two urinals, and three sinks; the women's have four toilets and three sinks. Assume that each lavatory will be used by 35 people per day.

Solution:

Use table 7.12 to find the typical water usage flow and wastewater generation flow. Multiply these by the number of units (male and female) and number of floors.

$$Daily\ water\ demand = 6\ floors \times \left[\left(2\ units \times 550 \frac{gal}{unit - day}\right) + \left(2\ units \times 550 \frac{gal}{unit - day}\right)\right]$$
$$= \mathbf{13,200\ gal/day}$$

$$Daily\ wastewater\ generated = 6\ floors \times 4\ units \times 400 \frac{gal}{unit - day} = \mathbf{9,600} \frac{\mathbf{gal}}{\mathbf{day}}$$

7.13 Estimate the daily water demand and wastewater generation for a small commercial area that has the following buildings. Clearly indicate all assumptions and the estimated water usage for each building: (a) a 200-room hotel with 35 employees and one kitchen; (b) three restaurants, one being an organic restaurant with regionally produced foods, another an all-you-can-eat buffet (dinner only), and the third a vegan deli open from 5:00 A.M. to 3:00 P.M.; (c) a newsstand that sells magazines, refreshments, and snacks with one lavatory used only by the employees; and (d) a three-story office building with basement employing 140 people and with two sets of men's and women's lavatories per floor.

Solution:
Varies based on assumptions used to estimate water use. Use table 7.12 for water usage flow and wastewater generation flow values. For example:

Building	Unit Number	Water Demand		Wastewater Generation	
		gpd/unit	gpd	gpd/unit	gpd
Hotel	300 customers	50	15,000	45	13,500
Organic Restaurant	150 customers	9	1,350	3	450
Buffet Restaurant	200 customers	9	1,800	3	600
Deli	150 customers	9	1,350	3	450
Newsstand	2 employees	20	40	20	40
Office Building	140 employees	15	2,100	13	1,820
Total			**21,640**		**16,860**

7.14 Estimate the maximum-day demand plus fire flow for a residential area. The residential area is 400 acres divided into .25-acre lots with yards that are 75 ft. wide. Assume the average population density is 2.8 people per home and the maximum-day demand factor is 2.1.

Solution:

Use Equation 7-1:

$$\begin{aligned}
&\text{Y} = 37.2 \times 2.8 + 69.2 = 173.4 \text{ gpd / house } (\text{average day}) \\
&\text{Number houses} = 4 \times 400 = 1600 \text{ homes} \\
&\text{Max day residential demand} = 173.4 \text{ gal / house} \times 1600 \text{ homes} \times 2.1 \approx 582{,}600 \text{ gpd} \\
&\text{From Table } 9-11 \text{ and Table } 9-12: \text{NFF} = 750 \text{ gpm} \times 2 \text{ h} \times \frac{60 \text{ min}}{1 \text{ h}} = 90{,}000 \text{ gallons} \\
&\text{Total water demand} = 582{,}600 \text{ gpd} + 90{,}000 \text{ gpd} = \boxed{672{,}600 \text{ gpd}}
\end{aligned}$$

7.15 You are working on a project to put in a new set of townhouse apartments. Estimate the daily and yearly water demand given 30 apartment units with an average of three people living in each unit.

Solution:

Consult table 7.12 for the typical water usage flow value for apartments (100 gallons/unit/day).

$$daily\ water\ demand = 30\ unit \times 100 \frac{gal}{unit - day} = \mathbf{9,000} \frac{\boldsymbol{gallons}}{\boldsymbol{day}}$$

$$yearly\ water\ demand = 9{,}000 \frac{gallons}{day} \times 365 \frac{days}{year} = \mathbf{3,900,000} \frac{\boldsymbol{gallons}}{\boldsymbol{year}}$$

7.16 A 2.5 MGD wastewater treatment plant is currently running at 80 percent capacity during the annual maximum day, servicing a city of 38,500 people with 26.7 mi. sewers. During the next 10 years, it is expected that new residential developments for 15,000 people will be built, along with an additional 6.5 mi. sewers. The sewer is assumed to leak 8,500 gpd/mi. (a) Project the maximum daily demand for the wastewater treatment plant after the new development is built. (b) Should the wastewater treatment plant's capacity be increased?

Solution:

a)

$$\text{Total current water use} = 2,500,000 \text{ gpd} \times 0.8 = 2,000,000 \text{ gpd}$$

$$\text{Current I / I} = 8500 \text{ gpd / mi} \times 26.7\text{mi} \approx 227,000 \text{ gpd}$$

$$\text{Current domestic use} = 2,000,000 \text{ gpd} - 227,000 \text{ gpd} = 1,773,000 \text{ gpd}$$

$$\text{Per capita use} = \frac{1,773,000 \text{ gpd}}{38,500 \text{ people}} = 46 \text{ gpcd}$$

$$\text{Forcast water use:}$$

$$\text{Domestic use} = 46 \text{ gpcd} \times (38,500 + 15,000) = 2,461,000 \text{ gpd}$$

$$\text{I / I} = 8500\text{gpd / mi} \times (26.7 + 6.5) = 282,200 \text{ gpd}$$

$$\text{Total forcasted use} = 2,461,000 + 282,200 = \boxed{2,743,200 \text{ gpd}}$$

b) Yes, the treatment plant should be increased.

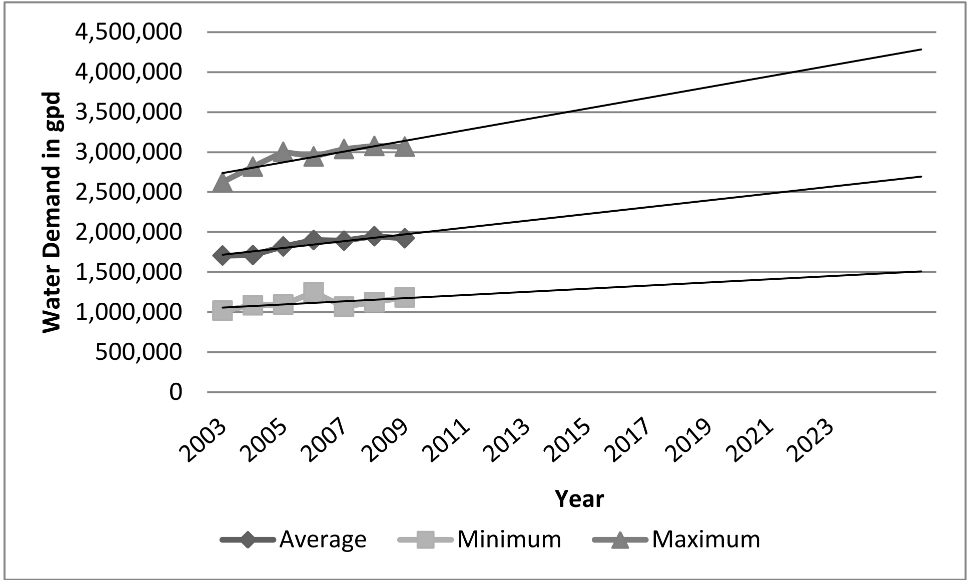
7.17 You are hired to upgrade the existing water treatment plant for Nittany Lion City. Using the historical records provided in Table 7.24, forecast the water demand through 2024. The population is expected to increase about 1.8 percent per year. (a) Create a graph that has the historical average, minimum-day, and maximum-day water demand in gpd for each year. Extrapolate trend lines for the projected future water demand through 2015. (b) Use your graph to predict the average, minimum-day, and maximum-day water demand for years 2014, 2019, and 2024. (c) Estimate the 2009, 2014, 2019, and 2024 per capita water use by calculating the average water use divided by the population served. (d) Determine a demand factor for the minimum-day and maximum-day demand, using the historical records.

Table /7.24

Historical Records Used to Solve Problem 7.17				
Year	Water Demand (gpd)			Population Served
	Average	Minimum	Maximum	
2003	1,707,190	1,018,655	2,624,414	14,251
2004	1,713,230	1,086,201	2,817,674	14,352
2005	1,820,602	1,094,415	3,003,411	14,354
2006	1,901,145	1,248,011	2,945,221	14,598
2007	1,891,860	1,068,574	3,038,157	14,587
2008	1,948,648	1,124,125	3,076,542	14,684
2009	1,923,458	1,184,214	3,067,821	14,857

Solution:

a)



b) & c) Flow rates estimated from the plot. Population is calculated using 1.8% growth per year.

Year	Average (gpd)	Minimum (gpd)	Maximum (gpd)	Population	Average Per Capita Demand (gpcd)
2009	1,923,458	1,184,214	3,067,821	14,857	129.5
2014	2,136,000	1,282,000	3,404,000	16,243	131.5
2019	2,349,000	1,379,000	3,740,000	17,759	132.3
2024	2,561,000	1,477,000	4,076,000	19,415	131.9

d)

Year	Average (gpd)	Minimum (gpd)	Maximum (gpd)	Min/Ave	Max/Ave
2003	1,707,190	1,018,655	2,624,414	0.60	1.54
2004	1,713,230	1,086,201	2,817,674	0.63	1.64
2005	1,820,602	1,094,415	3,003,411	0.60	1.65
2006	1,901,145	1,248,011	2,945,221	0.66	1.55
2007	1,891,860	1,068,574	3,038,157	0.56	1.61
2008	1,948,648	1,124,125	3,076,542	0.58	1.58
2009	1,923,458	1,184,214	3,067,821	0.62	1.59
Average Demand Factor				0.61	1.59

7.18 You are hired to upgrade the existing water treatment plant for USF City. Using the historical records in Table 7.25, forecast the water demand through 2024. A new industry is expected to require 65,000 gpd starting in 2016.

Table /7.25

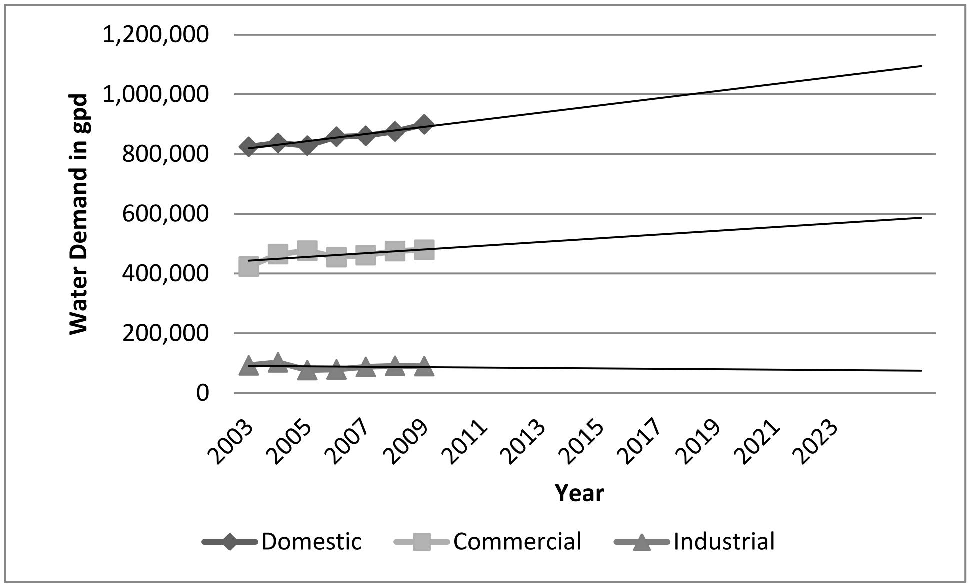
Historical Records Used to Solve Problem 7.17

Year	Metered Flow from Treatment Plant (gpd)	Metered Flow Based on Billing Records (gpd)		
		Domestic	Commercial	Industrial
2003	1,687,517	824,247	423,229	92,676
2004	1,789,453	837,055	465,232	102,707
2005	1,745,658	828,103	476,429	76,916
2006	1,728,750	858,076	454,928	79,029
2007	1,779,854	861,003	461,669	87,422
2008	1,826,650	875,548	475,254	91,214
2009	1,872,456	899,545	479,451	90,248

(a) Create a graph that has the historical domestic, commercial, and industrial demand for each year. Extrapolate trend lines for the projected future water demand through 2024 for each category. Take into account the additional industry water demand in 2016. (b) Estimate the percent of produced water that is unaccounted-for water based on the historical records. (c) Use the graph and estimated percent unaccounted-for water to predict the total water demand for years 2014, 2019, and 2024.

Solution:

a)



b) $$\text{Unaccounted}-\text{For}-\text{Water}(\%)=\left(1-\left(\frac{\sum \text{Dom}+\text{Com}+\text{Ind}}{\text{Total Metered Flow}}\right)\right)\times 100$$

Year	Total Metered Flow(gpd)	Sum of recorded Domestic, Commercial and Industrial Flows	Unaccounted-For-Water (%)
2003	1,687,517	1,340,152	20.6
2004	1,789,453	1,404,994	21.5
2005	1,745,658	1,381,448	20.9
2006	1,728,750	1,392,033	19.5
2007	1,779,854	1,410,094	20.8
2008	1,826,650	1,442,016	21.1
2009	1,872,456	1,469,244	21.5
		Average =	20.8

c) $\text{Total Water Demand} = \dfrac{\sum \text{Dom} + \text{Com} + \text{Ind}}{1 - (20.8/100)}$

Year	Domestic (gpd)	Commercial (gpd)	Industrial (gpd)	Total (gpd)
2014	960,000	511,000	87,000	1,967,000
2019	1,020,000	542,000	148,000	2,159,000
2024	1,079,000	573,000	145,000	2,269,000

7.19 The recorded metered flow for June 3 at the Wilkes City wastewater treatment plant is shown in Figure 7.38. (a) Estimate the average flow rate for June 3.

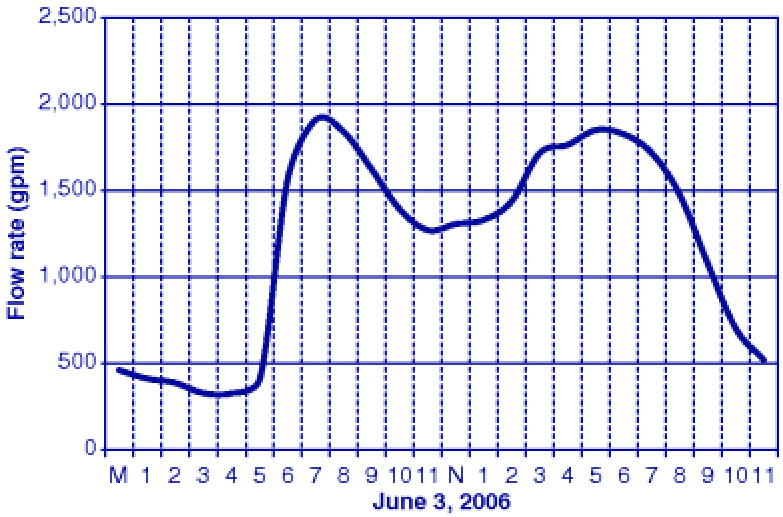


Figure 7.38 **Wilkes City Wastewater Metered Flow Rate (Used in Problem 7.19)**

Solution:

Time	Flow Rate in gpm
M	459
1	411
2	387
3	326
4	326
5	411
6	1571
7	1909
8	1837
9	1619
10	1389
11	1269
N	1305
1	1329
2	1438
3	1716
4	1764
5	1849
6	1824
7	1716
8	1474
9	1075
10	701
11	520
TOAL	**28625**

a)

$$Average\ flow\ rate = \frac{\sum flow\ rate}{24} = \frac{28{,}625\ gpm}{24}$$

$$= \mathbf{1193\ gpm}$$

7.20 A storage tank is designed to supply water for fire protection at a small industry. The NFF for this industry is 3,400 gpm. (a) Estimate the volume of water that would be needed for fire protection. (b) Estimate the nominal pipe size of a single pipe supplying the fire protection water from the tank if the design velocity for the pipe is 9.5 ft./sec.

Solution:

a)

$$\text{Use Table } 7\text{–}12: \text{For NFF} = 3400 \text{ gpm, } t = 3 \text{ h}$$

$$\text{Storage} = 3400 \text{ gpm} \times 3 \text{ h} \times \frac{60 \text{ min}}{1 \text{ h}} = \boxed{612{,}000 \text{ gallons}}$$

b)

$$\text{Use equation } 7\text{–}6 \text{ for US customary units:}$$

$$k = 0.64 \quad Q = 3400 \text{ gpm} \quad \nu = 9.5 \text{ fps}$$

$$D = 0.64\sqrt{\frac{3400}{9.5}} = 12.1 \text{ in.}$$

$$\boxed{D = 12 \text{ inch pipe}}$$

7.21 Estimate the size of a storage tank to supply water for fire protection to a 65,000 ft^2 department store (O = 1.0). The building is constructed from fire resistant materials (F = 0.8), with a total exposure and communication factors equal to 0.45.

Solution:

Use equation 7.6 to solve for NFF (the needed fire flow in gpm).

$$\mathrm{NEF} = 18 \times F \times A^{0.5} \times O \times (1 + \sum(X+P))$$

Where:
$F = 0.8$
$A = 65{,}00\ ft^2$
$O = 1.0$
$\sum(X+P) = 0.45$

$$NFF = 18 \times 0.8 \times 65{,}000^{0.5} \times 1.0 \times (1 + 0.45) = 5{,}300\ gpm$$

To calculate the storage, multiply the needed fire flow by the fire protection duration (4 hours from table 7.17 since the NFF is > 3,500).

$$storage = 5{,}300 gpm \times 4hr \times 60\frac{min}{hr} = \boldsymbol{1,257,000\ gallons}$$

7.22 A pumping station with wet well is to be sized in a wastewater collection system for a design pumping rate of 1,200 gpm. (a) Estimate the minimum active wet-well volume with a pump cycle of 4 times per hour. (b) Size the force main (pumping station discharge pipe) with a design velocity of 7.5 ft./sec.

Solution:

a) Each pump cycle is 15 minutes. Use Equation 7-7:

$$V_{\text{min}} = \frac{1200\ \text{gpm} \times 15\,\text{min}}{4} = \boxed{4,500\ \text{gallons}}$$

b) Use Equation 7-6 for US customary units:

$$k = 0.64 \quad Q = 1200\ \text{gpm} \quad \nu = 7.5\ \text{fps}$$

$$D = 0.64\sqrt{\frac{1200}{7.5}} = 8.1\,\text{in.}$$

$$\boxed{D = 8\ \text{inch pipe}}$$

7.23 Identify one regional and one global water scarcity issue. Develop a long-term sustainable solution that protects future generations of humans and the environment.

Solution:

Students’ responses will vary.

7.24 Go to the U.S. Green Building Council Website (http://www.usgbc.org) and research the LEED credits associated with new commercial construction and major renovation (Version 2.2, from U.S. Green Building Council). A project can obtain a maximum of 69 points. (a) How many possible points directly relate to the category water efficiency? (b) What are the specific credits provided for the category water efficiency?

Solution:

a) There are 5 possible points out of the 69 maximum points that are directly related to water efficiency.

b) The 5 credits are for:

Water Efficiency (5 Possible Points)
  Credit 1.1 Water Efficient Landscaping, Reduce by 50% (1 point)
  Credit 1.2 Water Efficient Landscaping, No Potable Use or No Irrigation (1 point)
  Credit 2 Innovative Wastewater Technologies (1 point)
  Credit 3.1 Water Use Reduction, 20% Reduction (1 point)
  Credit 3.2 Water Use Reduction, 30% Reduction (1 point)

Note that project could obtain additional points for water efficiency through the category: innovation and design processes.

Innovation & Design Process (5 Possible Points)
  Credit 1.1 Innovation in Design (1 point)
  Credit 1.2 Innovation in Design (1 point)
  Credit 1.3 Innovation in Design (1 point)
  Credit 1.4 Innovation in Design (1 point)
Credit 2 LEED Accredited Professional (1 point)

7.25 Go the following web site (http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/) and look up the report, *The 1st UN World Water Development Report: Water for People, Water for Life.* (a) Of the 11 challenge areas, list the ones related to "life and well being" and the ones related to "management". (b) Access the link on "facts and figures on securing the food supply". Develop a table with columns of product, unit equivalent, and water in m^3 per unit for the following products: cattle, sheep and goats, fresh beef, fresh lamb, fresh poultry, cereals, citrus fruits, palm oil, and roots and tubers. Use this table to answer the question, on a per kg basis, does providing meat or grains/fruits use more water?

Solution:

a) The six challenges for Life and Well Being are:
1) meeting basic needs, 2) protecting ecosystems, 3) water and cities, 4) securing the food supply, 5) water and industry, and 6) water and energy

The five Challenges for Management (Stewardship and Governance) are:
1) managing risks, 2) sharing water resources, 3) valuing water, 4)ensuring the knowledge base, and 5) governing water wisely.

b) Raising grains and fruits uses less water on a per kg basis.

Water equivalent requirements for several food products.

Product	**Unit Equivalent**	**Water in m^3 per unit**
Cattle	Head	4,000
Sheep and goats	Head	500
Fresh beef	Kg	15
Fresh lamb	Kg	10
Fresh poultry	Kg	6
Cereals	Kg	1.5
Citrus fruits	Kg	1
Palm oil	Kg	2
Roots and tubers	Kg	1

7.26 Go to the following web site to learn how you can save water at home (http://www.epa.gov/WaterSense/pubs/simple_steps.html). For the following three areas (in the bathroom, in kitchen/laundry, outdoors) list a minimum of 3 items you can do at home to conserve water.

Solution:

The following is obtained directly from the EPA web site.

In the Bathroom

- Install a toilet dam or plastic bottle in your toilet tank.
- Install a water-efficient showerhead (2.5 gallons or less per minute).
- Take short showers and draw less water for baths.
- When you buy a new toilet, purchase a low flow model (1.6 gallons or less per flush).
- Check your toilet for "silent" leaks by placing a little food coloring in the tank and seeing if it leaks into the bowl.
- Turn off water while brushing teeth and shaving.

In the Kitchen or Laundry

- Compost your food scraps rather than using a garbage disposal in your sink.
- Keep a gallon of drinking water in the refrigerator rather than running the tap for cold water.
- Run your washing machine with a full load of clothes. Wash with warm water instead of hot, rinse with cold water instead of warm. Wash with cold water when you can. (When possible) hang your wash out to dry.

Outdoors

- Install a drip-irrigation water system for valuable plants.
- Use drought-tolerant plants and grasses for landscaping and reduce grass-covered areas.
- Cut your grass at least three inches high to shade the roots, making it more drought tolerant; keep your mower sharp for the healthiest grass.
- Try to water only in the evening or very early morning to minimize evaporation.
- If you use porous pavement (gravel is a good example) instead of asphalt for driveways and walkways, the rain can recharge groundwater supplies instead of running off and contributing to erosion.
- Use a broom instead of a hose to clean off your driveway or sidewalk.
- Wash your car less often or wash it at a car wash where they clean and recycle the water. If you do wash your car at home, use a bucket of soapy water rather than running the hose. Keep a spring-loaded nozzle on the hose.

7.27 If the Henry's constant (K_H) for dissolved oxygen is 0.00136 moles/L-atm at 20^oC and the concentration of carbon dioxide in the atmosphere is 390 ppm_v, what is the concentration of oxygen dissolved in water equilibrated with the atmosphere in: (a) moles/L, (b) mg/L, (c) µg/L, and (d) ppm_m? (e) How does your answer to part (b) change if the Henry's constant is reported in different units (K_H equal to 735.3 L-atm/moles).

Solution:

This problem is similar to example to example 7.6.

a) $DO_{sat} = 1.36 * 10^{-3} \frac{moles}{L{-}atm} \times 0.21\ atm = \mathbf{2.85 \times 10^{-4} \frac{mol\ O_2}{L}}$

b) $2.85 * 10^{-4} \frac{mol\ O_2}{L} \times \frac{32\ gO_2}{mol\ O_2} \times \frac{1000\ mg\ O_2}{g\ O_2} = \mathbf{9.1 \frac{mg\ O_2}{L}}$

c) $9.1 \frac{mg\ O_2}{L} \times \frac{1000\ \mu g}{1\ mg} = \mathbf{9,100 \frac{\mu g}{L}}$

d) Recall from chapter 6 that 1 mg/L=1ppm in water

$$9.1 \frac{mg\ O_2}{L} = \mathbf{9.1\ ppm_m}$$

e) If K_H is equal to 735.3 L-atm/moles, take the inverse to convert to the correct units moles/L-atm

$$\frac{1}{735.5 \frac{L - atm}{moles}} = 0.00136 \frac{moles}{L - atm}$$

The conversion yields the same Henry's constant given in the problem, therefore **the answer to part b does not change.**

7.28 A stream at 25°C has a dissolved-oxygen concentration of 4 mg/L. What is the dissolved-oxygen deficit in (a) mg/L, (b) ppm, (c) ppb, and (d) moles/L?

Solution:

a) First, calculate DOsat as in example 7.6. In example 3.4, the Henry's law constant for oxygen at 25°C is 1.29×10^{-3} mole/L-atm

$$DO_{sat} = 1.29 * 10^{-3}\frac{moles}{L-atm} \times 0.21\,atm = 2.85 * 10^{-4}\frac{mol\ O_2}{L} \times \frac{32\ gO_2}{mol\ O_2} \times \frac{1000\ mg\ O_2}{g\ O_2}$$
$$= 8.7\frac{mg\ O_2}{L}$$

Use equation 7.11 to solve for the dissolved-oxygen deficit:

$$D = DO_{sat} - DO_{act} = 8.7\frac{mg\ O_2}{L} - 4\frac{mg\ O_2}{L} = \mathbf{4.7\frac{mg\ O_2}{L}}$$

b) From chapter 2, 1 ppm is equivalent to 1 mg/L in water.

$$4.7\frac{mg\ O_2}{L} = \mathbf{4.7 ppm_m\ O_2}$$

c) $4.7 ppm_m\ O_2 \times \frac{10^3 ppb_m}{ppm_m} = \mathbf{4700\ ppb_m}$

d) $4.7\frac{mg\ O_2}{L} \times \frac{1g\ O_2}{1000\ g\ O_2} \times \frac{1\ mol\ O_2}{32\ g\ O_2} = \mathbf{1.5 * 10^{-4}\frac{moles\ O_2}{L}}$

7.29 The oxygen concentration of a stream is 4 mg/L, and DO saturation is 10 mg/L. What is the oxygen deficit?

Solution:

Use equation 7.11 to solve for the oxygen deficit:

$$D = DO_{sat} - DO_{act} = 10\frac{mgO_2}{L} - 4\,\frac{mgO_2}{L} = \mathbf{6}\frac{\boldsymbol{mgO_2}}{\boldsymbol{L}}$$

7.30 The measured dissolved oxygen concentration using a DO meter of a river is 6 mg/L. The oxygen deficit is 2 mg/L at the same location. What is the saturation concentration of dissolved oxygen in (a) mg/L, (b) ppm, (c) ppb, and (d) moles/L?

Solution:

a) Use equation 7.11 to solve for the saturation concentration of dissolved oxygen (DO_{sat}):

$D = DO_{sat} - DO_{act}$

$$DO_{sat} = D + DO_{act} = 2\frac{mgO_2}{L} + 6\ \frac{mgO_2}{L} = \mathbf{8}\ \boldsymbol{\frac{mgO_2}{L}}$$

b) From chapter 2, 1 ppm is equivalent to 1 mg/L in water.

$$8\ \frac{mg\ O_2}{L} = \mathbf{8}\ \boldsymbol{ppm_m\ O_2}$$

c) $8\ ppm_m\ O_2 \times \frac{10^3 ppb_m}{ppm_m} = \mathbf{8000}\ \boldsymbol{ppb_m}$

d) $8\frac{mg\ O_2}{L} \times \frac{1g\ O_2}{1000\ g\ O_2} \times \frac{1\ mol\ O_2}{32\ g\ O_2} = \mathbf{3 \times 10^{-4}}\ \boldsymbol{\frac{moles\ O_2}{L}}$

7.31 Dr. Mihelcic is canoeing on the Hillsborough River in Florida, just upstream of Trout Creek Wilderness Area. He is collecting dissolved oxygen readings with his DO meter. He spots several roseate spoonbills, woodstorks, and green herons feeding near the water's edge, gets excited, and drops his oxygen meter into the water. Assuming he is afraid to gather the meter from the bottom of the river because of the presence of alligators, what is the river's dissolved oxygen at this point if he learns later that the water temperature is 20°C and the oxygen deficit at this point is 3 mg/L at the time he was paddling.

Solution:

Use equation 7.11 to solve for the river's dissolved oxygen concentration (DO_{act}):

$$D = DO_{sat} - DO_{act}$$

$$DO_{act} = DO_{sat} - D$$

First, calculate DOsat as in example 7.6.

$$DO_{sat} = 1.36 \times 10^{-3} \frac{moles}{L - atm} \times 0.21\ atm = 2.85 \times 10^{-4} \frac{mol\ O_2}{L} \times \frac{32\ gO_2}{mol\ O_2} \times \frac{1000\ mg\ O_2}{g\ O_2}$$
$$= 9.1 \frac{mg\ O_2}{L}$$

$$DO_{act} = DO_{sat} - D = 9.1\ \frac{mgO_2}{L} - 3\ \frac{mgO_2}{L} = \mathbf{6.2\ \frac{mgO_2}{L}}$$

7.32 Calculate the dissolved-oxygen deficit for a river at 30°C and a measured dissolved-oxygen concentration of 3 mg/L. The Henry's law constant at that temperature is 1.125×10^{-3} mole/L-atm, and the partial pressure of oxygen is 0.21 atm.

Solution:

Determine DO_{sat} from the appropriate temperature-dependent Henry's Law constant and the partial pressure of oxygen:

$$DO_{sat} = \frac{1.125\times10^{-3}\ moles}{L\cdot atm}\times 0.21\,atm = \frac{2.36\times10^{-4}\ moles\ O_2}{L}$$

Convert to mg O_2/L:

$$DO_{sat} = \frac{2.36\times10^{-4}\ moles\ O_2}{L}\times\frac{32\ g\ O_2}{mole\ O_2}\times\frac{1{,}000\ mg\ O_2}{g\ O_2} = \frac{7.6\ mg\ O_2}{L}$$

Now calculate the oxygen deficit:

$$D = DO_{sat} - DO_{act}$$

$$D = 7.6\frac{mg}{L} - 3\frac{mg}{L} = \boxed{4.6\frac{mg}{L}}$$

7.33 A wastewater treatment plant discharges an effluent containing 2 mg/L of dissolved oxygen to a river that has a dissolved-oxygen concentration of 8 mg/L upstream of the discharge. Calculate the dissolved-oxygen deficit at the mixing basin if the saturation dissolved oxygen for the river is 9 mg/L. Assume that the river and plant discharge have the same flow rate.

Solution:

Determine the actual oxygen concentration at the mixing basin:

$$Q_{river} = Q_{disch\arg e} = Q$$

$$DO = \frac{\left(Q_{river} \times 8\frac{mg}{L}\right) + \left(Q_{disch\arg e} \times 2\frac{mg}{L}\right)}{2Q} = 5\frac{mg}{L}$$

Now determine the dissolved-oxygen deficit:

$$D = DO_{sat} - DO_{act}$$

$$D = 9\frac{mg}{L} - 5\frac{mg}{L} = \boxed{4\frac{mg}{L}}$$

7.34 A combined sewer overflow (CSO) discharges an effluent containing 0 mg/L of dissolved oxygen to a stream that has a dissolved-oxygen concentration of 7 mg/L upstream of the discharge. Calculate the dissolved-oxygen deficit at the mixing basin if the saturation dissolved oxygen for the river is 9 mg/L. Assume that the CSO flowrate is one half of the stream flowrate.

Solution:

Use equation 7.11 to solve for the dissolved-oxygen concentration (D):

$$D = DO_{sat} - DO_{act} = 9\frac{mgO_2}{L} - \frac{0\frac{mgO_2}{L} + 7\frac{mgO_2}{L}}{2} = \mathbf{5.5}\frac{\boldsymbol{mgO_2}}{\boldsymbol{L}}$$

7.35 A river traveling at a velocity of 10 km/day has a dissolved-oxygen content of 5 mg/L and an ultimate CBOD of 25 mg/L at distance $x =$ 0 km, that is, immediately downstream of a waste discharge. The waste has a CBOD decay coefficient k_1 of 0.2/day. The stream has a reaeration rate coefficient k_2 of 0.4/day and a saturation dissolved-oxygen concentration of 9 mg/L. (a) What is the initial dissolved-oxygen deficit? (b) What is the location of the critical point, in time and distance? (c) What is the dissolved-oxygen deficit at the critical point? (d) What is the dissolved-oxygen concentration at the critical point?

a) $D_0 = DO_{sat} - DO_{act} \Rightarrow 9 - 5 = \boxed{4\,\frac{mg}{L}}$

b) Use Equation 7-7 to determine the critical time and knowledge of the river's velocity to determine the critical distance:

$$t_{crit} = \frac{1}{k_2 - k_1} \times \ln\left(\frac{k_2}{k_1} \times \left(1 - \frac{D_0 \times (k_2 - k_1)}{k_1 \times L_0}\right)\right)$$

$$t_{crit} = \frac{1}{0.4/day - 0.2/day} \times \ln\left(\frac{0.4/day}{0.2/day} \times \left(1 - \frac{4\,\frac{mg}{L} \times (0.4/day - 0.2/day)}{0.2/day \times 25\,\frac{mg}{L}}\right)\right)$$

$$\boxed{t_{crit} = 2.6\,day}$$

$$x_{crit} = 2.6\,day \times 10\,km/day = \boxed{26\,km}$$

c) Use Equation 7-5 to determine the oxygen deficit and

$$D_t = \frac{k_1 \times L_0}{(k_2 - k_1)} \times \left(e^{-k_1 \times t} - e^{-k_2 \times t}\right) + D_0 \times e^{-k_2 \times t}$$

$$D_t = \frac{0.2/day \times 25\,\frac{mg}{L}}{(0.4/day - 0.2/day)} \times \left(e^{-0.2/day \times 2.6\,day} - e^{-0.4/day \times 2.6\,day}\right) + 4\,\frac{mg}{L} \times e^{-0.4/day \times 2.6\,day}$$

$$\boxed{D_t = 7.4\,\frac{mg}{L}}$$

7.36 The wastewater treatment plant for Pine City discharges 1 × 10^5 m^3/day of treated waste to the Pine River. Immediately upstream of the treatment plant, the Pine River has an ultimate CBOD of 2 mg/L and a flow of 9 × 10^5 m^3/day. At a distance of 20 km downstream of the treatment plant, the Pine River has an ultimate CBOD of 10 mg/L. The state's Department of Environmental Quality (DEQ) has set an ultimate CBOD discharge limit for the treatment plant of 2,000 kg/day. The river has a velocity of 20 km/day. The CBOD decay coefficient is 0.1/day. Is the plant in violation of the DEQ discharge limit?

Solution:

Determine the initial concentration at the mixing basin from:

$$L_t = L_0 \times e^{-k_L \times t}$$

$$t = \frac{x}{U} = \frac{20km}{20\frac{km}{day}} = 1\ day$$

$$10\frac{mg}{L} = L_o \times e^{-0.1\times 1} \quad \Rightarrow \boxed{L_o = 11\frac{mg}{L}}$$

Apply mass balance to determine the ultimate CBOD of the discharged wastewater:

$$CBOD_5\ after\ mixing = \frac{Q_{river} \times CBOD_{5\ \ river} + Q_{waste} \times CBOD_{5\ \ waste}}{Q_{river} + Q_{waste}}$$

$$\frac{\left(1\ \times 10^5 \frac{m^3}{day}\ \times x\frac{mg}{L}\right) + \left(9\ \times 10^5 \frac{m^3}{day}\ \times 2\frac{mg}{L}\right)}{\left(1\ \times 10^5 \frac{m^3}{day}\right) + \left(9\ \times 10^5 \frac{m^3}{day}\right)} = \boxed{11\frac{mg}{L}}$$

Solve for x = 92 mg/L ultimate CBOD concentration of the wastewater discharge

$$92\frac{mg}{L} \times \frac{kg}{1\times 10^6 mg} \times \frac{1000\ L}{m^3} \times \frac{1\times 10^5 m^3}{day} = \boxed{9200\ kg / day}$$

9200 kg/day >> 2000 kg/day so the plant is in violation.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

7.37 An industry discharges 0.5 m^3/s of a waste with a 5-day CBOD of 500 mg/L to a river with a flow of 2 m^3/s and a 5-day CBOD of 2 mg/L. Calculate the 5-day CBOD of the river after mixing with the waste.

Solution:

$$CBOD_5\ after\ mixing = \frac{Q_{river} \times CBOD_{5\ \ river} + Q_{waste} \times CBOD_{5\ \ waste}}{Q_{river} + Q_{waste}}$$

$$CBOD_5\ after\ mixing = \frac{2\frac{m^3}{\mathrm{s}} \times 2\frac{mg}{L} + 0.5\frac{m^3}{\mathrm{s}} \times 500\frac{mg}{L}}{2.5\frac{m^3}{\mathrm{s}}} = \boxed{102\frac{mg}{L}}$$

7.38 A high strength waste having an ultimate CBOD of 1,000 mg/L is discharged to a river at a rate of 2 m^3/s. The river has an ultimate CBOD of 10 mg/L and is flowing at a rate of 8 m^3/s. Assuming a reaction rate coefficient of 0.1/day, calculate the ultimate and 5-day CBOD of the waste at the point of discharge (0 km) and 20 km downstream. The river is flowing at a velocity of 10 km/day.

Solution:

Determine ultimate CBOD at the point of discharge Lo:

$$L_o = \frac{Q_{river} \times CBOD_{river} + Q_{waste} \times CBOD_{waste}}{Q_{river} + Q_{waste}}$$

$$L_o = \frac{8\frac{m^3}{s} \times 10\frac{mg}{L} + 2\frac{m^3}{s} \times 1000\frac{mg}{L}}{10\frac{m^3}{s}} = \boxed{208\frac{mg}{L}}$$

Determine ultimate CBOD downstream

$$t = \frac{x}{U} = \frac{20\ km}{10\ km/day} = 2\ days$$

$$L_t = L_0 \times e^{-k_L \times t} \qquad L_t = 208\frac{mg}{L} \times e^{-0.1/day \times 2days} = 170\frac{mg}{L}$$

$$5\ day\ CBOD = Ultimate\ CBOD \times (1 - e^{-kt})$$

$$5\ day\ CBOD = 170\frac{mg}{L} \times \left(1 - e^{-0.1/day \times 5days}\right)$$

$$= \boxed{67\frac{mg}{L}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

7.39 A new wastewater treatment plant proposes a discharge of 5 m^3/s of treated waste to a river. State regulations prohibit discharges that would raise the ultimate CBOD of the river above 10 mg/L. The river has a flow of 5 m^3/s and an ultimate CBOD of 2 mg/L. Calculate the maximum 5-day CBOD that can be discharged without violating state regulations. Assume a CBOD decay coefficient of 0.1/day for both the river and the proposed treatment plant.

Solution:

Determine the maximum ultimate CBOD that can be discharged without violating state regulations:

$$10\frac{mg}{L} = \frac{\left(5\frac{m^3}{\text{s}} \times 2\frac{mg}{L}\right) + \left(5\frac{m^3}{\text{s}} \times x\frac{mg}{L}\right)}{10\frac{m^3}{\text{s}}}$$

Solve for x = $18\frac{mg}{L}$ maximum ultimate CBOD

Now determine 5-day CBOD for the $18\frac{mg}{L}$ maximum ultimate CBOD:

$$\text{maximum 5} - \text{day CBOD } = 18\frac{mg}{L} \times \left(1 - e^{-0.1/day \times 5 days}\right) = \boxed{7.1\frac{mg}{L}}$$

7.40 A river flowing with a velocity of 20 km/day has an ultimate CBOD of 20 mg/L. If the organic matter has a decay coefficient of 0.2/day, what is the ultimate CBOD 40 km downstream?

Solution:

$$t = \frac{x}{U} = \frac{40\ km}{20\ km/day} = 2\ days$$

ultimate CBOD at 40 km $=20\frac{mg}{L} \times e^{-0.2/day\ \times\ 2\ days}$

$$= \boxed{13.4\frac{mg}{L}}$$

7.41 A river traveling at a velocity of 10 km/day has an initial oxygen deficit of 4 mg/L and an ultimate CBOD of 10 mg/L. The CBOD has a decay coefficient of 0.2/day, and the stream's reaeration coefficient is 0.4/day. What is the location of the critical point: (a) in time; (b) in distance?

Solution:

a)

$$t_{crit} = \frac{1}{k_2 - k_1} \times \ln\left(\frac{k_2}{k_1} \times \left(1 - \frac{D_0 \times (k_2 - k_1)}{k_1 \times L_0}\right)\right)$$

$$t_{crit} = \frac{1}{0.4/day - 0.2/day} \times \ln\left(\frac{0.4/day}{0.2/day} \times \left(1 - \frac{4\,\frac{mg}{L} \times (0.4/day - 0.2/day)}{0.2/day \times 10\,\frac{mg}{L}}\right)\right)$$

$\boxed{\text{Critical time = 0.91 days}}$

b)

The critical distance = $0.91\,day \times 10\,\frac{km}{day} = \boxed{9.1\ km}$

7.42 A paper mill discharges its waste ($k_L = 0.05/\text{day}$) to a river flowing with a velocity of 20 km/day. After mixing with the waste, the river has an ultimate carbonaceous BOD of 50 mg/L. Calculate the 5-day carbonaceous BOD at that location and the ultimate carbonaceous BOD remaining 10 km downstream.

Solution:

At the location, 5-day carbonaceous BOD = $50\frac{\text{mg}}{\text{L}} \times \left(1 - e^{-0.05/day \times 5 day}\right) = 11\frac{\text{mg}}{\text{L}}$

The ultimate carbonaceous BOD remaining 10 km downstream:

$$t = \frac{x}{U} = \frac{10\ km}{20\ km/day} = 0.5\ days$$

$$CBOD\ downstream = 50\frac{mg}{L} \times e^{-0.05/day \times 0.5\ day} = \boxed{49\frac{mg}{L}}$$

7.43 For each of the following cases, assuming all other things unchanged, describe the effect of the following parameter variations on the magnitude of the maximum oxygen deficit in a river. Use the following symbols to indicate your answers: increase (+), decrease (-), or remain the same (=).

Parameter	Magnitude of the Deficit
Increased initial deficit	______________
Increased ultimate CBOD @ x =0	______________
Increased deoxygenation rate	______________
Increased reaeration rate	______________
Increased ThOD @ x = 0	

Solution:

Parameter	Magnitude of the Deficit
Increased initial deficit	+
Increased ultimate CBOD @ x = 0	+
Increased deoxygenation rate	=
Increased reaeration rate	=
Increased ThOD @ x = 0	+ or = depending on biodegradability

7.44 Humans produce 0.8 to 1.6 L of urine per day. The annual mass of phosphorus in this urine on a per capita basis ranges from 0.2 to 0.4 kg P. a) What is the maximum concentration of phosphorus in human urine in mg P/L? b) What is the concentration in moles P/L? c) Most of this phosphorus is present as HPO_4^{2-}. What is the concentration of phosphorus in mg HPO_4^{2}-/L?

Solution:

a) $[P]_{max} = \frac{0.4\,kg}{year} \times \frac{1000g}{1\,kg} \times \frac{1000\,mg}{1\,g} \times \frac{1day}{0.8\,L} \times \frac{year}{365\,days} = \mathbf{1369}\,\frac{\boldsymbol{mg}}{\boldsymbol{L}.}$

b) $1369\,\frac{mg}{L} \times \frac{1\,g}{1000\,mg} \times \frac{1\,mol\,\mathrm{P}}{30.97\,g} = \mathbf{0.04}\,\frac{\boldsymbol{mol}\,\mathbf{P}}{\boldsymbol{L}}$

c) $0.04\,\frac{mol\,\mathrm{P}}{L} \times \frac{1\,mol\,\mathrm{HPO_4}^{2-}}{1\,mol\,\mathrm{P}} \times \frac{95.97\,g}{1\,mol\,\mathrm{HPO_4}^{2-}} \times \frac{1000\,mg}{1\,g} = \mathbf{3838}\,\frac{\boldsymbol{mg}}{\boldsymbol{L}}$

7.45 Assume 66% of phosphorus in human excrement in found in urine (the remaining 34% is found in feces). Assume humans produce 1 L of urine per day and the annual mass of phosphorus in this urine is 0.3 kg P. If indoor water usage is 80 gallons per capita per day in a single individual apartment, what is concentration (in mg P/L) in the wastewater that is discharged from the apartment unit? Account for phosphorus in urine and feces.

Solution:

First, solve for x, the total mass of phosphorous in feces and urine.

$$0.66 \times x = 0.3\ kg$$

$$x = \frac{0.3\ kg}{.66} = 0.45\ kg\ \mathrm{P}$$

$$\frac{0.45\ kg\ \mathrm{P}}{(80+1)L} \times \frac{1000\ g}{1\ kg} \times \frac{1000\ mg}{1\ g} = \mathbf{5.5 \times 10^3 \frac{mg\ P}{L}}$$

7.46 Contact your local wastewater treatment plant to find out the average daily treated flow rate and average concentration of phosphorus in the untreated influent and treated effluent. Use census data to determine the current population of your area and assuming a growth rate of 3%, the population in 2025 and 2050. (a) If nothing is done in how the plant treats phosphorus and how each human discharges phosphorus, what is the current and future P loading (kg P/day) to the local surface water that takes the plant effluent? (b) Identify one technical and two nontechnical solutions to reduce future phosphorus loading to the wastewater treatment plant. (c) If 50 percent of the treated wastewater is reclaimed and applied to land for residential and agricultural purposes, how would the current loading of phosphorus to local water change? (assume all the reclaimed water infiltrates to groundwater)

Solution:

Students' responses will vary.

7.47 Use the library or Internet to research one dead zone located in the United States and one located overseas, such as the Baltic Sea, northern Adriatic Sea, Yellow Sea, or Gulf of Thailand. Write a two-page report discussing environmental, social, and economic issues associated with the dead zones. What management solutions would you propose to reverse the dead zones?

Solution:

Students' responses will vary.

7.48 Go to EPA's Region 9 web page that is devoted to Lake Tahoe (http://www.epa.gov/region9/water/watershed/tahoe/). Lake Tahoe (California and Nevada) can be differentiated into deep water and near shore zones. EPA reports that "in addition to being a scenic and ecological treasure, the Lake Tahoe Basin is one of the outstanding recreational resources of the United States. The communities and the economy in the Lake Tahoe Basin depend on the protection and restoration of its stunning natural beauty and diverse recreational opportunities in the region." (a) List the States which EPA's Region 9 serves. (b) Lake Tahoe is listed under Clean Water Act Section 303(d) as impaired by input of what 3 pollutants? (c) What one pollutant has the greatest impact on the lake's deep water quality as measured by water transparency? (d) what two additional pollutants play an important role regarding water quality of the near shore zone?

Solution:

a) At the top of the website given in the problem, there is a list of states which EPA's region 9 serves:

Pacific Southwest, Region 9

Serving: Arizona, California, Hawaii, Nevada, Pacific Islands, Tribal Nations

EPA region 9 serves the following states: **Arizona, California, Hawaii, Nevada, Pacific Islands, Tribal Nations**

b) The website, under "Water Quality Issues", states that: "Because these three pollutants are responsible for Lake Tahoe's deep water transparency loss, Lake Tahoe is listed under Clean Water Act Section 303(d) as impaired by input of nitrogen, phosphorus, and sediment."

Therefore, Lake Tahoe is listed under Clean Water Act Section 303(d) as impaired by **nitrogen, phosphorus, and sediment**.

c) Also under "Water Quality Issues" on the website, it states: "Fine sediment particles are the most dominant pollutant contributing to the impairment of the lake's deep water transparency, accounting for roughly two thirds of the lake's impairment."

Thus, one pollutant that has the greatest impact on the lake's deep water quality are **fine sediment particles**.

d) Again under the "Water Quality Issues" section of the EPA website it states: "Similarly, the nearshore environment has experienced degraded conditions due to proliferation of algae and other aquatic invasive plants and animals, particularly in urbanized areas."

Two additional pollutants that play an important role regarding water quality of the near shore zone are **algae and other aquatic invasive plants and animals**.

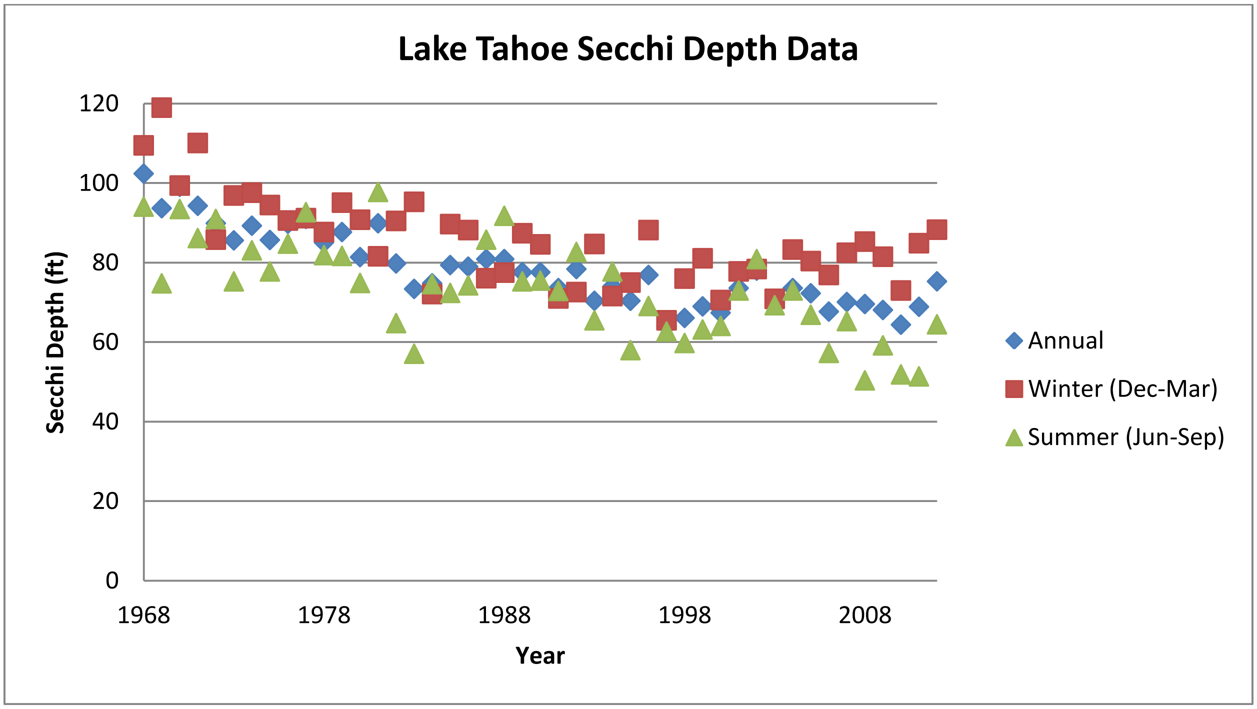
Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

7.49 EPA reports that "in addition to being a scenic and ecological treasure, the Lake Tahoe Basin is one of the outstanding recreational resources of the United States. Go to the following web site to obtain Secchi depth data at Lake Tahoe (http://terc.ucdavis.edu/research/SecchiData.pdf). (a) Describe how a Secchi depth measurement is performed. (b) Produce one properly labeled and captioned graph that provides the summer average, winter average, and annual average Secchi depth of Lake Tahoe from 1968 – 2011. Use this figure to answer the question, has water quality in the lake improved since 1968?

Solution:

(a) By just looking at the data it looks that the Secchi Depth had a higher average in the 80-100 ft range between 1968-1988 but then was between 70 and 80ft for the next ten years (1988-1998). From 1988 to 2012, the depth has been between 60-80ft but as low as the 50s and a lower average in the summer months (June-September) through 2011. In general the summer depth data is lower than the winter depth data.

b) **Water quality has not improved but actually declined since 1968.** However there appears to be a slight increase in water quality since 2008.



7.50 Go to the web site of the Mississippi River/Gulf of Mexico Watershed Nutrient (Hypoxia) Task Force. (http://water.epa.gov/type/watersheds/named/msbasin/index.cfm). On this web site, EPA reports that "hypoxia can be caused by a variety of factors, including excess nutrients, primarily nitrogen and phosphorus, and waterbody stratification due to saline or temperature gradients." Under the Hypoxia 101 web site, hypoxic waters have dissolved oxygen concentrations of less than 2-3mg/L. (http://water.epa.gov/type/watersheds/named/msbasin/hypoxia101.cfm). (a) List the four sources of nutrients that impact this water body.

Solution:

You can find the following key information from the websites below:

http://water.epa.gov/type/watersheds/named/msbasin/hypoxia101.cfm

Nutrients can come from many sources, including any of the following:

- Fertilizers from agriculture, golf courses, and suburban lawns
- Erosion of soil full of nutrients
- Discharges from sewage treatment plants
- Deposition of atmospheric nitrogen

http://www.gulfhypoxia.net/overview/ and
http://www.smm.org/deadzone/causes/top.html

1. Freshwater discharge and nutrient loading of the Mississippi River (ex. Nitrogen and phosphorus nutrients used in agriculture or on lawns)
2. Nutrient-enhanced primary production, or eutrophication
3. Decomposition of biomass by bacteria on the ocean floor
4. Depletion of oxygen due to stratification

The main sources of nutrients for the Mississippi/Gulf of Mexico water body: **fertilizers, sewage, atmospheric nitrogen, freshwater discharge, soil erosion.**

7.51 (a) What was the size (in square miles) of the 2012 Gulf of Mexico hypoxic zone reported by NOAA scientists on July 27, 2012? (b) Was this larger or smaller than in 2011? (c) What caused the change in the dead zone from 2011 to 2012?

Solution:

a) Click on upper left link "2012 Gulf Dead Zone" from the following website:
http://water.epa.gov/type/watersheds/named/msbasin/gulfnews.cfm#2012zone

"NOAA-supported scientists released the size of the 2012 Gulf of Mexico hypoxic zone on July 27, 2012. The dead zone measured ***2,889 square miles*** this year…."

b) the quote continues on: "…which is significantly **smaller** than 2011."

c) Also on the website in part a, it states: "**Summer drought conditions** in the Mississippi River Basin are considered to be largely the cause for the fourth smallest dead zone since the mapping of the zone has occured."

7.52 List the three most common contributors to wetland loss in the U.S.

Solution:

According to table 7.22 the most common contributors to wetland loss are: **agricultural activities, residential and commercial development (urbanization), and construction of roads and highways**.

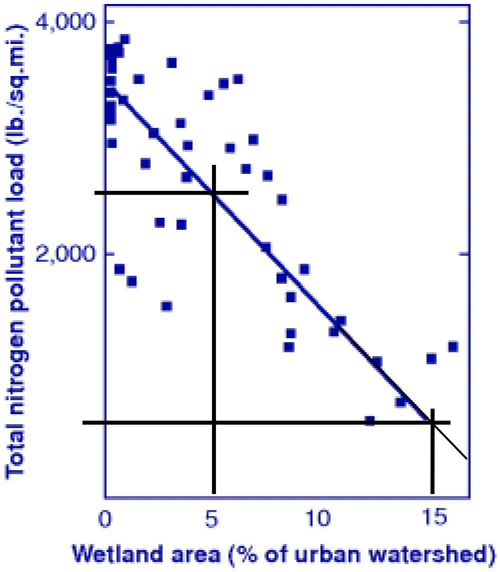
Table / 7.22

Most Common Contributors to Wetland Loss
Agricultural activities
Residential and commercial development (urbanization)
Construction of roads and highways

7.53 Using Figure 7.29, estimate the nitrogen loading (lbs N/square mile) to a urban watershed if the watershed protects (a) 5 percent of its wetlands and (b) 15 percent of its wetlands.

Solution:

Below is figure 7.29. Draw lines on the graph for the appropriate percentage of wetland area and determine the total nitrogen pollutant load.



Draw lines

a) **~2,800 lb N/sq mi** total nitrogen pollutant load at 5 percent of its wetlands

b) **~600 lb N/sq mi** total nitrogen pollutant load at 15 percent of its wetlands

7.54 Two groundwater wells are located 100 m apart in permeable sand and gravel. The water level in well 1 is 50 m below the surface, and in well 2 the water level is 75 m below the surface. The hydraulic conductivity is 1 m/day, and porosity is 0.60. What is: (a) the Darcy velocity; (b) the true velocity of the groundwater flowing between wells; and (c) the period it takes water to travel between the two wells, in days?

Solution:

a. Use the equation for Darcy velocity (7.19):

$$v = \frac{Q}{A} = K\left(\frac{dh}{dl}\right) = 1\frac{m}{day} \times \frac{(75-50)\ m}{100m} = \mathbf{0.25}\frac{\boldsymbol{m}}{\boldsymbol{day}}$$

b. This problem is similar to example 7.9. Use equation 7.20 to solve for the true velocity of the groundwater flowing between the wells (include porosity):

$$v_a = \frac{v_a}{\eta} = 1\frac{m}{day}0.60 \times \frac{(75-50)\ m}{100m} = \mathbf{0.42}\frac{\boldsymbol{m}}{\boldsymbol{day}}$$

c. Velocity is distance traveled over time. To solve for time, divide the distance to be traveled by the velocity.

$$t = \frac{L}{v} = \frac{100m}{0.42\frac{m}{day}} = \mathbf{240\ \boldsymbol{days}}$$

7.55 The hydraulic gradient of groundwater in a certain location is 2 m/100 m. Here, groundwater flows through sand, with a hydraulic conductivity equal to 40 m/day and a porosity of 0.5. An oil spill has caused the pollution of the groundwater in a small region beneath an industrial site. How long would it take the polluted water from that location to reach a drinking-water well located 100 m downgradient? Assume no retardation of the pollutant's movement.

Solution:

First, use equation 7.20 to solve for the average velocity:

$$v_a = \frac{v_a}{\eta} = \frac{40\,\frac{m}{day}}{0.50} \times \frac{2\ m}{100m} = \mathbf{1.6\,\frac{m}{day}}$$

Velocity is distance traveled over time. To solve for time, divide the distance to be traveled by the velocity.

$$t = \frac{L}{v} = \frac{100m}{1.6\ \frac{m}{day}} = \boldsymbol{63\ days}$$

7.56 An underground storage tank has discharged diesel fuel into groundwater. A drinking-water well is located 200 m downgradient from the fuel spill. To ensure the safety of the drinking-water supply, a monitoring well is drilled halfway between the drinking-water well and the fuel spill. The difference in hydraulic head between the drinking-water well and the monitoring well is 40 cm (with the head in the monitoring well higher). If the porosity is 39 percent and hydraulic conductivity is 45 m/day, how long after the contaminated water reaches the monitoring well would it reach the drinking-water well? Assume the pollutants move at the same speed as the groundwater.

Solution:

This problem is similar to example 7.9. Use equation 7.20 to solve for the average velocity):

$$v_a = \frac{v_a}{\eta} = \frac{-45\frac{m}{day}}{0.39} \times \frac{-0.40\ m}{100m} = \boldsymbol{0.46\frac{m}{day}}$$

Velocity is distance traveled over time. To solve for time, divide the distance to be traveled by the velocity.

$$t = \frac{L}{v} = \frac{100m}{0.46\frac{m}{day}} = \boldsymbol{217\ days}$$

7.57 Spills of organic chemicals that contact the ground sometimes reach the groundwater table, where they are then carried downgradient with the groundwater flow. The rate at which they are transported with the groundwater is decreased by sorption to the solids in the groundwater aquifer. The contaminated groundwater can reach wells, which is dangerous if the water is used for drinking. (a) For a soil having ρ_b of 2.3 g/cm^3 and a porosity of 0.3, and for which the percent organic carbon equals 2 percent, determine the retardation factors of trichloroethylene $(\log K_{ow} = 2.42)$, hexachlorobenzene $(\log K_{ow} = 5.80)$, and dichloromethane $(\log K_{ow} = 1.31)$. (b) Which compound would be transported farthest, second farthest, and least far with the groundwater if these chemicals entered the same aquifer?

Solution:

a. You will use equation 7.22 to solve for the retardation factor, Rf. However, first you will need to calculate the soil-water partition coefficient, K_p. This can be determined by first calculating the soil-water partition coefficient normalized to organic carbon, K_{oc}, from the equation in figure 3.11 and then using the relationship between K_p, K_{oc}, and the fraction of organic carbon (F_{oc}) in equation 3.33 to calculate K_p. This process will be repeated three times for trichloroethylene, hexachlorobenzene, and dichloromethane.

First, calculate K_{oc} for trichloroethylene using the equation in figure 3.11:

$$\log K_{oc} = 0.903 \times \log K_{ow} + 0.094 = 0.903 \times 2.42 + 0.094 = 2.28$$

$$K_{oc} = 10^{2.28} cm^3/g$$

Now rearrange equation 3.33 from table 3.9 to calculate the linear isotherm (also referred to as Kp):

$K_{oc} = \frac{K}{f_{oc}}$ (equation 3.33)

$$Kp = K_{oc} \times f_{oc} = 10^{2.28} \times 0.02 = 3.8\ cm^3/g$$

Finally calculate the retardation factor using equation 7.22

$R_f = 1 + \frac{\rho_b}{\eta} K_p$ (equation 7.22)

$$R_{f\ trichoroethylene} = 1 + \frac{2.3 \frac{g}{cm^3}}{0.3}\left(3.8 \frac{cm^3}{g}\right) = \mathbf{30}$$

Repeat this process for hexachlorobenzene and dichloromethane starting with hexachlorobenzene.

$$\log K_{oc} = 0.903 \times \log K_{ow} + 0.094 = 0.903 \times 5.80 + 0.094 = 5.33$$

$$K_{oc} = 10^{5.33} cm^3/g$$

$$Kp = K_{oc} \times f_{oc} = 10^{5.33} \times 0.02 = 4290\ cm^3/g$$

$$R_{f\ hexachlorobenzene} = 1 + \frac{2.3 \frac{g}{cm^3}}{0.3}\left(4290 \frac{cm^3}{g}\right) = \mathbf{3300}$$

$$\log K_{oc} = 0.903 \times \log K_{ow} + 0.094 = 0.903 \times 1.31 + 0.094 = 1.28$$

$$K_{oc} = 10^{1.28} cm^3/g$$

$$Kp = K_{oc} \times f_{oc} = 10^{1.28} \times 0.02 = 0.38\ cm^3/g$$

$$R_{f\ dichloromethane} = 1 + \frac{2.3 \frac{g}{cm^3}}{0.3}\left(0.38 \frac{cm^3}{g}\right) = \mathbf{3.9}$$

b. The larger the retardation factor, the slower a chemicals movement relative to water.

$$R_{f\ dichloromethane} = 3.9 < R_{f\ trichoroethylene} = 30 < R_{f\ hexachlorobenzene} = 3300$$

Dicholoromethane would be transported the furthest followed by trichloroethylene. Hexachlorobenzene would travel the least far.

Chapter 8: Water Treatment

8.1 The EPA provides reports (sometimes referred to as consumer confidence reports) that explain where your drinking water comes from and whether any contaminants are in the water. Go to this information at the “Local Drinking Water Information” page of EPA’s Web site, (http://water.epa.gov/drink/local/index.cfm). Look up the utility that serves your university and the largest city near your hometown. (a) What is the source of water? (b) Are there any violations? (c) If so, are they for physical, biological, or chemical constituents?

Solution:

Students’ responses will vary based on their university and home town location. An example of results from the University of South Florida and Detroit, Michigan are shown in the table below:

Location	**Drinking water source**	**Violations**	**Constituent type**
University of South Florida	Groundwater	Coliform (2003), Failure to submit IDSE/Subpart V Plant Rpt	Biological, physical
Detroit, Michigan	Surface water	Total coliform (1990s)	Biological

8.2 Nitrate concentrations exceeding 10 mg NO_3^- as N/L are a concern in drinking water due to the infant disease known as methemoglobinemia. Nitrate concentrations near three rural wells were reported as 5 mg NO_3^-/L, 35 mg NO_3^-/L, and 50 mg NO_3^-/L Do any of these wells exceed this 10 ppm regulatory standard?

Solution:

Like from example 2.13 convert mgNO_3^-/L from the three rural wells to NO_3^- as mg N/L. From chapter two, in water mg/L is equivalent to ppm:

$$5\,\frac{mgNO_3{}^-}{L}\times\frac{1\,mol\,NO_3{}^-}{62\,g}\times\frac{1\,mol\,N}{1\,mol\,NO_3{}^-}\times\frac{14\,g}{mol\,N}=1.1\,\frac{mg\,NO_3{}^- - N}{L}=1.1\,ppm_m\,N$$

$$35\,\frac{mgNO_3{}^-}{L}\times\frac{1\,mol\,NO_3{}^-}{62\,g}\times\frac{1\,mol\,N}{1\,mol\,NO_3{}^-}\times\frac{14\,g}{mol\,N}=7.9\,\frac{mg\,NO_3{}^- - N}{L}=7.9\,ppm_m\,N$$

$$50\,\frac{mgNO_3{}^-}{L}\times\frac{1\,mol\,NO_3{}^-}{62\,g}\times\frac{1\,mol\,N}{1\,mol\,NO_3{}^-}\times\frac{14\,g}{mol\,N}=11.3\,\frac{mg\,NO_3{}^- - N}{L}=11.3\,ppm_m\,N$$

The well with the nitrate concentration of **50 mg NO_3^-/L exceeds the 10 ppm standard** at 11.3 ppm of NO_3^- as nitrogen.

8.3 What are the major differences and similarities between the water quality of a typical surface water and typical groundwater source?

Solution:

Information from Table 7.7 and sections 8.1-8.3 used to create this table.

Source of Water	**Similarities**	**Differences**
Surface water	Presence of: pathogens, particles, fluoride, sulfur, natural organic matter (NOM), and Iron and Manganese. Chloride concentrations similar to ocean from saltwater intrusion of trapped brine. Can contain high concentrations of nitrate and other nitrogen.	• Turbidity (1-20 NTU). • High flows. • Relatively high suspended solids (TSS). • TOC, a measure of NOM, (1-20 mg/L). • Large seasonal fluctuations in water quality. • Magnesium (less than 10, up to 20 mg/L). • Easy to contaminate.
Groundwater		• Turbidity (<1 NTU). • Lower flows. • Natural filtering capacity that removes suspended solids (TSS). • TOC, a measure of NOM, (0.1-2.0 mg/L). • May be high in dissolved solids (TDS), including Fe, Mn (less than 30, up to 40 mg/L), Ca, and Mg (hardness). • Difficult to clean up after contaminated.

8.4 Jar testing was performed using alum on a raw drinking-water source that contained an initial turbidity of 20 NTU and an alkalinity of 35 mg/L as $CaCO_3$. The optimum coagulant dosage was determined as 18 mg/L with a final turbidity of 0.25 NTU. Determine the quantity of alkalinity consumed as $CaCO_3$.

Solution:

Each 1 mg/L of alum consumes 0.5 mg/L of alkalinity as $CaCO_3$

$$18\ mg\ /\ L\ alum \times \frac{0.5\,mg\ /\ L\ alkalinity}{1\ mg\ /\ L\ alum} = \boxed{9\,mg\ /\ L\ alkalinity\ consumed}$$

Or

Molecular weight of alum ($Al_2(SO_4)_3{\cdot}14H_2O$) equals g/moles; therefore, alkalinity consumed equals,

$$\left(18\ \frac{\text{mg}}{\text{L}}\right)\left(\frac{1\ \text{g}}{1000\ \text{mg}}\right)\left(\frac{1\ \text{mole/L}}{594\,\text{g/mole}}\right)\left(\frac{6\,\text{mole HCO}_3^-}{1\ \text{mole}}\right)\left(\frac{1\ \text{eqv. of alk}}{1\ \text{mole HCO}_3^-}\right)\left(\frac{50\,\text{g CaCO}_3}{1\ \text{eqv. of alk}}\right)$$

$$= 0.009\ \text{g / L as CaCO}_3 = 9\ \ \text{mg / L as CaCO}_3$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.5 Jar tests were performed on untreated river water. An optimum dose of 12.5 mg/L of alum was determined. Determine the amount of natural alkalinity (mg/L as $CaCO_3$) consumed. If 50×10^6 gal./day of raw water are to be treated, determine the amount of alum required (kg/yr).

Solution:

$$12.5\ mg/L\ alum \times \frac{0.5 mg/L\ alkalinity}{1 mg/L\ alum} = 6.25 mg/L\ alkalinity\ consumed$$

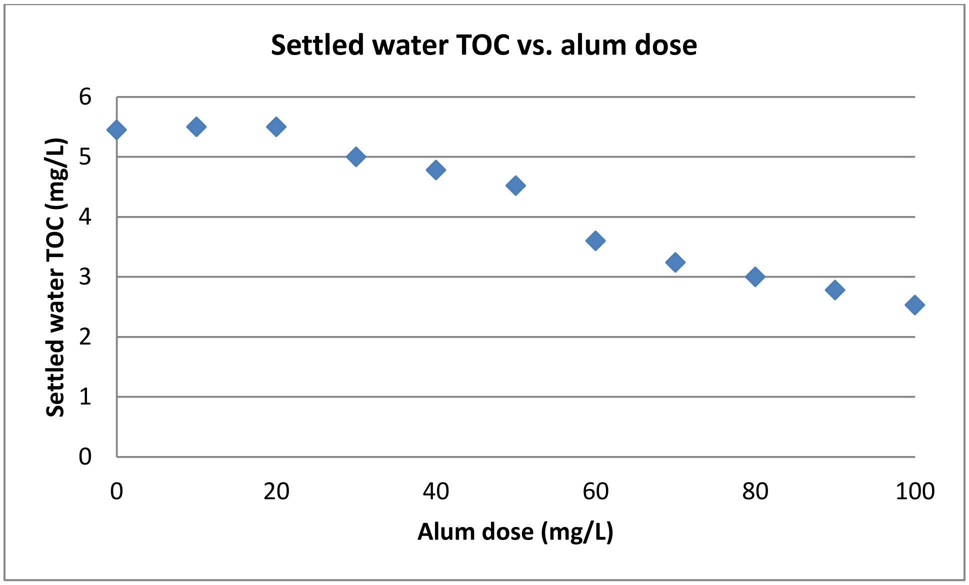
$$12.5\frac{mg}{L} \times (50 \times 10^6)\frac{gal}{day} \times \frac{3.78\ L}{gal} \times \frac{365\ day}{year} \times \frac{kg}{10^6\ mg} = \boxed{862,300\ \frac{kg\ alum}{yr}}$$

8.6 A utility is trying to achieve 25% removal of TOC and is using jar test to determine the optimal coagulant dose. The following table contains their jar test data (data from EPA 815-R-99-012, 1999). What is the optimal coagulant dose (mg/L)?

Alum dose (mg/L)	**Settled water TOC (mg/l)**	**Alum dose (mg/L)**	**Settled water TOC (mg/L)**
0	5.45	60	3.60
10	5.50	70	3.24
20	5.50	80	3.00
30	5.00	90	2.78
40	4.78	100	2.53
50	4.52		

Solution:

Plot the settled water TOC vs. alum dose data from the table.



The minimum of the graph is the optimal coagulant dose which occurs at an alum dosage of **100 mg/L**.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.7 Ferric sulfate is available as a commercial coagulant and is popular at removing turbidity and color. The chemical reaction for its addition to water is:

$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \text{ ----> } 2\ Fe(OH)_{3\ (s)} + 3CaSO_4 + 6CO_2$

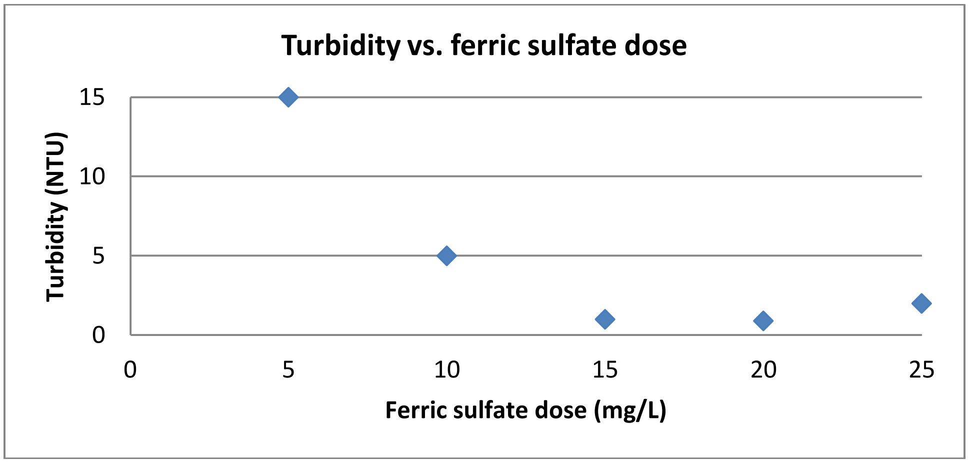
Results of a jar test to determine the optimal coagulant dose are provided below. The initial water sample has a pH = 6.5, turbidity of 30 NTU, and alkalinity of 250 mg/L as $CaCO_3$.

Ferric Sulfate dose, mg/L	5	10	15	20	25
Turbidity, NTU	15	5	1	0.9	2

(a) What is the optimal mass of ferric sulfate you would need to purchase every day to treat 1 x 10^6 gallons/day to a turbidity below 1 NTU (assume 100% purity of the coagulant). (b) Do you have to add alkalinity to the system? If so, how much (in concentration units as mg $CaCO_3$/L)?

Solution:

a. Plot the turbidity vs. ferric sulfate dose values in the table provided. The optimal mass of ferric sulfate you would need to purchase every day to treat 1 MDG to a turbidity of 1 NTU is 20 mg/L of ferric sulfate (the minimum on the graph) resulting in a turbidity of 0.9 NTU.



Use unit conversions to convert 20 mg/L to mass:

$$20\frac{mg}{L}\times\frac{1\ gallon}{3.785\ L}\times 1*10^6\frac{gallons}{day}\times\frac{1\ g}{1000\ mg}\times\frac{1\ kg}{1000g}=\mathbf{5.3}\frac{\mathbf{kg}}{\mathbf{day}}$$

b. A good assumption is that alkalinity is approximately equal to HCO_3^-

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

$$20\frac{mg\ Fe_2(SO_4)_3}{L}\times\frac{1\ g}{1000\ mg}\times\frac{1\ mole\ Fe_2(SO_4)_3}{399.79g\ Fe_2(SO_4)_3}\times\frac{3\ mole\ Ca(HCO_3)_2}{1\ mole\ Fe_2(SO_4)_3}\times\frac{2\ mole\ al\ as\ HCO_3{}^-}{1\ mole\ Ca(HCO_3)_2}$$
$$\times\frac{1\ eqv\ HCO_3{}^-}{1\ mole\ HCO_3{}^-}\times\frac{1\ mole\ CaCO_3}{2\ eqv\ CaCO_3}\times\frac{100gCaCO_3}{1\ mole\ CaCO_3}\times\frac{1000mg}{1\ g}=15\ mgCaCO_3/L$$

15 mg $CaCO_3$/L is less than the initial alkalinity of the water sample 250 mg $CaCO_3$/L. Thus:

$$250\frac{mgCaCO_3}{L}-\ 15\frac{mgCaCO_3}{L}=\boldsymbol{235\frac{mgCaCO_3}{L}\ must\ be\ added}$$

8.8 A mechanical rapid-mix tank is to be designed to treat 50 m^3/day of water at a temperature of 12°C. Using typical design values in the chapter, determine the (a) tank volume and (b) power requirement.

Solution:

Assume 60 seconds of detention time:

$$V = Q \times \theta = 50\frac{m^3}{day} \times 60\ s \times \frac{day}{86400\,\mathrm{s}} = \boxed{0.035\ m^3}$$

Using table 10-13 select a $\bar{G}$ value of 900/sec. At 12°C, $\mu = 1.2388\text{x}10^{-3}$ N·sec/m^2.

$$\mathrm{P} = \bar{\mathrm{G}}^2 \times \mu \times \mathrm{V}$$

$$= (900/\mathrm{s})^2 \times \left(1.2388 \times 10^{-3}\,\frac{\mathrm{N\cdot s}}{\mathrm{m}^2}\right) \times \left(0.0347\ \mathrm{m}^3\right) \times \left(\frac{1\,\mathrm{kN}}{1{,}000\ \mathrm{N}}\right) = 0.035\frac{\mathrm{kN\cdot m}}{\mathrm{s}} = \boxed{35\ \mathrm{W}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.9 An in-line mixer is to be used for rapid mixing. The plant flow is 3,780 m^3/day, the water viscosity is 0.001307 N – sec/m^2, and the RMS velocity gradient is 10^4/s. Estimate the daily power requirement for the in-line mixer.

Solution:

This problem is similar to example 8.2. The detention time for an in-line mixer is 1 s according to table 8.12.

First, solve for the volume of the mixing vessel.

$$V = Q \times \theta = 3{,}780\,\frac{m^3}{day} \times 1s \times \frac{1\ min}{60s} \times \frac{1\ day}{1{,}440\ min} = 0.044\ m^3$$

As in example 8.2, rearrange equation 8.2 to solve for P:

$$P = \bar{G}^2 \times \mu \times V = (10^4/s)^2 \times 0.001307\ N - \frac{sec}{m^2} \times 0.044m^3 \times \frac{1\ kN}{1{,}000N} = 5.7\ \frac{kN - m}{s}$$

$$= \mathbf{5.7\ kW}$$

8.10 The city of Melbourne, Florida has a surface water treatment plant that produces 20 MGD of potable drinking water. The water source has hardness measured as 94 mg/L as $CaCO_3$ and after treatment, the hardness is reduced to 85 mg/L as $CaCO_3$. (a) Is the treated water, soft, moderately hard, or hard? (b) Assuming all the hardness is derived from calcium ion, what would the concentration of calcium be in the treated water (mg Ca^{2+}/L). (c) Assuming all the hardness is derived from magnesium ion, what would the concentration of magnesium be in the treated water (mg Mg^{2+}/L).

Solution:

See figure 8.10 in chapter 8 for ranges of water hardness:
Soft water: 0-55 mg/L
Moderately hard water: 55-120 mg/L
Hard water: 120-250 mg/L
Very hard water: 250+ mg/L

a) Both the water source hardness (94 mg/L as $CaCO_3$) and after treatment (85 mg/L as $CaCO_3$) are in the **moderately hard** water range.

b) $85\,\frac{mg}{L} \times \frac{(\frac{40\ g\mathrm{CaCO_3}}{2\ eqv})}{(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv})} = \mathbf{34}\,\frac{\boldsymbol{mg}\ \mathbf{Ca^{2+}}}{\boldsymbol{L}}$

c) $85\,\frac{mg}{L} \times \frac{(\frac{24\ g\mathrm{CaCO_3}}{2\ eqv})}{(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv})} = \mathbf{20.4}\ \frac{\boldsymbol{mg}\ \mathbf{Mg^{2+}}}{\boldsymbol{L}}$

8.11 A laboratory provides the following analysis obtained from a 50-ml sample of raw water. $[Ca^{2+}]$ = 60 mg/L, $[Mg^{2+}]$ = 10 mg/L, $[Fe^{2+}]$ = 5 mg/L, $[Fe^{3+}]$ = 10 mg/L, Total solids = 200 mg/L, suspended solids = 160 mg/L, fixed suspended solids = 40 mg/L, and volatile suspended solids = 120 mg/L. (a) What is the hardness of this water sample in units of mg/L as $CaCO_3$? (b) What is the concentration of total dissolved solids of this sample?

Solution:

a) See example 2.14.

$$60\,\frac{mg\ \mathrm{Ca}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{40\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=150\,\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$10\,\frac{mg\ \mathrm{Mg}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{24\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=41.7\,\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$5\,\frac{mg\ \mathrm{Mg}^{2+}}{L}\times\frac{\left(\frac{50\ g\ \mathrm{CaCO_3}}{1\ eqv}\right)}{\left(\frac{56\ g\mathrm{CaCO_3}}{2\ eqv}\right)}=8.93\,\frac{mg\ \mathrm{CaCO_3}}{L}$$

$$total\ hardness=150\,\frac{mg\ \mathrm{CaCO_3}}{L}+41.7\,\frac{mg\ \mathrm{CaCO_3}}{L}+8.93\,\frac{mg\ \mathrm{CaCO_3}}{L}=\mathbf{201}\ \frac{\boldsymbol{mg}\ \mathbf{CaCO_3}}{\boldsymbol{L}}$$

b) TDS= TS – TSS

$$\mathrm{TDS}=200\,\frac{\mathrm{mg}}{\mathrm{L}}-160\,\frac{\mathrm{mg}}{\mathrm{L}}=\mathbf{40}\,\frac{\mathbf{mg}}{\mathbf{L}}$$

c) See example 2.16.

$$\mathrm{FSS}=40\,\frac{\mathrm{mg}}{\mathrm{L}}=\frac{\mathrm{X}}{50\ \mathrm{ml}}\times\frac{1000\ \mathrm{mL}}{1\ \mathrm{L}}=\frac{\mathrm{x}}{0.05\ \mathrm{L}}$$

Solve for x

$$x=40\,\frac{mg}{L}\times 0.05\ \mathrm{L}=\mathbf{2\ mg}$$

8.12 A source water mineral analysis shows the following ion concentrations in the water: $\mathrm{Ca^{2+} = 70\,mg/L, Mg^{2+} = 40\,mg/L, and\ HCO_3^- = 250\,mg/L\ as\ CaCO_3}$. Determine the water's carbonate hardness, noncarbonated hardness, and total hardness.

Solution:

$$\mathrm{Mg^{2+}}\text{ concentration as }\mathrm{CaCO_3} = 40\frac{mg}{L}\times\frac{100\ g\ CaCO_3/mole}{24.4\ g\ Mg^{+2}/mole} = 164\frac{mg}{L}$$

$$\mathrm{Ca^{2+}}\text{ concentration as }\mathrm{CaCO_3} = 70\frac{mg}{L}\times\frac{100\ g\ CaCO_3/mole}{40\ g\ Ca^{+2}/mole} = 175\frac{mg}{L}$$

Total Hardness = $\mathrm{Mg^{2+}}$ conc. as $\mathrm{CaCO_3}$ + $\mathrm{Ca^{2+}}$ conc. as $\mathrm{CaCO_3}$
= 164 mg/L + 175 mg/L

$\boxed{\text{Total Hardness = 339 mg/L as CaCO}_3}$

$\boxed{\text{Carbonate Hardness = 250 mg/L as CaCO}_3}$

(175 mg/L $\mathrm{Ca^{2+}}$ + 75 mg/L $\mathrm{Mg^{2+}}$ → $\mathrm{Mg^{2+}}$ concentration is the difference between $\mathrm{HCO_3^-}$ and $\mathrm{Ca^{2+}}$)

Noncarbonate Hardness = 164 mg/L – 75 mg/L

$\boxed{\text{Noncarbonate Hardness = 89 mg/L}}$

8.13 **(a)** Calculate the lime dosage required for softening by selective calcium removal for the following water analysis. The chemical constituents in the water are $CO_2 = 17.6\,mg/L, Ca^{2+} = 63\,mg/L, Mg^{2+} = 15\,mg/L, Na^{+} = 20\,mg/L, Alk(HCO_3^-) = 189\,mg/L\ as\ CaCO_3, SO_4^{2-} = 80\,mg/L, and\ Cl^- = 10\,mg/L$. What is the finished-water hardness?

Solution:

Determine the chemical concentration as $CaCO_3$.

Chemical	Conc. mg/L	MWCaCO$_3$/MW	Conc. mg/L As CaCO$_3$
CO_2	17.6	100/44	40
Cations			
Ca^{+2}	63	100/40	157.5
Mg^{+2}	15	100/24.4	61.5
Na^{+}	20	100/23	87
			306
Anions			
Alk(HCO_3^-)			189
SO_4^{2-}	80	100/96	83
Cl^-	10	100/35.5	28
			300

Carbonate Hardness = 157.5 + 31.5 = 189 mg/L as $CaCO_3$
Noncarbonate Hardness = 61.5 - 31.5 = 30 mg/L as $CaCO_3$
Total Hardness = 157.5 + 61.5 = 219mg/L as $CaCO_3$
$Ca(OH)_2$ required to react with CO_2 = 40 mg/L as $CaCO_3$
$Ca(OH)_2$ required to react with $Ca(HCO_3)_2$ = 157.5 mg/L as $CaCO_3$
Dosage of lime required for selective calcium removal is 40+157.5 = **197.5 mg/L as $CaCO_3$**

Finished water hardness = Mg carbonate hardness left + noncarbonate hardness
$= 31.5 + 30 = \boxed{61.5\ mg/L\ as\ CaCO_3}$

Further treatment with lime is possible, a dosage of 63 mg/L as $CaCO_3$ will remove the 31.5 mg/L as $CaCO_3$ of Mg carbonate hardness. The noncarbonate hardness also can be removed by using 30 mg/L lime as $CaCO_3$ and then use soda ash with concentration of 30 mg/l as $CaCO_3$.

8.14 A municipality treats $15\times10^6\ \text{gal./day}$ of groundwater containing the following: $CO_2=17.6\,mg/L, Ca^{2+}=80\,mg/L, Mg^{2+}=48.8\,mg/L, Na^+=23\,mg/L, Alk\left(HCO_3^-\right)=270\,mg/L\ as\ CaCO_3, SO_4^2=125\,mg/L, and\ Cl^-=35\,mg/L$. The water is to be softened by excess lime treatment. Assume that the soda ash is 90 percent sodium carbonate, and the lime is 85 percent weight CaO. Determine the lime and soda ash dosages necessary for precipitation softening (kg/day).

Solution:

Chemical	Conc.mg/L	MWCaCO$_3$/MW	Conc. mg/L As CaCO$_3$
CO2	17.6	100/44	40
Ca^{+2}	80	100/40	200
Mg^{+2}	48.8	100/24.4	200
Na$^+$	23	100/23	100
Cations			**500**
Alk(HCO$_3^-$)			270
SO$_4^{2-}$	125	100/96	130
Cl$^-$	35	100/35.5	100
Anions			**500**

$Ca(HCO_3)_2$ = 200 mg/L as $CaCO_3$; $Mg(HCO_3)_2$ = 270 – 200 = 70 mg/L as $CaCO_3$; $MgSO_4$ = 200 – 70 = 130 mg/L as $CaCO_3$

Lime required: (30m g/L is added for pH adjustment)

$$\left[40\frac{mg\ CaCO_3}{L}+200\frac{mg\ CaCO_3}{L}+2\times70\frac{mg\ CaCO_3}{L}+130\frac{mg\ CaCO_3}{L}+30\frac{mg\ CaCO_3}{L}\right]$$

$$\times\frac{56\ g/mole\ CaO}{100\ g/mole\ CaCO_3}\times\frac{Kg}{10^6\,mg}\times\frac{15\times10^6\,gal}{day}\times\frac{3.78L}{gal}\times\frac{kg\ bulk\ lime}{0.85\ kg\ CaO}=\boxed{20{,}172\ kg}$$

Soda ash required:

$$\left(130\frac{mg\ CaCO_3}{L}\right)\times\left(\frac{106\ mg\ Na_2CO_3\ /\ mole}{100\ mg\ CaCO_3\ /\ mole}\right)\times\left(\frac{kg}{10^6\,mg}\right)\times\left(\frac{15\times10^6\,gal}{day}\right)\times$$

$$\left(\frac{3.78L}{gal}\right)\times\left(\frac{kg\ bulk\ soda\ ash}{0.9\ kg\ sodium\ carbonate}\right)=\boxed{8{,}681\ kg}$$

8.15 Water contains 7.0 mg/L of soluble ion (Fe^{2+}) that is to be oxidized by aeration to a concentration of 0.25 mg/L. The pH of the water is 6.0, and the temperature is 12°C. Assume the dissolved oxygen in the water is in equilibrium with the surrounding atmosphere. Laboratory results indicate the pseudo first-order rate constant for oxygenation of Fe^{2+} is 0.175/min. Assuming steady-state operations and a flow rate of 40,000 m^3/day, calculate the minimum detention time and reactor volume necessary for oxidation of Fe^{2+} to Fe^{3+}. Perform the calculations for both a CMFR and a PFR. (You should be able to work this out from information provided in Chapters 3 and 4.)

Solution:

For the CMFR at steady state

$$\frac{dm}{dt} = 0 = m_{in} - m_{out} + m_{rxn} \Rightarrow QC_{in} - QC - VkC$$

$$0 = \left(40000\frac{m^3}{day} \times 7\frac{mg}{L} \times \frac{1000\ L}{m^3}\right) - \left(40000\frac{m^3}{day} \times 0.25\frac{mg}{L} \times \frac{1000\ L}{m^3}\right)$$

$$-\left(V \times \frac{0.175}{\min} \times \frac{1440 \min}{day} \times 0.25\frac{mg}{L} \times \frac{1000\ L}{m^3}\right)$$

$$\boxed{V = 4{,}286\ m^3}$$

So minimum detention time is $\frac{V}{Q} = \frac{4285.7\ m^3}{40000\frac{m^3}{day}} = 0.11\ day = \boxed{2.6\ h}$

For PFR

$$\frac{dm}{dt} = m_{in} - m_{out} + m_{rxn} \Rightarrow 0 - 0 - V\frac{dC}{dt}$$

$$C_t = C_o \times e^{-kt} \qquad 0.25\frac{mg}{L} = 7\frac{mg}{L} \times e^{\left(-\frac{0.175}{\min}\times t\right)}$$

$$Solve\ \ for\ t$$

$$\boxed{t = 19 \min}$$

$$V = 40000\frac{m^3}{day} \times 19\ \min\ \times\ \frac{day}{1440\ \min} = \boxed{528\ m^3}$$

8.16 Calculate the settling velocity of a particle with 100 μm diameter and a specific gravity of 2.4 in 10°C water.

Solution:

Find settling velocity using Stoke's law (Table 10 15).
Particle density = specific gravity x water density at 4 ^oC
= 2.4 x 1000 kg/m^3 = 2400 kg/m^3

$$v_s = \frac{g\left(\rho_p - \rho\right)d_p^2}{18\mu}$$

$$= \frac{\left(9.81\ m/s^2\right)\times\left(2400 - 999.7\ kg/m^3\right)\times\left(1.0\times10^{-4}\ m\right)^2}{18\times\left(1.307\times10^{-3}\ N\cdot s/m^2\right)}\times\frac{3,600\ \ s}{h} = \boxed{21\frac{m}{h}}$$

Check Reynolds number

$$Re = \frac{d_p\ v_s}{\nu} = \frac{\left(1.0\times10^{-4}\ \ m\right)\left(21\ \ m/h\right)\left(1h/3600\ \ s\right)}{\left(1.306\times10^{-6}\ m^2/s\right)} = 0.45$$

Since Re is less than 1, the flow is laminar and Stoke's law is valid.

8.17 Calculate the settling velocity of a particle with 10 μm diameter and a specific gravity of 1.05 in 15°C water.

Solution:

Particle density = specific gravity x water density at 4 ^{o}C

$$=1.05 \text{ x } 1000 \text{ kg/m}^3 = 1050 \text{ kg/m}^3$$

$$v_s = \frac{g\left(\rho_p - \rho\right)d_p^2}{18\mu}$$

$$= \frac{(9.81 \text{ m/s}^2)\times(1050-999.7 \text{ kg/m}^3)\times(1.0\times10^{-5}\text{ m})^2}{18\times(1.139\times10^{-3}\text{ N}\cdot\text{s/m}^2)}\times\frac{3,600 \text{ s}}{\text{h}} = \boxed{8.7\times10^{-3}\frac{\text{m}}{\text{h}}}$$

Check Reynolds number

$$\text{Re} = \frac{d_p\, v_s}{\nu} = \frac{(1.0\times10^{-5}\text{ m})(8.7\times10^{-3}\text{ m/h})(1\text{h}/3600\text{ s})}{(1.139\times10^{-6}\text{ m}^2/\text{s})} = 2.1\times10^{-5}$$

Since Re is less than 1, the flow is laminar and Stoke’s law is valid.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.18 A water treatment plant processes 21,000 m^3 of water per day. Assume two types of flocculated particles enter a rectangular sedimentation basin that has dimensions of: depth = 4 m, width = 6m, and length = 40 m. The first type of particle has a settling velocity of 0.5 m/hr and the other type has a settling velocity of 1.8 m/hr. What percent of particles are removed for each of the two types of particles?

Solution:

This problem is similar to example 8.6. First, use equation 8.10 to determine the sedimentation basin overflow rate (critical settling velocity).

$$OR = v_c = \frac{Q}{A} = \frac{21{,}000\,\frac{m^3}{day} \times \frac{1\ day}{24\ hr}}{6m\ \times 40m} = 3.7\ m^3/m^2 - hr$$

For particles with a settling velocity of 0.5 m/hr and 1.8 m/hr (which is less than the v_c of 3.7 m/hr), the percentage of removal is calculated using Equation 8.11:

$$fraction\ of\ particles\ removed = \frac{v_s}{OR} = \frac{0.5\ m/hr}{3.7\ m/hr} = \mathbf{0.14}$$

$$fraction\ of\ particles\ removed = \frac{v_s}{OR} = \frac{1.8\ m/hr}{3.7\ m/hr} = \mathbf{0.49}$$

8.19 What percent of particles with diameter of 100 µm and a particle density of 2,650 kg/m^3 are removed in a 1,500 m^3 rectangular sedimentation basin of that contains water at 10°C? Assume the plant flow rate is 1.26×10^6 m^3/day .

Solution:

First solve for the terminal settling velocity using Stokes' law (Table 8.15) as in example 8.4/8.5. For water at 10°C, $\rho = 999.7\,\mathrm{kg/m^3}, \mu = 1.307\times10^{-3}\,\mathrm{N\cdot s/m^2}, \text{and}\ v = 1.306\times10^{-6}\,\mathrm{m^2/s}$.

$$v_s = \frac{g(\rho_p - \rho)d_p^2}{18\mu}$$

$$= \frac{9.81\,\mathrm{m/s^2} \times (2,650 - 999.7\,\mathrm{kg/m^3}) \times (1.0\times10^{-4}\,\mathrm{m})^2}{18\times1.307\times10^{-3}\,\mathrm{N\cdot s/m^2}} \times \frac{3,600\,\mathrm{s}}{\mathrm{hr}} = 24.8\,\frac{\mathrm{m}}{\mathrm{hr}}$$

We must verify the flow conditions to ensure Stokes' law is applicable. The Reynold's number is calculated to verify that the particle is settling under laminar conditions:

$$\mathrm{Re} = \frac{d_p v_s}{v} = \frac{1.0\times10^{-4}\,\mathrm{m} \times 24.8\,\mathrm{m/hr} \times (1\,\mathrm{hr}/3,600\,\mathrm{s})}{1.306\times10^{-6}\,\mathrm{m^2/s}} = 0.53$$

Because Re < 1, laminar flow exists, and Stokes' law is applicable.

Now use equation 8.10 to determine the sedimentation basin overflow rate (critical settling velocity).

$$OR = v_c = \frac{Q}{A} = \frac{1.26 * 10^6\,\frac{m^3}{day} \times \frac{1\ day}{24\ hr}}{1{,}500\ m^3} = 35\ m^3/m^2 - hr$$

For particles with a settling velocity of 24.8 (which is less than the v_c of 35 m/hr), the percentage of removal is calculated using Equation 8.11:

$$fraction\ of\ particles\ removed = \frac{v_s}{OR} = \frac{24.8\ m/hr}{35\ m/hr} = \mathbf{0.71}$$

8.20 A treatment plant has a horizontal flow sedimentation basin with a depth of 4 m, width of 6 m, and length of 36 m. It has a process flow rate of 400 m^3/hr. What is the percent removal for particles entering this basin, assuming they all have a diameter of 0.0029 cm, a particle density of 2,650 kg/m^3, and they are in water at a temperature of 10°C?

Solution:

First solve for the terminal settling velocity using Stokes' law (Table 8.15) as in example 8.4/8.5. For water at 10°C, $\rho = 999.7\,\mathrm{kg/m^3}, \mu = 1.307\times10^{-3}\,\mathrm{N\cdot s/m^2}, \mathrm{and}\ v = 1.306\times10^{-6}\,\mathrm{m^2/s}$.

$$v_s = \frac{g(\rho_p - \rho)d_p{}^2}{18\mu} = \frac{\frac{9.81m}{s^2} \times \left(2{,}650\,\frac{kg}{m^3} - 999.7\,\frac{kg}{m^3}\right) \times \left(0.0029cm \times \frac{1\ m}{100\ cm}\right)^2}{18\ \times 1.307 * 10^{-3}N - s/m^2} \times \frac{3{,}600s}{hr}$$
$$= 2.1\ m/hr$$

Check the Reynold's number (Equation 8.8) to verify the particle is settling under laminar conditions:

$$Re = \frac{d_p v_s}{v} = \frac{\left(0.0029cm \times \frac{1m}{100\ cm}\right) \times 2.1\,\frac{m}{hr} \times \frac{1\ hr}{3{,}600\ s}}{1.306 * 10^{-6}m^2/s} = 0.013$$

Because Re < 1, laminar flow exists, and Stokes' law is applicable.

Now use equation 8.10 to determine the sedimentation basin overflow rate (critical settling velocity).

$$OR = v_c = \frac{Q}{A} = \frac{400\,\frac{m^3}{hr}}{6m \times 36m} = 1.85\ m^3/m^2 - hr$$

Since 2.1 m/hr is greater than the critical settling velocity, 1.85 $m^3/m^2 - hr$, **100%** of the particles are removed.

8.21 Research the use of a filtration method that provides household (point-of-use) treatment in the developing world. Write a one-page report that is clearly referenced. In your report, describe the technology and address these issues: Is the technology affordable to the local population? Does it use local materials and local labor for its construction? What are the observed health improvements after implementation of the treatment system? What specific training do you believe is required to ensure proper operation of the technology?

Solution:

Students' responses will vary.

8.22 Research the global arsenic problem in the United States and in Bangladesh. In a two-page essay, identify, compare, and contrast the extent of the problem (spatially and in terms of population affected). What are the current methods of treatment employed to remove the arsenic in both countries? What is the current regulatory standard for arsenic set by the EPA and the guideline suggested by the World Health Organization?

Solution:

Students’ responses will vary.

8.23 A 1,000-g sample of naturally occurring sand was sifted through a stack of sieves and the weight retained on each sieve is recorded as shown in the table below. Determine the effective size and uniformity coefficient for the media.

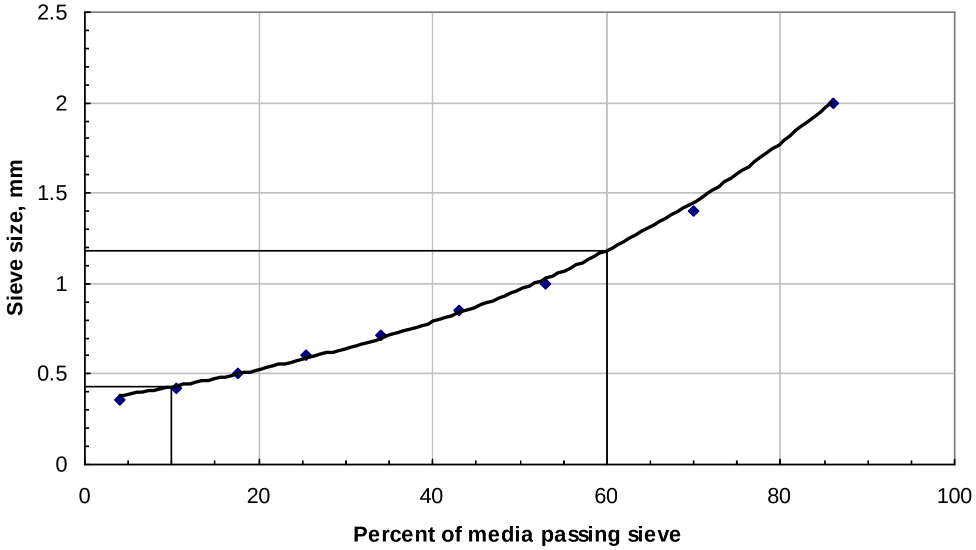
Sieve Designation	Sieve opening, mm	Weight of retained media, g
10	2.000	140
14	1.400	160
18	1.000	170
20	0.850	100
25	0.710	90
30	0.600	85
35	0.500	80
40	0.425	70
45	0.355	65

Solution:

A spreadsheet can be used to determine the cumulative fraction passing each sieve. The cumulative fraction passing is calculated as the total of the mass below the sieve size divided by the total weight of the sample. Note that 4 percent of the sample has passed through the smallest sieve listed, which is equal to 40-g sample of sand. The total weight retained is 960g.

Sieve opening, mm	Weight retained, g	Cumulative fraction passing
2.000	140	0.86
1.400	160	0.70
1.000	170	0.53
0.850	100	0.43
0.710	90	0.34
0.600	85	0.26
0.500	80	0.18
0.425	70	0.11
0.355	65	0.04
Total =	960	

The given data can then be plotted as follows.



The above graph can be used to select the sieve sizes corresponding to the 10 percent size and the 60 percent size. In the graph the d_{10} = 0.43 mm and the d_{60} = 1.18 mm.

The effective size is the 10th percentile media grain diameter.

$$\boxed{ES = d_{10} = 0.43\text{ mm}}$$

The uniformity coefficient can be calculated using Equation found in Table 10.19.

$$UC = \frac{d_{60}}{d_{10}} = \frac{1.18\text{ mm}}{0.43\text{ mm}} = \boxed{2.74}$$

Note that the uniformity coefficient of naturally occurring sand is much higher compared to typical values used in rapid filters (1.3 to 1.7). As explained before, the higher uniformity coefficient will result in severe media stratification during backwash and consequently causing excessive head loss and reducing overall effectiveness of the filter. Therefore, our sample will need to be processed to a fairly uniform size.

8.24 When Cl_2 gas is added to water during the disinfection of drinking water, it hydrolyzes with the water to form HOCl (Equation 8.13). Assume that the disinfection power of the acid HOCl is 88 times greater than the conjugate base, OCl^-. The pK_a for HOCl is 7.5. (a) What percentage of the total disinfection power measured as free chlorine ($HOCl + OCl^-$) exists in the acid form at pH = 6? (b) At pH = 7?

Solution:

Equation 8.13 (referenced in the problem) is found in table 8.21.

$$Cl_{2(g)} + H_2O \rightarrow HOCl + HCl \quad (8.13)$$

From chapter 2

$$k_a = \frac{[H^+][A^-]}{[HA]} = \frac{[H^+][OCl^-]}{[HOCl]}$$

a) pK_a of HOCl is given in the problem as 7.5 and for part a the pH is 6. This can be plugged into the equation above.

$$10^{-7.5} = \frac{[10^{-6}][OCl^-]}{[HOCl]}$$

Solve in terms of the acid, HOCl

$$[HOCl] = \frac{[10^{-6}][OCl^-]}{10^{-7.5}} = 31.6[OCl^-]$$

Derive an expression for the percentage of the total disinfection power measured as free chlorine ($HOCl + OCl^-$) that exists in the acid form.

$$\%\ of\ total\ disinfection\ power = \frac{[HOCl]}{[HOCl]+[OCl^-]} \times 100\% = \frac{31.6[OCl^-]}{31.6[OCl^-]+[OCl^-]} \times 100\% = \mathbf{97}\%$$

b) Use the same method as part a. but with a pH of 7.

$$[HOCl] = \frac{[10^{-7}][OCl^-]}{10^{-7.5}} = 3.16[OCl^-]$$

$$\%\ of\ total\ disinfection\ power = \frac{3.16[OCl^-]}{3.16[OCl^-]+[OCl^-]} \times 100\% = \mathbf{76}\%$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.25 Given the following data, graph the data for the *Poliomyelitis* virus, using hypobromite as a disinfectant. Determine the Chick's law rate constant and the time required for 99.99 percent (4 log removals) inactivation of this virus.

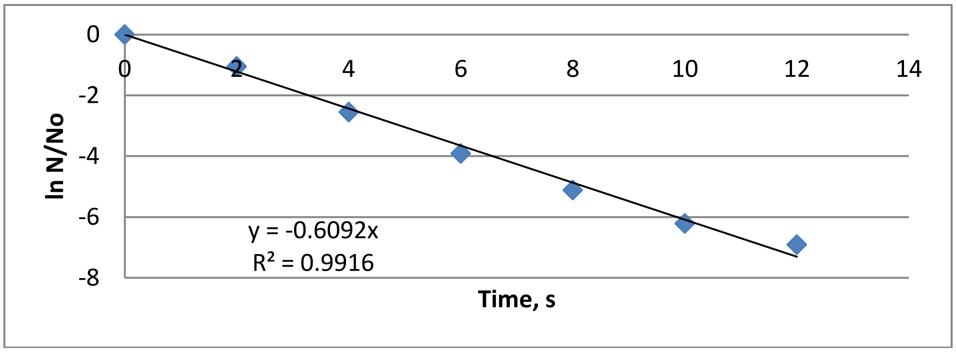
Time (s)	N (# org/L)
0.0	1,000
2.0	350
4.0	78
6.0	20
8.0	6
10.0	2
12.0	1

Solution:

First add N/No and ln N/No to the table

Time sec	N/L	N/No	ln N/No
0	1,000	1	0
2	350	0.35	-1.04982
4	78	0.078	-2.55105
6	20	0.02	-3.91202
8	6	0.006	-5.116
10	2	0.002	-6.21461
12	1	0.001	-6.90776

Plot log N/No as a function of time.



The slope (-0.6092) is the Chick's law rate constant.

For 99.99 removal,

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

$$\ln 0.0001 = -0.6092 \times t$$

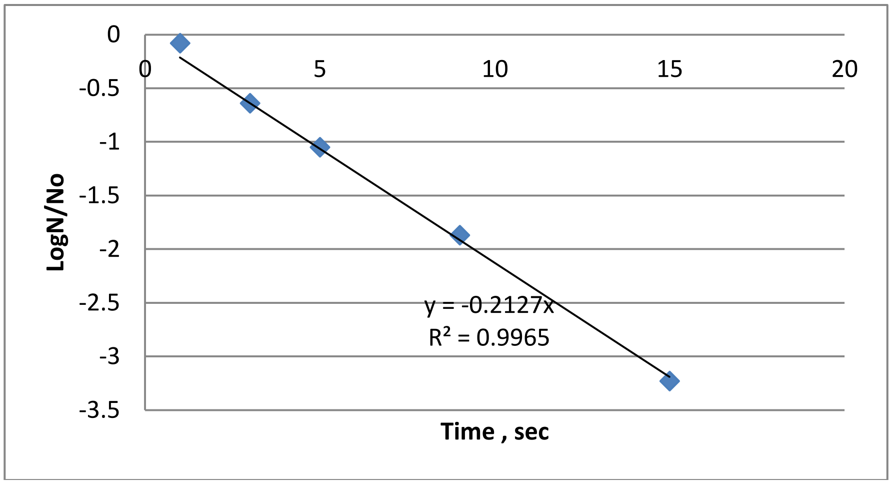
$$\boxed{t = 15 \text{ s}}$$

8.26 Graph the following data for the inactivation of a virus using hypochlorous acid (HOCl). Determine the coefficient of specific lethality and the time required to obtain 99.99 percent inactivation using 1.0 mg/L of HOCl.

Time	$\log[N/N_0]$
1.0	-0.08
3.0	-0.64
5.0	-1.05
9.0	-1.87
15.0	-3.23

Solution:

Plot the data to determine Chick's law rate constant



K_{10} = -0.2127

For 99.99 % removal

$$\log 0.0001 = -0.2127 \times t$$

$$t = 18.8\text{ s} = \boxed{0.31\text{min}}$$

Use the Chick-Watson equation to determine the specific lethality (λ).

$$\ln \frac{N}{No} = -\lambda Ct \qquad C = mg/L, t = \text{min}$$

$$\ln 0.0001 = -\lambda \times 1 \frac{mg}{L} \times 0.31\text{min}$$

$$\Rightarrow \boxed{\lambda = 30}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

8.27 (a) Define the meaning of *Ct* product. (b) In addition to *C* and *t*, what factors influence the rate of chemical disinfection? (c) What kind of microorganism is most readily inactivated by free chlorine? (d) What kind is most difficult to inactivate?

Solution :

a) ***Ct* product is a combined effect of disinfectant concentration and time of contact to achieve certain level of inactivation for a given microorganism.** It can also be viewed as the dosage of disinfectant.

b) The other main factors that influence the rate of chemical disinfection are **pH and temperature**.

From figure 10-17:

c) **Adenovirus and Calicivirus** are most readily inactivated by free chlorine

d) **C.parvum** is the most difficult to inactivate.

8.28 During drinking water treatment, 17 lb. of chlorine are added daily to disinfect 5 million gallons of water. (a) What is the aqueous concentration of chlorine in mg/L? (b) The chlorine demand is the concentration of chlorine used during disinfection. The chlorine residual is the concentration of chlorine that remains after treatment so the water maintains its disinfecting power in the distribution system. If the chlorine residual is 0.20 mg/L, what is the chlorine demand in mg/L?

Solution:

a) Use unit conversions of the given variables to calculate the aqueous concentration of chlorine:

$$[Cl] = \frac{17lb \times \frac{1\ kg}{2.205lb} \times \frac{1{,}000g}{1kg} \times \frac{1000mg}{1\ g}}{5 * 10^6 gallons \times \frac{3.785\ L}{1\ gal}} = \mathbf{0.41\ mg/L}$$

b)

$$chlorine\ demand = Cl^-\ used\ in\ disinfection - Cl^- residual = 0.41\frac{mg}{L} - 0.20\frac{mg}{L} = \mathbf{0.21\frac{mg}{L}}$$

8.29 Visit the Web site for the World Health Organization (www.who.org). Write a referenced essay of up to two pages about a particular pathogen and associated disease that is transmitted through contaminated water. What is the global extent of the public health crisis in terms of spatial and population effects? Does the disease affect wealthy or poor communities? What are the social and engineered barriers that can be used to reduce human exposure to the specific pathogen?

Solution:

Students' responses will vary.

8.30 Research the professional engineering society Water for People that works on water supply in the developing world. Determine how you could contribute to such a professional society as a student and after graduation. Provide specific detail about membership requirements, costs, and how you might be involved.

Solution:

Students' responses will vary though an example as of October 2013, based on information found on the Water for People website is provided below:

There are many ways to contribute to Water for People as a student and after graduation whether serving on a committee, through monetary donations, hosting fundraisers, sharing their message through social media, or participating in the World Water Corps. Concerning water committees, there are over 60 throughout North America that "support Water for People's mission [to work with people and partners to develop innovative and long-lasting solutions to the water, sanitation, and hygiene problems in the developing world] through community outreach, advocacy, and fundraising." Many of the Water for People committees are sub groups of other professional societies such as the American Water Works Association and Water Environment Federation Association. There is usually an annual membership fee to join a Water for People committee which will vary depending on the location. Membership is open to people of all backgrounds from students, engineers, and educators such as with the Sacramento committee.

The World Water Corps monitors Water for People's projects in the field through short visits. This is another voluntary position and Corps members may be asked to fundraise for their own transportation and travel expenses for the visit. There is an application process involved for the World Water Corps and language and technical skill requirements vary on the assignment and location. For example, many may require fluency in Spanish and an engineering background.

8.31 (a) Use the Internet to research the number of people in the world who do not have access to an improved water supply. Then look up the Millennium Development Goals (MDGs) at the United Nations Web site, www.un.org. MDG 7 states that by 2015 the world will decrease by half the number of people without access to an improved water supply. Select a country in Africa and another country in Asia or Latin America. Compare the progress of these two countries in meeting goal 7 in terms of the number of people still not served by an improved water supply.

Solution:

To answer this question, students should refer to the 2013 Joint Monitoring Report (JMP) on Water and Sanitation (http://www.wssinfo.org/fileadmin/user_upload/resources/JMPreport2013.pdf). In the JMP 2013 highlights, it states that in 2011 768 million people relied on unimproved drinking-water sources which was still on track to meet the MDG target. The progress of two countries, Mali and Vietnam, are highlighted in the table below. Mali went from 72% that were not served by an improved water supply to 35% between 1990 and 2011 while Vietnam went from 42% to 4%. Though both have achieved this MDG in each country to halve the proportion without improved drinking water, there still remains millions (about 9 million between the two countries) of people without access to improved water supply particularly in Mali compared to Vietnam. This is because the population of Mali increased dramatically, almost double, between 1990 and 2011, from 8.7 million to 15.8 million. In Vietnam, the population increase was not as dramatic 67 million to 89 million. This is consistent with the trends between Africa and Asia, where Asia tends to be ahead of Africa in their achievement of the MDGs and population growth plays a large factor. A higher proportion may have access to improved water sources but with an increase in population, more people do not have access to improved sources.

Target	**Indicator**	**Mali**		**Vietnam**	
		1990	**2011**	**1990**	**2011**
Goal 7: Ensure environmental sustainability					
Halve proportion without improved drinking water	Number of people still not served by an improved water supply source (in 1,000s)	6,245	5,544	28,182	3,551

8.32 What is the source of drinking water in the town where you currently live (groundwater, surface water, reclaimed water, or a mixture)? Sketch the unit processes used to treat this water in order of occurrence as currently practiced. What water constituent(s) does each unit process remove?

Solution:

Students' responses will vary.

8.33 Identify three significant water users in your town or city that could benefit from the use of reclaimed water. What economic, social, and environmental challenges do you see that might need to be overcome before you can implement your plan for these users to use reclaimed water? What would you do as engineer to overcome these barriers?

Solution:

Students' responses will vary.

8.34 A city is upgrading its water supply capacity to 81,378 m^3/day, using microfiltration. The new plant membrane system will consist of 25 arrays with 90 modules per array. The modules have an inside diameter of 120 mm, a length of 1,200 mm, and an available surface area of 30 m^2. The membranes have an outside diameter of 1.0 mm, and a length of 1,200 mm. Determine: (a) the total surface area available for filtration, (b) the membrane flux rate in L/m2•hr, and (c) the total number of membrane fibers required for the plant and each module.

Solution:

a)

$$\left\{\begin{matrix}\text{Total}\\ \text{surface}\\ \text{area}\end{matrix}\right\} = (25\ \text{arrays}) \times \left(\frac{90\ \text{modules}}{\text{array}}\right) \times \left(\frac{23.4\ \text{m}^2}{\text{module}}\right) = \boxed{52{,}650\ \text{m}^2}$$

b)

$$\left\{\begin{matrix}\text{Flux}\\ \text{rate}\end{matrix}\right\} = \frac{(\text{Total plant flow rate})}{(\text{total surface area available for filtration})}$$

$$= \left(\frac{81378\ \text{m}^3/\text{d}}{52650\ \text{m}^2}\right) \times \left(\frac{\text{d}}{24\ \text{h}}\right) \times \left(\frac{1{,}000\ \text{L}}{\text{m}^3}\right) = \boxed{64.4\frac{\text{L}}{\text{m}^2 - \text{h}}}$$

c)

$$\left\{\begin{matrix}\text{Total}\\ \text{number}\\ \text{of fibers}\end{matrix}\right\} = \frac{(\text{Total plant surface area available for filtration})}{(\text{external surface area of a single fiber})}$$

$$= \frac{52650\ \text{m}^2}{2\pi r L} = \frac{52650\ \text{m}^2}{2\pi \times (0.001\ \text{m}) \times (1.194\ \text{m})} = \boxed{7{,}018{,}013}$$

$$\left\{\begin{matrix}\text{Number}\\ \text{of fibers}\\ \text{per module}\end{matrix}\right\} = \frac{(\text{total number of fibers})}{(\text{number of modules})} = \frac{7{,}018{,}013}{(25\ \text{arrays}) \times \left(\frac{90\ \text{modules}}{\text{array}}\right)} = \boxed{3{,}119}$$

8.35 A municipality uses a microfiltration membrane system to treat 35,000 m^3/day. The membrane system consists of nine arrays with 80 modules per array. The modules are 119 mm in inside diameter and 1,194 mm in length, and have an available filtration surface area of 27 m^2. Determine the (a) total surface area available for filtration, and (b) membrane flux rate in L/m^2•hr and gpm/sq. ft.

Solution:

This problem is similar to example 8.9.

a) $total\ surface\ area = 9\ arrays \times \frac{80\ modules}{array} \times \frac{27\ m^2}{module} = 19{,}440 m^2$

b) $flux\ rate = \frac{total\ plant\ flow\ rate}{total\ surface\ area\ available\ for\ filtration}$

$$flux\ rate = \frac{35{,}000\ m^3/day}{19{,}440 m^2} \times \frac{1\ day}{24\ hr} \times \frac{1{,}000 L}{1\ m^3} = \mathbf{75 \frac{L}{m^2} - hr}$$

$$flux\ rate = 75 \frac{L}{m^2} - hr \times \frac{1\ gal}{3.785\ L} \times \frac{1\ m^2}{(3.28\ ft)^2} \times \frac{1\ hr}{60\ min} = \mathbf{0.031\ gpm/ft^2}$$

8.36 Atrazine and trichloroethylene can be removed from water by adsorption to activated carbon. The Freundlich parameters for atrazine are K = 182 mg/g $(L/mg)^{1/n}$ and 1/n = 0.18. The parameters for trichloroethylene are K = 56 mg/g $(L/mg)^{1/n}$ and 1/n = 0.48. What is the adsorbed concentration of both contaminants (units of mg chemical per gram of activated carbon) if you want the aqueous phase concentration at equilibrium to be 10 µg/L? (this problem may require you review information presented in Chapter 3).

Solution:

From chapter 3, use equation 3.31 in table 3.9 for the Freunlich isotherm:

$$q = KC^{1/n}$$

$$q_{atrazine} = 182\ mg/g(L/mg)^{\frac{1}{n}} \times (10 * 10^{-6}\ mg/L)^{0.18} = \mathbf{23\ mg/g}$$

$$q_{trichoroethylene} = 56\ mg/g\left(\frac{L}{mg}\right)^{\frac{1}{n}} \times \left(10 * 10^{-6}\frac{mg}{L}\right)^{0.48} = \mathbf{0.22\ mg/g}$$

8.37 A methyl tert butyl ether (MTBE) adsorption isotherm was performed on an activated carbon at 15 ºC using 0.250-L amber bottles with an initial MTBE concentration, C_o, of 150 mg/L. The isotherm data for each experimental point is summarized below. Calculate the adsorbed-phase concentration, q_e, for each isotherm point, plot the log (q_e) versus log (C_e) and determine the Freundlich isotherm parameters K and 1/n (this problem may require you review information presented in Chapter 3).

Mass of GAC, g	MTBE equilibrium liquid-phase concentration, C_e, mg/L
0.155	79.76
0.339	42.06
0.589	24.78
0.956	12.98
1.71	6.03
2.4	4.64
2.9	3.49
4.2	1.69

Solution:

An adsorption isotherm is typically conducted using the bottle-point isotherm method. The method involves placing different masses, M (g), of powdered carbon in amber bottles (typically 250 ml) and adding a known volume aqueous solution, V (L), containing the know concentration of the adsorbate, C_o (mg/L), into various bottles and sealing them air tight with little or no headspace. If GAC is to be used it is usually crushed to less than 200 mesh size, washed and dried to a constant weight before using and moisture content of the carbon also needs to be determined and accounted for in the adsorbate mass measurement.

The bottles are placed in a shaker device in a temperature controlled environment and allowed to equilibrate for a period of at least 7 days. At the end of the equilibration period, the bottles are allowed to stand for a few hours to allow the carbon to settle out and then the equilibrated concentration, C_e (mg/L), is measured in each bottle and the adsorption equilibrium capacity, q_e (mg/g), in each bottle is calculated from the following mass balance:

$$\underbrace{\begin{bmatrix}\text{Initial mass of}\\ \text{adsorbate}\\ \text{placed in bottle}\end{bmatrix}}_{MC_o} = \underbrace{\begin{bmatrix}\text{Mass of adsorbate}\\ \text{in liquid} - \text{phase}\\ \text{in bottle after}\\ \text{equilibrition}\end{bmatrix}}_{VC_e} + \underbrace{\begin{bmatrix}\text{Mass of adsorbate}\\ \text{adsorbed onto adsorbent}\\ \text{in bottle after}\\ \text{equilibrition}\end{bmatrix}}_{Mq_e}$$

Solving for the adsorption capacity (qe) in the above equation:

$$q_e = \frac{V(C_o - C_e)}{M}$$

This equation can be used to calculate the quantity of adsorbate adsorbed per mass of carbon for each bottle point.

The Freundlich adsorption isotherm equation is the most common expression used to describe isotherms for adsorbates in water and air. At equilibrium, the amount adsorbed is related to amount in fluid-phase using the following expression:

$$q_e = KC_e^{1/n}$$

where q_e is the mass of adsorbate adsorbed per unit mass of adsorbent after equilibrium (mg/g); C_e is the mass of adsorbate in the fluid-phase after equilibrium (mg/L); K is the Freundlich isotherm capacity parameter ($(\text{mg/g})(\text{L/mg})^{1/n}$); and 1/n is the Freundlich isotherm intensity parameter (unitless).

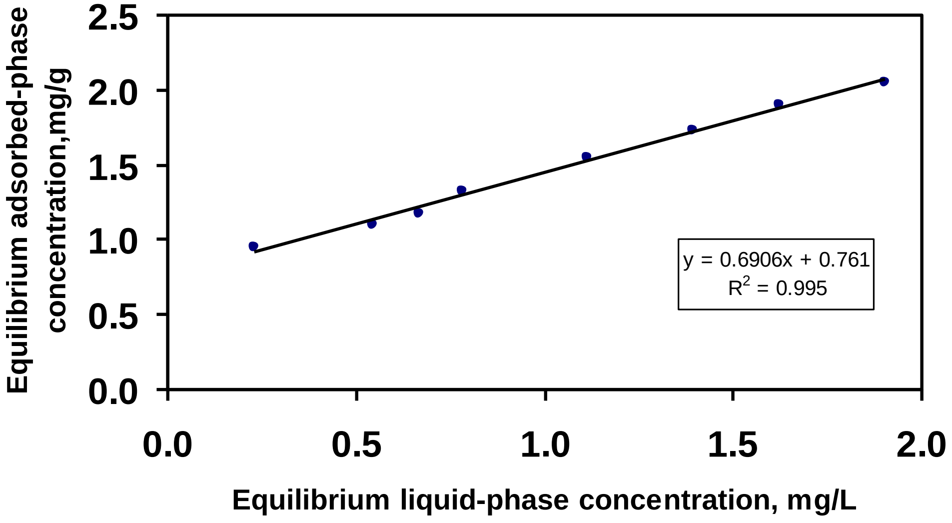
The Freundlich isotherm parameters can be determined by fitting the logs of the isotherm data [e.g. $\log(q_e)$ versus $\log(C_e)$] using the linear form of the above equation which is expressed as:

$$\log(q_e) = \log(K) + \left(\frac{1}{n}\right)\log(C_e)$$

With this knowledge, we can now solve the specific solution,

C_o (mg/L)	M (g)	C_e (mg/L)	$q_e = (V/M)(C_o\text{-}C_e)$ (mg/g)	log (q_e)	log (C_e)
150	0.155	79.76	113.290	2.0542	1.9018
150	0.339	42.06	79.602	1.9009	1.6239
150	0.589	24.78	53.149	1.7255	1.3941
150	0.956	12.98	35.832	1.5543	1.1133
150	1.71	6.03	21.048	1.3232	0.7803
150	2.4	4.64	15.142	1.1802	0.6665
150	2.9	3.49	12.630	1.1014	0.5428
150	4.2	1.69	8.828	0.9459	0.2279

Graph log (q_e) versus log (C_e) as shown below and use a linear regression to fit the data using Equation 10-62 to determine K and 1/n.



From the graph above, an earlier equation is expressed as:

$$\log(q_e) = 0.761 + (0.6906)\log(C_e)$$

Here log (K) equals 0.761 or K = $10^{0.761}$ = 5.77 (mg/g)$(L/mg)^{1/n}$

Thus, K equals 5.77 (mg/g)$(L/mg)^{1/n}$ and 1/n = 0.6906

8.38 Powdered activated carbon (PAC) is to be added to a water treatment plant to remove 10 ng/L of MIB which is causing odor problems in the finished water. A standard jar test is performed to evaluate the impact of PAC dosage on the removal of MIB. The results are shown Figure 8.26. If 60 percent MIB removal is required, determine the dosage of PAC required and quantity of PAC needed for 3 months (90 days) of treatment if the plant flow rate for is 40,000 m^3/d.

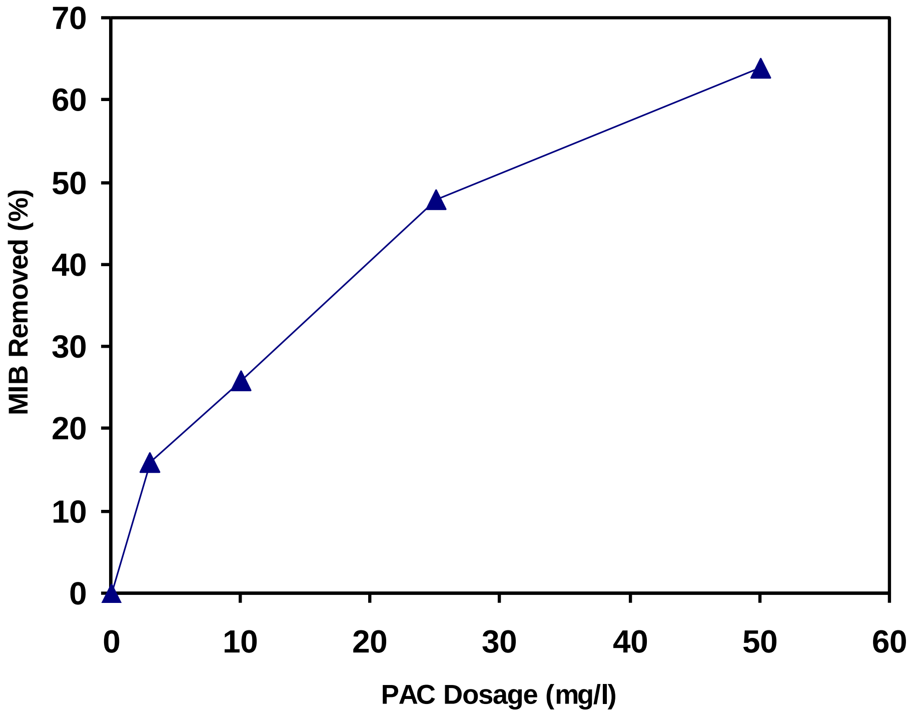


Figure 8.25. Results from Jar Test Investigating Powdered Activated Carbon Usage at a Water Treatment Plant.

Solution:

Determine the PAC dosage from the experimental data provided in Figure 10.25. Based on the results of the jar tests, for a required removal of 60 %, the required PAC dosage determined from the figure is 44 mg/L.

The quantity of PAC required for 3 months of operation is determined as:

$$\begin{Bmatrix} \text{Mass} \\ \text{PAC} \\ \text{required} \end{Bmatrix} = \left(\frac{44 \text{ mg PAC}}{\text{L}}\right) \times \left(\frac{1{,}000 \text{ L}}{\text{m}^3}\right) \times \left(\frac{\text{kg}}{10^6 \text{ mg}}\right) \times \left(\frac{40{,}000 \text{ m}^3}{\text{day}}\right) \times (90 \text{ day})$$

$$= \boxed{158{,}400 \text{ kg}}$$

8.39 Reverse osmosis is used to treat brackish groundwater water and requires 1 kWh of energy per 1 m^3 of treated water. In comparison, reverse osmosis of seawater requires 4 kWh of energy per 1 m^3 of treated water (this difference is because of the higher TDS concentration of seawater). According to eGRID, the carbon dioxide equivalent emission rate is 1,324.79 lb CO_2e/MWh in Florida and 727.26 lb CO_2e/MWh in California. Estimate the carbon footprint of using reverse osmosis to desalinate 1 m^3 brackish groundwater and 1 m^3 sea water in Florida and California. Ignore line losses in your estimate (you may have to go back to Chapter 2 to review carbon footprints and eGRID).

Solution:

FL brackish water

$$\frac{1\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{1{,}324.79\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{1.32}\ \boldsymbol{lb}\,\frac{\mathbf{CO_{2e}}}{\mathbf{m^3}}$$

CA brackish water

$$\frac{1\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{727.26\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{0.73}\ \boldsymbol{lb}\,\frac{\mathbf{CO_{2e}}}{\mathbf{m^3}}$$

FL sea water

$$\frac{4\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{1{,}324.79\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{5.28}\ \boldsymbol{lb}\,\frac{\mathbf{CO_{2e}}}{\mathbf{m^3}}$$

CA sea water

$$\frac{4\ kWh}{1\ m^3} \times \frac{1\ MWh}{10^3 kWh} \times \frac{727.26\ lb\ \mathbf{CO_{2e}}}{MWh} = \mathbf{2.92}\ \boldsymbol{lb}\,\frac{\mathbf{CO_{2e}}}{\mathbf{m^3}}$$

8.40 Fill in the rest of this table, providing the electricity requirements to treat 1 MDG of treated water. Fill in the carbon footprint assuming the treatment plant is located in California. According to eGRID, the carbon dioxide equivalent emission rate is 727.26 lb CO_2e/MWh in California. (you may have to review Chapter 2 for information on carbon footprints and eGRID).

Solution:

Convert 1 MGD to cubic meters:

$$1 * 10^6 gallon \times \frac{3.785\ L}{gallon} \times \frac{1\ m^3}{1{,}000L} = 3785\ m^3$$

Find the kWh/m^3 required to treat 1 MGD for each unit process in the text.

Multiply this by the cubic meters to get the kWh required to treat 1 MGD. Below is example for coagulation/flocculation:

$$kWh\ requierd\ to\ treat\ 1MGD\ of\ \frac{coag}{floc} = 3785m^3 \times 0.0164 = 62.1\ kWh$$

To calculate the carbon footprint, multiply the kWh required to treat 1 MGD by the CO_2 equivalent emission rate given in the problem:

$$carbon\ footprint\ of\ \frac{Coag}{Flocc} = 62.1\ kWh\ \times \frac{1\ MWh}{10^3 kWh} \times 727.26\ lb\ \mathrm{CO2e/MWh} = \mathbf{45.1\ CO2e}$$

Unit Process	**kWh/m^3 required to treat 1 MGD**	**kWh required to treat 1 MGD**	**Carbon Footprint to treat 1 MGD (CO_2e)**
Coagulation/flocculation	=0.011+ 0.003 (table 8.13)+0.0024=0.0164	62.1	45.1
Sedimentation	0.0037 (section 8.7.3 last paragraph)	14.0	10.2
Disinfection with Chlorine	2 (end of section 8.9.2)	7570	5505
Adsorption with GAC	0.01 (box 8.7)	37.9	27.6

Chapter 9. Wastewater and Stormwater: Collection, Treatment, Resource Recovery

9.1 Research an emerging chemical of concern that might be discharged to a wastewater treatment plant or household septic systems. Examples would include pharmaceuticals, caffeine, surfactants found in detergents, fragrances, and perfumes. Write an essay of up to three pages on the concentration of this chemical found in wastewater influent. Determine whether the chemical you are researching is treated in the plant, passes through untreated, or accumulates on the sludge. Identify any adverse ecosystem or human health impacts that have been found for this chemical.

Solution:

Students' responses will vary.

9.2 Research whether there are state or regional pollution prevention programs to keep mercury out of your local municipal wastewater treatment plant. This mercury might come from your university laboratories or local dental offices and hospitals. What are some of the specifics of these programs? How much mercury has been kept out of the environment since the program's inception?

Solution:

Students' responses will vary.

9.3 A laboratory provides the following solids analysis for a wastewater sample: TS = 225 mg/L, TDS = 40 mg/L, FSS = 30 mg.L. (a) What is the total suspended solids concentration of this sample? (b) Does this sample have appreciable organic matter? Why or why not?

Solution:

Look back to figure 2.3 and example 2.16 for relationships among the various measurements of solids in aqueous samples.

a.

$$TS = TDS + TSS$$

$$TSS = TS - TDS = 225\frac{mg}{L} - 40\frac{mg}{L} = \mathbf{185\frac{mg}{L}}$$

b.

$$TSS = VSS + FSS$$

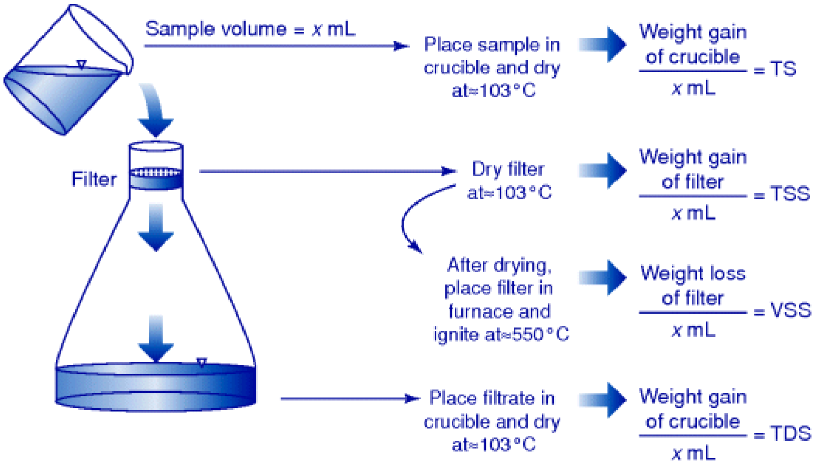
$$VSS = TSS - FSS = 185\frac{mg}{L} - 30\frac{mg}{L} = 155\frac{mg}{L}$$

$$\%\ organic\ matter = \frac{VSS}{TS} = \frac{155\ mg/L}{225\ mg/L} \times 100\% = 70\%$$

Yes, the sample has appreciable organic matter at over half, 70%.

9.4 A 100 mL water sample is collected from the activated sludge process of municipal wastewater treatment. The sample is placed in a drying dish (weight 5 0.5000 g before the sample is added) and then placed in an oven at 104°C until all moisture is evaporated. The weight of the dried dish is recorded as 0.5625 g. A similar 100 mL sample is filtered, and the 100 mL liquid sample that passes through the filter is collected and placed in another drying dish (weight 0.5000 g before the sample is added). This sample is dried at 104°C, and the dried dish's weight is recorded as 0.5325 g. Determine the concentration (in mg/L) of (a) total solids, (b) total suspended solids, (c) total dissolved solids, and (d) volatile suspended solids. (Assume VSS=0.7TSS .).

Solution:



Look back at figure 2.2 to answer these questions.

a. $TS = \frac{weight\ gain\ of\ crucible}{x\ mL} = \frac{0.565g - 0.500g}{100\ mL} \times \frac{1{,}000\ mg}{g} = \mathbf{0.65\ mg/L}$

b. $TSS = \frac{weight\ gain\ on\ filter}{x\ mL} = \frac{0.5325g - 0.500g}{100\ mL} \times \frac{1{,}000\ mg}{g} = \mathbf{0.33\ mg/L}$

c. From figure 2.3: $TS = TDS + TSS$

$$TDS = TS - TSS = 0.65\frac{mg}{L} - 0.33\frac{mg}{L} = \mathbf{0.32\frac{mg}{L}}$$

d. $VSS = 0.7 \times TSS = 0.7 \times 0.33\frac{mg}{L} = \mathbf{0.23\ mg/L}$

9.5 Obtain the World Health Organization (WHO) report on "Urine diversion: Hygienic risks and microbial guidelines for reuse." Review Figure 2 in Chapter 1 of this report (Introduction). (a) How many grams of N, P, and K are excreted every day in a Swedish person's urine?

Solution:

This report can be found at:

http://www.who.int/water_sanitation_health/wastewater/urineguidelines.pdf

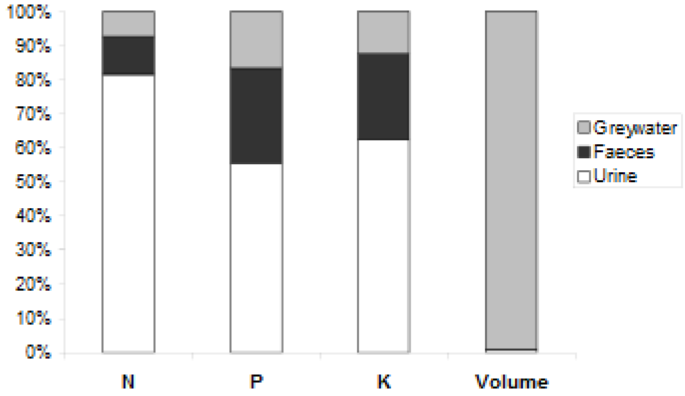


Figure 2. *Content of major plant nutrients and volume in Swedish domestic wastewater. The daily mean excretion per person and day is: 14 g N, 2 g P and 4 g K in a volume of 150-200 litre.*

According to the figure **14 g N, 2g P, and 4g K are excreted every day in a Swedish person's urine.**

9.6 Humans produce 0.8 to 1.6 L of urine per day. The annual mass of phosphorus in this urine on a per capita basis ranges from 0.2 to 0.4 kg P. a) What is the maximum concentration of phosphorus in human urine in mg P/L? b) What is the concentration in moles P/L? c) Most of this phosphorus is present as HPO_4^{2-}. What is the concentration of phosphorus in mg HPO_4^{2}-/L?

Solution:

a) $[P]_{max} = \frac{0.4\ kg}{year} \times \frac{1000g}{1\ kg} \times \frac{1000\ mg}{1\ g} \times \frac{1day}{0.8\ L} \times \frac{year}{365\ days} = \mathbf{1369}\,\frac{\boldsymbol{mg}}{\boldsymbol{L}.}$

b) $1369\,\frac{mg}{L} \times \frac{1\ g}{1000\ mg} \times \frac{1\ mol\ \mathrm{P}}{30.97\ g} = \mathbf{0.04}\ \frac{\boldsymbol{mol}\ \mathbf{P}}{\boldsymbol{L}}$

c) $0.04\ \frac{mol\ \mathrm{P}}{L} \times \frac{1\ mol\ \mathrm{HPO_4}^{2-}}{1\ mol\ \mathrm{P}} \times \frac{95.97\ g}{1\ mol\ \mathrm{HPO_4}^{2-}} \times \frac{1000\ mg}{1\ g} = \mathbf{3838}\,\frac{\boldsymbol{mg}}{\boldsymbol{L}}$

9.7 Assume 50% of phosphorus in human excrement in found in urine (the remaining 50% is found in feces). Assume humans produce 1 L of urine per day and the annual mass of phosphorus in this urine is 0.3 kg P. If indoor water usage is 80 gallons per day in a single individual apartment, what is the concentration (in mg P/L) in the wastewater that is discharged from the apartment unit? Make sure you account for phosphorus found in urine and feces.

Solution:

First, solve for x, the total mass of phosphorous in feces and urine.

$$0.50 \times x = 0.30\ kg$$

$$x = \frac{0.30\ kg}{.50} = 0.60\ kg\ \mathrm{P}$$

$$\frac{0.60\ kg\ \mathrm{P}}{(80+1)L} \times \frac{1000\ g}{1\ kg} \times \frac{1000\ mg}{1\ g} = \mathbf{7.4 \times 10^3}\ \frac{\boldsymbol{mg}\ \mathbf{P}}{\boldsymbol{L}}$$

9.8 The following equation shows the stoichiometry for recovery of phosphorus and nitrogen from wastewater through preciptation of struvite.

$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \leftrightarrow MgNH_4PO_4 \bullet 6H_2O_{(s)}$)

If the composition of the wastewater under consideration for struvite recovery is 7 mg P/L, NH_4^+ is 25 mg NH_4^+ - N/L, and Mg is 40 mg Mg^{2+}/L, is there sufficient Mg and NH_4^+ to precipitate all the phosphorus, assuming it all exists as PO_4^{3-}?

Solution:

$$7\frac{mgP}{L} \times \frac{1g}{1000g} \times \frac{1\ mol\ P}{30.97\ g} = 2.26 * 10^{-4} mol\ P \times \frac{1\ mol\ N}{1\ mol\ P} \times \frac{14.01\ g\ N}{1\ mol\ N} \times \frac{1{,}000\ mg}{1\ g} = 3.2\ mgN/L$$

$$2.26 * 10^{-4} mol\ P \times \frac{1\ mol\ Mg}{1\ mol\ P} \times \frac{24.31\ g\ Mg}{1\ mol\ Mg} \times \frac{1{,}000\ mg}{1\ g} = 5.5\ mg\ Mg/L$$

$$3.2\frac{mgN}{L} < 25\ \mathrm{mg\ NH_4}^+ - \frac{\mathrm{N}}{\mathrm{L}}\ and\ 5.5\ mg\frac{Mg}{L} < 40\ \mathrm{mg}\frac{\mathrm{Mg}^{2+}}{\mathrm{L}}$$

$\therefore$ **Yes, it is sufficient** to precipitate all the phosphorus

9.9 Design an aerated grit chamber system to treat a 1 day sustained peak hourly flow of 1.6 m^3/s with an average flow of 0.65 m^3/s. Determine: (a) the grit chamber volume (assuming two chambers will be used); (b) the dimensions of the two grit chambers; (c) the average hydraulic retention time in each grit chamber; (d) air requirements, assuming 0.20 m^3 of air per m length of tank per minute; and (e) the quantity of grit removed at peak flow, assuming a typical value of 0.20 m^3 of grit per one thousand m^3 of untreated wastewater.

Solution:

This problem is similar to example 9.1

a. The volume of the grit chambers can be calculated below, assuming a detention time of 3 minutes:

$$total\ grit\ chamber\ volume = 1.6\frac{m^3}{s} \times 3\ min \times \frac{60\ s}{min} = 288\ m^3$$

$$volume\ of\ each\ grit\ chamber = \frac{1}{2} \times 288\ m^3 = \mathbf{144\ m^3}$$

b. Assuming a width-to-depth ratio of 1.5:1 and a depth of 3 meters, the dimensions of the two grit chambers are:

$$grit\ chamber\ width = 1.5 \times 3m = \mathbf{4.5\ m}$$

$$grit\ chamber\ length = \frac{volume}{width \times depth} = \frac{144\ m^3}{4.5\ m\ \times 3m} = \mathbf{10.7\ m}$$

c. The average hydraulic detention time in each grit chamber is based on the average flow rate:

$$detention\ time = \frac{volume}{flow} = \frac{144\ m^3}{\frac{0.65\ m^3/s}{2\ tanks}} \times \frac{1\ min}{60\ s} = \mathbf{7.4\ min}$$

d. The air requirements, assuming 0.35m^3/m-min of air are:

$$total\ air\ requirement = 2\ tanks\ \times 10.7\ m\ length \times 0.35\ \frac{m^3 air}{m - min} = \mathbf{7.5\ m^3/min}$$

e. Solve for amount of grit to be disposed of assuming peak flow conditions:

$$grit\ volume = \frac{1.6\ m^3}{s} \times \frac{0.015\ m^3}{10^3 m^3} \times 86{,}400\frac{s}{day} = \mathbf{2.1\frac{m^3}{day}}$$

9.10 A wastewater treatment plant receives a flow of 35,000 m^3/day. Calculate the required volume (m^3) for a 3 m deep horizontal flow grit chamber that will remove particles with a specific gravity of more than 1.9 and a size greater than 0.2 mm diameter.

Solution:

The basic design equation is: $V \geq \frac{hQ}{v_s}$

Calculate the particle settling velocity (v_s) using Stokes' Law.

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

$$v_s = \frac{(9.81)(1.9-1.0)(998)\left(0.2\times10^{-3}\right)^2}{(18)\left(1.002\times10^{-3}\right)}$$

$$v_s = 0.02 \text{ m/s} \quad \text{or} \quad 1{,}728 \text{ m/day}$$

The design particle (and all larger, denser particles) will be removed.

$$V \geq \frac{hQ}{v_s} = \frac{(3\ m)\left(35{,}000\ \frac{\text{m}^3}{\text{day}}\right)}{1{,}728\ \frac{\text{m}}{\text{day}}} = \boxed{60.8 \text{ m}^3}$$

Consider the same plant, utilizing an upward flow clarifier. Calculate the required surface area of the tank. The basic design equation is:

$$A_{\text{top}} \geq \frac{Q}{v_s} \geq \frac{35{,}000\frac{\text{m}^3}{\text{day}}}{1{,}728\frac{\text{m}}{\text{day}}} = 20.3 \text{ m}^2$$

9.11 A wastewater treatment plant will receive a flow of 35,000 m^3/day. Calculate the surface area (m^2), diameter (m), volume (m^3), and hydraulic retention time of a 3 m deep circular, primary clarifier that would remove 50 percent of suspended solids. Assume the surface overflow rate used for the design is 60 m^3/m^2-day.

Solution:

The basic design equation is, $SOR = \dfrac{Q}{A_{\text{top}}}$

Calculate the required surface area.

$$A_{top} = \frac{Q}{SOR} = \frac{35,000}{60} = \frac{\text{m}^3/\text{day}}{\text{m}^3/\text{m}^2\text{-day}} = \boxed{583\ \text{m}^2}$$

Calculate the tank diameter.

$$A_{\text{top}} = \pi r^2;\quad r = \sqrt{\frac{A_{\text{top}}}{\pi}} = \sqrt{\frac{583}{\pi}} = 13.6\ \text{m};\ \ D = 2r = \boxed{27.2\ \text{m}}$$

Calculate the tank volume.

$$V = A_{\text{top}}h = \left(583\ \text{m}^2\right)\left(3\ \text{m}\right) = \boxed{1,749\ \text{m}^3}$$

Calculate the retention time.

$$\theta = \frac{V}{Q} = \frac{1,749\ \text{m}^3}{35,000\,\frac{\text{m}^3}{\text{day}}} = 0.05\ \text{day} = \boxed{1.2\ \text{h}}$$

From the design plot, a BOD removal efficiency of ~25% could be expected.

9.12 Assume a plant flow of 12,000 m^3/day. Determine the actual detention time observed in the field of two circular settling tanks with depth of 3.5 m that were designed to have an overflow rate not to exceed 60 m^3/m^2-day and a detention time of at least 2 hr.

Solution:

Size settling tanks based on both overflow rate and hydraulic detention time. Select largest reactor to ensure both design criteria are met.

Solving by overflow rate,

$$OR = \frac{Q}{A} = 60\frac{\text{m}^3}{\text{m}^2\text{- day}} = \frac{12,000\,\frac{\text{m}^3}{\text{day}}}{A}$$

$$A = 200\ \text{m}^2$$

However,

$$t = \frac{V}{Q} = \frac{200\ m^2 * 3.5\,m}{12,000 m^3\ /\ day} \times \frac{24\ h}{day} = 1.4\ h$$

Solving by detention time,

$$2\ \text{hours} = \frac{V}{Q}$$

$$2\ \text{h}\left(\frac{\text{day}}{24\ \text{h}}\right) = A\left(\frac{3.5\ \text{m}}{12,000\,\frac{\text{m}^3}{\text{day}}}\right)$$

$$A = 286\ \text{m}^2$$

$$OR = \frac{12,000\ m^3\ /\ day}{286\ m^2} = 42\frac{m^3}{m^2 - day}$$

Therefore, the larger area should be used.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

9.13 A wastewater treatment plant has a flow of 35,000 m^3/day. Calculate the mass of sludge wasted each day ($Q_w X_w$, expressed in kg/day) for an activated-sludge system operated at a solids retention time (SRT) of 5 days. Assume an aeration tank volume of 1,640 m^3 and an MLSS concentration of 2,000 mg/L.

Solution:

2,000 mg/L = 2 kg/m^3

Set up the SRT design equation.

$$\theta_c = \frac{XV}{X_w Q_w} \Rightarrow X_w Q_w = \frac{XV}{\theta_c}$$

$$X_w Q_w = \frac{\left(1,640\ m^3\right)\left(2\ \text{kg}/m^3\right)}{5\ days} = \boxed{656\ \text{kg}/day}$$

9.14 You are provided with the following information about a municipal wastewater treatment plant. This plant uses the traditional activated-sludge process. Assume the microorganisms are 55 percent efficient at converting food to biomass, the organisms have a first-order death rate constant of 0.05/day, and the microbes reach half of their maximum growth rate when the BOD_5 concentration is 10 mg/L. There are 150,000 people in the community (their wastewater production is 225 L/day-capita, 0.1 kg BOD_5/capita-day). The effluent standard is $\text{BOD}_5 = 20\ \text{mg/L}$ and $\text{TSS} = 20\ \text{mg/L}$. Suspended solids were measured as 4,300 mg/L in a wastewater sample obtained from the biological reactor, 15,000 mg/L in the secondary sludge, 200 mg/L in the plant influent, and 100 mg/L in the primary clarifier effluent. SRT is equal to 4 days. (a) What is the design volume of the aeration basin (m^3)? (b) What is the plant's aeration period (days)? (c) How many kg of secondary dry solids need to be processed daily from the treatment plants? (d) If the sludge wastage rate (Q_w) is increased in the plant, will the solids retention time go up, go down, or remain the same? (e) Determine the F/M ratio in units of kg BOD_5/kg MLVSS-day. (f) What is the mean cell residence time?

Solution:

a) First determine Q_o and BOD influent.

$$(150,000)\left(225\frac{\text{L}}{\text{capita-day}}\right)=33.75\times10^6\ \frac{\text{L}}{\text{day}}$$

$$\text{BOD influent}=(150,000)\left(0.1\frac{\text{kg BOD}_5}{\text{person-day}}\right)\left(\frac{10^6\ \frac{mg}{kg}}{33.75\times10^6\ \frac{\text{L}}{\text{day}}}\right)=444\ \frac{mg}{L}$$

$$\frac{Q_wX_w}{VX}=\frac{Q_oY}{VX}(S_o-S)-k_d$$

Note that left side of equation is the inverse of the SRT = 4 days. Also, assume 30% of incoming BOD is removed during primary treatment so 70% reaches the aeration basin.

The problem tells us what the microorganisms are 55% efficient at converting food to biomass so the yield coefficient is (Y = 0.55 gm SS/gm BOD)

The organisms have a first-order death rate constant of 0.05/day which is k_d.

$$\frac{1}{4}\text{ day} = \frac{\left(33.75\times10^{6}\,\frac{\text{L}}{\text{day}}\right)\left(0.55\,\frac{\text{g SS}}{\text{g BOD}}\right)}{V\left(4{,}300\,\frac{\text{mg SS}}{\text{L}}\right)}\left[\left(444\,\frac{\text{mg}}{\text{L}}\right)(0.7)-\left(20\,\frac{\text{mg}}{\text{L}}\right)\right]-\frac{0.05}{\text{day}}$$

Solve for $\boxed{V = 4.2\times10^{6}\text{ L}}$

b) Aeration period is hydraulic detention time

$$=\frac{V}{Q}=\frac{4.2\times10^{6}\text{ L}}{33.75\times10^{6}\,\frac{\text{L}}{\text{day}}}=0.12\text{ day}=\boxed{2.9\text{ h}}$$

c) Using the SRT equation again,

$$SRT=\frac{VX}{Q_wX_w}\Rightarrow Q_wX_w=\frac{VX}{SRT}=\frac{\left(4.2\times10^{6}\text{ L}\right)\left(4{,}300\,\frac{\text{mg SS}}{\text{L}}\right)}{4\ days}$$

$$Q_wX_w=4.515\times10^{9}\,\frac{\text{mg SS}}{\text{day}}\left(\frac{\text{kg}}{10^{6}\text{ mg}}\right)=\boxed{4{,}515\,\frac{\text{kg}}{\text{day}}}$$

d) If Q_w is increased the SRT will decrease

e)

$$F/M=\frac{Q_oS_o}{XV}=\frac{\left(33.75\times10^{6}\,\frac{\text{L}}{\text{day}}\right)\left(444\,\frac{\text{mg}}{\text{L}}\right)(0.7)}{\left(4{,}300\,\frac{\text{mg SS}}{\text{L}}\right)\left(0.6\,\frac{\text{MLVSS}}{\text{MLSS}}\right)\left(4.2\times10^{6}\text{ L}\right)}$$

$$=\boxed{0.97\,\frac{\text{lbs BOD}}{\text{lbs MLVSS-day}}}$$

f) Mean cell residence time equals sludge age equals solids retention time = 4 days

9.15 Using information provided in Example 9.7, determine the critical SRT value (sometimes referred to as $\mathrm{SRT_{min}}$). This term refers to the SRT where the cells in the activated-sludge process would be washed out or removed from the system faster than they can reproduce.

Solution:

$$\frac{1}{SRT_{\min}} \approx \mu_{\max} - k_d = \frac{0.1}{\text{day}} - \frac{0.05}{\text{day}}$$

$$\frac{1}{SRT_{\min}} = \frac{0.05}{\text{day}}$$

$$\boxed{SRT_{\min} = 20 \text{ days}}$$

9.16 If the specific growth rate for a completed mixed activated sludge process equals 0.10 day^{-1}, what is the solids retention time for this system (units of days). (b) what is the mean cell retention time for the same system (units of day)?

Solution

Use equation 9.14 and solve for SRT which is the same as the mean cell retention time.

$$\mu = \frac{1}{SRT} \therefore SRT = \frac{1}{\mu} = \frac{1}{\frac{0.10}{day}} = \mathbf{10\ days}$$

9.17 In the following sentences, circle the correct term in boldface. If the solids retention time (SRT) is low (for example, 4 days), which conditions exist? (a) The F/M ratio is **low/high**. (b) The power requirements for aeration will be **less/greater**. (c) The microorganisms will be **starved/saturated** with food. (d) The mean cell retention time is **low/high**. (e) The sludge age is **low/high**. (f) The sludge wastage rate may have been recently **increased/decreased**. (g) The MLSS may have been **increased/decreased**.

Solution:

a) F/M ratio is low/**high**

b) There will **less**/greater power requirements for aeration

c) The microorganisms will be starved**/saturated** with food

d) Mean cell retention time is **low/**high

e) The sludge age is **low/**high

f) The sludge wastage rate may have been recently **increased/**decreased

g) The MLSS may have been **increased/**decreased

9.18 The suspended-solids concentration entering a treatment and resource recovery plant is 200 mg/L in the plant influent; 3,000 mg/L in the primary sludge; 12,500 mg/L in the secondary sludge; and 3,500 mg/L exiting the aeration basin. The concentration of total dissolved solids in the plant influent is 350 mg/L, and the concentration of total dissolved solids exiting the aeration basins is 2,300 mg/L. The BOD_5 is 100 mg/L measured after primary treatment and 3 mg/L exiting the plant. Total nitrogen levels in the plant are approximately 35 mg N/L.

If the F/M ratio is 0.35 gram BOD_5/ gram MLSS-day, estimate the hydraulic retention time of the aeration basins if the daily plant flow is 15 million liters.

Solution:

Used equation 9.16 and solve for the hydraulic retention time (V/Q). The problem provides a lot of excess information.

$$\mathrm{F/M} = \frac{S_o Q_o}{XV}$$

$$\frac{V}{Q} = \frac{S_o}{F/M \times X} = \frac{100\ mg/L}{\left(0.35 \frac{BOD_5}{g\ MLSS - day}\right)\left(3500 \frac{mg}{L} \times \frac{1\ g}{1{,}000\ mg}\right)} = \boldsymbol{82\ days}$$

9.19 Determine the sludge volume index (SVI) for a test where 3 g MLSS occupy a 450 mL volume after 30 min settling.

Solution:

$$SVI = \frac{450\text{ mL}}{3\text{ g MLSS}} = \boxed{150\frac{\text{mL}}{\text{g}}}$$

9.20 A 2 g sample of MLSS obtained from an aeration basin is placed in a 1,000 mL graduated cylinder. After 30 min settling, the MLSS occupies 600 mL. Does the following sludge have good, acceptable, or poor settling characteristics?

Solution:

$$SVI = \frac{600\text{ mL}}{2\text{ g MLSS}} = 300\frac{\text{mL}}{\text{g}}$$

<u>Since the SVI is well above 200, the sludge sample has poor settling characteristics.</u>

9.21 Figure 9.16 showed the modified Ludzak– Ettinger (MLE) process, which is used to configure a biological reactor to remove nitrogen. Explain the role of the two compartments in terms of: (a) whether they are oxygenated; (b) whether CBOD is removed in the compartment; (c) whether ammonia is converted in the compartment; (d) whether nitrogen is removed from the aqueous phase in the compartment; and (e) the primary electron donor(s) and electron acceptor(s) in each compartment.

Solution:

See discussion in the text.

9.22 Investigate the specific mechanisms by which ammonia nitrogen, total nitrogen, and phosphorus are treated or recovered at your local municipal wastewater treatment plant. Are the processes chemical or biochemical (or a combination)? Discuss your answer.

Solution:

Students’ responses will be specific to student’s location.

9.23 Investigate the specific mechanisms that your local municipal wastewater treatment plant uses for aeration. Is it surface aeration, fine- or coarse-bubble aeration, or natural aeration (via a facultative lagoon or attached growth system)?

Solution:

Students' responses will be specific to student's location.

9.24 A wastewater treatment plant will receive a flow of 35,000 m^3/d (~10 MGD) with a raw wastewater $CBOD_5$ of 250 mg/L. Primary treatment removes ~25% of the BOD. Calculate the volume (m^3) and approximate hydraulic retention time (hr) of the aeration basin required to run the plant as a “high rate” facility (F/M 5 2 kg BOD/kg MLSS-day). The aeration basin MLSS concentration will be maintained at 2,000 mg MLSS/L.

Solution:

Calculate the $CBOD_5$ feed to the aeration tank.

$$S_o = 250 \text{ mg/L} = \left(250 \frac{\text{g}}{\text{m}^3}\right)\left(0.75 \times 10^{-3} \frac{\text{kg}}{\text{g}}\right) = 0.1875 \frac{\text{kg}}{\text{m}^3}$$

Calculate the MLSS concentration of the aeration tank.

$$X = 2,000 \frac{\text{mg}}{\text{L}} = \left(2,000 \frac{\text{g}}{\text{m}^3}\right)\left(10^{-3} \frac{\text{kg}}{\text{g}}\right) = 2 \frac{\text{kg}}{\text{m}^3}$$

Use the definition of F/M and the data above to calculate V.

$$F/M = \frac{Q_o S_o}{VX} = \frac{\left(35,000 \frac{\text{m}^3}{\text{day}}\right)\left(0.1875 \frac{\text{kg}}{\text{m}^3}\right)}{V\left(2 \frac{\text{kg}}{\text{m}^3}\right)} = 2.0 / day$$

$$\boxed{V = 1,640 \text{ m}^3}$$

Calculate the retention time.

$$\theta = \frac{V}{Q} = \frac{1,640}{35,000} = 0.047 \text{ day} = \boxed{1.1 \text{ h}}$$

This retention time is approximate, because the flow estimate does not include return activated sludge.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
*Environmental Engineering: Fundamentals, Sustainability, Design,*2nd *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

9.25 Table 9.28 provides suspended solids concentrations in several different wastestreams at a municipal wastewater treatment plant. The BOD_5 is measured in the sewer located just before the treatment plant as 250 mg/L, after primary treatment is 150 mg/L, and after secondary treatment is 15 mg/L. Total nitrogen levels in the plant are approximately 30 mg N/L.

Table 9.28. Suspended solids concentration for different process streams in Problem 9.25

Process stream	**Suspended Solids Concentration (mg SS/L)**
Plant influent	200
Primary sludge	5,000
Secondary sludge	15,000
Aeration basin Effluent	3,000

If the design hydraulic retention time of each of four aeration basins operated in parallel equals 6 hours and the total plant flow is 5 million gallons per day, what is the F/M ratio in units of lbs BOD_5/lbs MLVSS-day. (b) Suppose the plant engineer wishes to increase the concentration of microorganisms in the biological reactor because she expects the substrate level to increase. What would she command the operator to do to accomplish this goal?

Solution:

a) $F/M = \dfrac{Q_o S_o}{VX}$

Assume MLVSS is 0.6 to 0.8 of MLSS (reported here as 3,000 mg/L). Using 0.6, MLVSS = 1,800 mg VSS/L.

To determine V, use the hydraulic retention time

6 hours = V/Q = V/5 million gallons

$$C = 1.25 \times 10^6 \text{ gal}$$

$$\text{So} = \frac{\left(5\times10^6 \dfrac{\text{gal}}{\text{day}}\right)\left(150\dfrac{\text{mg}}{\text{L}}\right)}{\left(1.25\times10^6 \text{ gal}\right)\left(1{,}800\dfrac{\text{mg VSS}}{\text{L}}\right)}$$

$$\boxed{F/M = 0.33\frac{\text{lbs BOD}_5}{\text{lbs MLVSS-day}}}$$

Note this is the total aeration capacity of all 4 aeration basins as they are operated in parallel.

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design,2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

b) To increase the MLSS in the aeration basin, command the operator to reduce the amount of solids that are wasted from the secondary clarifier (increase the solids retention time, SRT).

9.26 Determine the minimum surface area for a facultative lagoon treating municipal wastewater to be sited in Tampa, Florida. Assume the conversion efficiency of the algae is 3.5% and that 24,000 kJ of sunlight are needed to produce one kg of algae biomass. The average daily concentration of CBOD in the wastewater to be treated is 250 mg/L and the average flowrate is 4 MGD.

Solution:

Example 9.8 is similar to this problem.

Use equation 9.25 to calculate the maximum surface loading rate.

$$SLRmax = \frac{I_s \cdot CE \cdot 1.55\,\frac{\text{kg O}_2}{\text{kg algae}}}{24{,}000\,\frac{\text{kJ}}{\text{kg algae}}} = \frac{1.2 * 10^8\,\frac{kJ}{ha - day} \times 0.035 \times 1.55\,\frac{\text{kg O}_2}{\text{kg algae}}}{24{,}000\,\frac{\text{kJ}}{\text{kg algae}}} = 271\,\frac{\text{kg O}_2}{\text{ha} \cdot \text{day}}$$

$$Pond\ area = \frac{CBOD_o \times Q}{SLRmax} = \frac{250\,\frac{mg}{L} \times \frac{1\ g}{1{,}000 mg} \times \frac{1\ kg}{1{,}000\ g} \times \frac{4 * 10^6 gallons}{day} \times \frac{3.785\ L}{gallon}}{271\,\frac{\text{kg O}_2}{\text{ha} \cdot \text{day}}} = \mathbf{14\ \boldsymbol{ha}}$$

9.27 Determine the minimum surface area for a facultative lagoon treating municipal wastewater to be sited in your local community. Assume the conversion efficiency of the algae is 3% and that 24,000 kJ of sunlight are needed to produce one kg of algae biomass. Use the solar radiation characteristics of your local area and obtain an average daily concentration of CBOD in the wastewater and average wastewater flow rate from your instructor that is for your area.

Solution:

Students answers may vary, though use the method is example 9.8 as in the solution to problem 9.26.

9.28 The community of San Antonio is located in the Caranavi Province, Bolivia. According to the 2005 year survey, there are 420 habitants of this community. The population is estimated to increase to 940 by the year 2035. The average peak flow is currently 1.2 L/sec and is expected to increase to 2.14 L/sec by 2035 The organic load is estimated to be 45 gram BOD_5/capita-day. The community is considering a free surface wetland to treat their wastewater. (a) What is the BOD_5 loading generated in the year 2035 (kg/day)? (b) Use the BOD loading to estimate the maximum surface area (ha) required for a free surface wetland that would serve the community in 2035 and remove BOD and TSS to 30 mg/L. (c) Assuming you are now considering sizing a facultative lagoon instead of a free surface wetland. Quickly estimate the required surface area (m2) for a facultative lagoon to handle a peak flow in 2035, assuming a design water depth of 4 m and a hydraulic detention time of 20 days.

Solution:

a) The BOD_5 loading in 2035 is:

$$45 \text{ g } BOD_5\text{/capita-day} \times 940 \text{ habitants} \times \text{kg/1,000 g} = \boxed{42.3 \text{ kg/day}}$$

b) To estimate the size of a free water surface wetland, first obtain design data from Table 11.17 on area mass loading rates. Table 11.17 provides information that shows that a free water surface wetland BOD loading of 60 kg/ha-day should result in an effluent concentration of 30 mg/L.

$$42.3 \text{ kg/day} / 60 \text{ kg/ha-day} = \boxed{0.70 \text{ ha}}$$

(this equals 1.7 acres because there are 2.471 acres in a ha)

c) Determine the volume of the facultative lagoon to meet the detention time

$$2.14 \text{ L/s} \times 60 \text{ sec/min} \times 60 \text{ min/h} \times 24 \text{ h/day} \times 20 \text{ days} \times \text{m}^3\text{/1,000L} = 3{,}700 \text{ m}^3$$

Area equals volume divided by the depth

$$3{,}700 \text{ m}^3 / 4 \text{ m} = \boxed{925 \text{ m}^2}$$

9.29 (a) What size septic tank would you recommend for a 2 bedroom cottage assuming the available tank sizes are: 750; 1,000; 1,200; and 1,500 gallons? Assume you wish to have three days of residence time for the pollutants in the tank. (b) How would your problem change for a 4 bedroom house with a two day residence time?

Solution:

This problem is similar to box 9.4. Also use the flow rate values from table 7.12.

a. $2\ bedrooms \times 150 \frac{gallons}{bedroom} \times 3\ days = 900\ gallons$

Select the **1,000 gallon tank** which is the closest size available to meet our design guidelines.

b. $4\ bedrooms \times 150 \frac{gallons}{bedroom} \times 2\ days = 1{,}200\ gallons$

Select the larger **1,200 gallon tank** which is the closest size available to meet our design guidelines.

9.30 Table 9.1 showed that pit latrines are considered an improved technology for treating wastewater. Determine the depth required for a pit latrine 1 m 3 1 m in area that serves a household of 7 people and has a design life of 10 yr. Assume the pit is dug above the water table and the occupants use bulky or nonbiodegradable materials for anal cleansing (e.g., corncobs, stones, newspaper); therefore, the solids accumulation rate is assumed to be 0.09 m^3/person/year. Allow a 0.5 m space between the ground surface and the top of the solids at the end of the design life which is the point when the pit is filled.

Solution:

The depth for solids storage is determined as

$$\text{Solids storage depth} = \frac{\text{Number of users} \times \text{Accumulation rate} \times \text{Design life}}{\text{Cross-sectional area}}$$

$$\text{Solids storage depth} = \frac{7\,people \times 0.09m^3\ /\ person - year \times 10\text{yr}}{(1m)(1m)} = 6.3m$$

The pit needs to be 6.3 m deep. A 0.5 m for the space required between the ground level and the top of the pit after it is filled up.

Thus, the total depth needed to be dug is 6.8 m.

9.31 (a) Estimate the volume of gas production produced from one metric ton of food waste and one ton of wastewater solids. (b) Based on the results from part (a), assuming the mass of food waste and wastewater solids generated in a community is the same, would you recommend a municipality develop a program to collect and digest (with energy recovery) food waste or wastewater solids? Explain your answer based on potential energy production but also an implementation stand point. Assume the methane production potential of wastewater solids is 120 m^3/ metric ton, food waste has 3 times the methane production potential per volume of wastewater solids, and methane makes up 60% of the total gas produced from anaerobic digestion.

Solution.

a) 1 metric ton wastewater solids × 120 m^3 methane / ton biosolids × 1/ 0.6 = 200 m^3 gas produced

   1 metric ton food × 360 m^3 methane / ton food × 1/ 0.6 = **600 m^3** gas produced

b) Assuming the same mass of food and wastewater solids are produced by the community, you can see from part (a) that anaerobically digesting food results in more gas and more methane production. Therefore, digesting food waste is preferable from an energy production viewpoint. However, in a community that has a centralized treatment system, the collection system is already in place to collect wastewater solids via sewer collection systems and systems at a centralized treatment plant. Starting up a food collection system could take advantage of collection systems already in place for solid waste and yard waste. You would have to develop an understanding of household behavior on how food waste is handled by homeowners and things might be different in northern and southern U.S. climates as temperature impacts the rate at which food waste would produce odors. In a community with decentralized treatment (e.g., individual septic tanks), developing a collection system for food waste may be more implementable because a septic tank functions partially as a digester where the energy is not collected.

9.32 (a) If methane has an energy content of 39 MJ per m^3 and digester gas is approximately 60% methane, what volume of total digester gas must an anaerobic digester produce annually to provide potable water for a family of six for a year? (b) If the methane is provided from anaerobic digestion of food waste, how many pounds of food waste would a family have to generate per day to provide this energy to heat water (lbs/day)? The United Nations states that the minimum potable water requirement is provide drinking water sanitation and hygiene is 20 L per person per day. Assume the water has an initial temperature of 25^oC and you must raise the temperature to 100^oC to produce potable water. The energy required to raise water up 1^oC is equal to 4,200 J/L-^oC and there is 39 MJ of energy per m3 of methane. Assume that 1 metric ton of food waste produces 600 m^3 of total gas.

Solution:

a. The volume of water required by the family every year is:

20 L water / person-day × 6 persons × 365 days/year = 43,800 L water/year

The amount of energy required to boil this volume of water is:

43,800 L water / year × 4,200 J/L-°C × (100°C-25°C) (to bring 25°C groundwater to boil) × 1 MJ/10^6 J = 13,797 MJ/year

The volume of methane required to provide this amount of energy is:

13,797 MJ/year × m^3 methane/39 MJ = 354 m^3 methane/year

The volume of digester gas that would provide this volume of methane is:

354 m^3 methane/year × 1 m^3 digester gas/0.6 m^3 methane = **590 m^3 digester gas/year**

b. We know from the problem statement that 1 ton of food waste produces 600 m^3 of total gas.

Thus, 590 m^3 digester gas/year × 1 ton food/600 m^3 gas = 0.98 ton of food waste/year

The amount of food waste that is needed every day to produce the needed digester gas is:

0.98 ton of food waste /year × 2,204 lbs/ metric ton × 1 year/365 days = **6 lbs. of food waste per day**

9.33 If 1 kg of volatile solids (VS) produces 0.5 m^3 of methane but only half of the VS added to the digester will be broken down to gaseous compounds. If you want to produce 120 L of methane per day, how many pigs will you need to maintain to contribute waste to the digester? Assume a 60-kg pig produces 5 kg of manure per day with 10% being VS.

Solution:

$$120\ L\ \times \frac{1\ m^3}{1{,}000\ L} = 0.120\ m^3$$

Set up an equation for the amount of pigs required to produce 120 liters of methane given the information in the problem statement.

$$n_{pigs} \times 5kg \times 0.10VS \times \frac{0.5\ m^3 methane}{1\ kg\ VS} \times 0.5_{broken\ down} = 0.120\ m^3$$

$$n_{pigs} = \frac{0.120\ m^3}{\left(5kg \times 0.10VS \times \frac{0.5\ m^3\ methane}{1\ kg\ VS} \times 0.5_{broken\ down}\right)} = 0.96\ pigs = \mathbf{1\ pig}$$

9.34 Waste must be held in the digester for a period of time for digestion to occur but the length of time depends on temperature. Using the data in Table 9.29, calculate the appropriate digester capacity and dimensions (diameter and height) in m for each temperature listed assuming 20 L of input per day. Fix the digester dimensions at 1:5 diameter to height.

Table 9.29 Data for Problem 9.34

Temperature (°C)	Retention Time (days) minimum recommended
10	55
20	20
30	8

Solution:

Starting to T=10°C, calculate the required digester volume based on the retention time.

$$V_{t=10°\text{C}} = 20\frac{L}{day} \times 55\ days \times \frac{1\ m^3}{1{,}000L} = 1.1\ m^3$$

Use the cylindrical volume equation. In the problem statement, it is given that the digester dimensions have a 1:5 diameter to height ratio. So we know that H=5D.

$$V = \frac{\pi D^2}{4}h = \frac{\pi D^2}{4}5D = \frac{5\pi D^3}{4}$$

$$D_{t=10°\text{C}} = \sqrt[3]{\frac{4V}{5\pi}} = \sqrt[3]{\frac{4 \times 1.1m^3}{5\pi}} = \mathbf{0.65m}$$

$$h_{t=10°\text{C}} = 5D = 5 \times 0.65m = \mathbf{3.3m}$$

Use the same method to calculate the digester dimensions for the other temperatures.

$$V_{t=20°\text{C}} = 20\frac{L}{day} \times 20\ days \times \frac{1\ m^3}{1{,}000L} = 0.4\ m^3$$

$$D_{t=20^\circ\mathrm{C}} = \sqrt[3]{\frac{4V}{5\pi}} = \sqrt[3]{\frac{4 \times 0.4m^3}{5\pi}} = \mathbf{0.47m}$$

$$h_{t=20^\circ\mathrm{C}} = 5D = 5 \times 0.47m = \mathbf{2.3m}$$

$$V_{t=30^\circ\mathrm{C}} = 20\frac{L}{day} \times 8\ days \times \frac{1\ m^3}{1{,}000L} = 0.16\ m^3$$

$$D_{t=30^\circ\mathrm{C}} = \sqrt[3]{\frac{4V}{5\pi}} = \sqrt[3]{\frac{4 \times 0.16m^3}{5\pi}} = \mathbf{0.34\ m}$$

$$h_{t=30^\circ\mathrm{C}} = 5D = 5 \times 0.34m = \mathbf{1.7\ m}$$

Final answers are given in the table below:

Temperature (°C)	**Retention Time (days) minimum recommended**	**Diameter (m)**	**Height (m)**
10	55	**0.65**	**3.3**
20	20	**0.47**	**2.3**
30	8	**0.34**	**1.7**

9.35 A 2.5-MGD wastewater treatment plant is currently running at 80% capacity during the annual maximum day servicing a city of 38,500 people with 26.7 miles of sewers. During the next ten years, it is expected that new residential developments for 15,000 people along with 6.5 more miles of sewer will be built. The sewer is projected to have an I/I equal to 8,500 gpd/mile. a) Project the maximum daily demand for the wastewater treatment plant after the new development is built. b) Should the wastewater treatment plant capacity be increased?

Solution:

a)

$$\text{Total current water use} = 2,500,000 \text{ gpd} \times 0.8 = 2,000,000 \text{ gpd}$$
$$\text{Current I / I} = 8500 \text{ gpd / mi} \times 26.7\text{mi} \approx 227,000 \text{ gpd}$$
$$\text{Current domestic use} = 2,000,000 \text{ gpd} - 227,000 \text{ gpd} = 1,773,000 \text{ gpd}$$
$$\text{Per capita use} = \frac{1,773,000 \text{ gpd}}{38,500 \text{ people}} = 46 \text{ gpcd}$$

$$\text{Forcast water use:}$$
$$\text{Domestic use} = 46 \text{ gpcd} \times (38,500 + 15,000) = 2,461,000 \text{ gpd}$$
$$\text{I / I} = 8500\text{gpd / mi} \times (26.7 + 6.5) = 282,200 \text{ gpd}$$
$$\text{Total forcasted use} = 2,461,000 + 282,200 = \boxed{2,743,200 \text{ gpd}}$$

b) Yes, the treatment plant should be increased.

9.36 A residential community with a population of 15,000 is planning to expand its wastewater treatment plant. In 20 years, the population is estimated to increase to 23,000 residents, and 1,000 students per day are expected to commute to proposed junior college from outside the area. A new industry will also move in and contribute an average flow of 350,000 gpd and maximum day flow of 420,000 gpd. The present average daily flow into the plant is 1.45 million-gpd. The average inflow and infiltration (I/I) is 6 gal/capita day and maximum day I/I is 42 gal/capita day (rainy day). Residential per capita water use is expected to be 15 percent less in 20 years due to in-house water saving strategies. The demand factor for domestic (residential use only) wastewater is determined to be 2.4 for the maximum day. Compute the future average **and** maximum day flow rates. Hint: Compute the present per capita flow rates first; [total flow rate – I/I] divided by current population.

Solution:

This problem is similar to example 9.9.

The current estimated per capita generation of wastewater from different sources is as follows:

1. Estimate the current average I/I:

$$I/I = \frac{6\ gal}{capita\text{−}day} \times 15{,}000\ people = 90{,}000\ gpd$$

2. Determine the current average domestic wastewater generation:

$$domestic\ wastewater\ generation = metered\ flow - I/I = 1.45 * 10^6 gpd - 90{,}000\ gpd = 1.36 * 10^6 gpd$$

3. The current per capita wastewater generation can then be calculated as:

$$per\ capita\ wastewater\ generation = \frac{domestic\ wastewater\ generation}{population\ served} = \frac{1.36 * 10^6 gpd}{15{,}000\ people} = 91\ gpdc$$

We can now estimate the future average wastewater flow rate

1. Future average domestic flow (including 8 percent wastewater reduction):

$$91\ gpdc \times 0.85 \times 23{,}000\ resid = 1.77 * 10^6 gpd$$

2. School average flow (using values from Table 7.12 in Chapter 7):

$$15\ gpdc \times 1{,}000\ people = 15{,}000\ gpd$$

3. New Industry (from problem statement)= 350,000 gpd

4. Average infiltration/inflow (I/I):

$$6\ \frac{gal}{capita-day} \times 23{,}000\ residents = 138{,}000\ gpd$$

Now add the results of 1-4 for the future average flow rate:

$$Future\ average\ flow\ rate = 1.77 * 10^6 gpd + 15{,}000\ gpd + 350{,}000\ gpd + 138{,}000\ gpd$$
$$= 2.3 * 10^6 gpd = \mathbf{2.3\ MGD}$$

In similar fashion, we can also estimate the future maximum-day wastewater flow:

1. Future domestic maximum flow (from equation 7.4: $DF = \frac{Q_{event}}{Q_{avg}}$. Solve for Qevent)

$$Q_{event} = 1.77 * 10^6 gpd \times 2.4 = 4.2 * 10^6 gpd$$

2. School average flow (using values from Table 7.12 in Chapter 7):

$$15\ gpdc \times 1{,}000\ people = 15{,}000\ gpd$$

3. New Industry (from problem statement) = 420,000 gpd

4. Maximum infiltration/inflow (I/I):

$$42\frac{gal}{capita} \times 23{,}000 = 966{,}000\ gpd$$

Now add the results of 1-4 for the maximum daily flow rate:

$$Future\ maximum\ flow\ rate = 4.2 * 10^6 gpd + 15{,}000\ gpd + 420{,}000\ \text{gpd} + 966{,}000\ gpd$$
$$= 5.3 * 10^6 gpd = \mathbf{5.3\ MGD}$$

9.37 List five advantages to precipitating struvite from the nitrogen and phosphorus found primarily in urine discharged to municipal wastewater.

Solution:

Students may have to do some research to answer this problem. Remember from our chapter reading that struvite ($MgNH_4PO_4•6H_2O_{(s)}$) is a way to precipitation out and thus recover the valuable nutrients, nitrogen and phosphorus. Some advantages could include:

1. Phosphorus as a useful and economically valuable product used in fertilizer which helps achieve resource recovery at the plant.
2. Struvite releases P at a slower rate than other fertilizers.
3. This process removes N and P from the water as a solid precipitation, thus it helps to reduce the amount of phosphate and ammonia in the plant's effluent; thus, it reduces eutrophication potential of discharged effluent as well as the energy and materials needed to treat N and P from the water.
4. Assists in compliance with increasingly strict nutrient discharge regulations.
5. Provides cost savings with lower cost nutrient removal methods.
6. Controls struvite eliminating precipitation on downstream processes in a treatment plant that include pipes, pumps, etc.

9.38 For the following influent water quality of a wastewater treatment plant that employs struvite recovery that is 70% effective in nutrients, determine which nutrient (N or P) in the influent is limiting for struvite precipitation and why? The influent contains [NH_4+$^-$N] (80.5 mg N/L) and PO_4^--P] (20.7 mg P/L).

Solution:

From the text, the molecular formula of struvite is: $MgNH_4PO_4•6H_2O_{(s)}$)
First we convert the concentrations in mg/L to mole/L for both NH_4 and PO_4.
Next we determine the number of moles present in 1 L of waste water.

80.5 mg N/L × 1 mole N/ 0.014 mg N × 1 mole NH4 / 1 mole N = 5,750 mole NH_4

20.7 mg P/L × 1 mole P / 0.031 mg P × 1 mole PO4 / 1 mole P = 667 mole PO_4

Looking at the molecular formula for struvite, $MgNH_4PO_4•6H_2O(s)$, see that you require one mole of ammonium ion (NH_4) per one mole of phosphate (PO_4). You can see there is excess ammonium; thus, there is not sufficient PO_4 to convert all the ammonium to struvite. Therefore, **PO_4 is the limiting nutrient in struvite precipitation in this situation**.

9.39 Assuming a homeowner installs a 60-gallon rain barrel at their home which has roof with 215 ft^2 of surface area, how much rainfall (in feet) could be stored? Assume that only 90% of the rain that falls on the roof enters the rain barrel due to leaky downspouts.

Solution:

First convert the rain barrel volume and roof surface area into meters.

$$60\ gallon \times \frac{3.785\ L}{gallon} \times \frac{1\ m^3}{1{,}000\ L} = 0.23\ m^3$$

$$215\ ft^2 \times \frac{1\ m^2}{(3.28\ ft)^2} = 20\ m^2$$

Develop an equation to solve for the rainfall that can be stored:

$$20\ m^2 \times 0.9 \times x = 0.23\ m^3$$

$$x = \frac{0.23\ m^3}{20m^2 \times 0.9} = 0.013\ m \times \frac{3.28\ ft}{1\ m} = \mathbf{0.041\ ft}$$

9.40 Assume that the roof area for a residential home is 12 ft. × 30 ft. If a green roof is placed on the home, what percentage of a 0.5 in. rain event will be stored on the roof if the growing medium has a water-holding capacity of 0.25? What is the volume of water (in gallons) that is stored during this rain event?

Solution:

The answer to the first part of this problem is **25%** (i.e., the water holding capacity of the growing medium). In terms of volume of water that is stored,

$$V = P \times A \times C$$

$$V = 0.5\ in \times (12\ ft \times 30\ ft) \times 12\ \ in/ft \times 7.48\ \ gal/ft^3 = \boxed{16{,}157\ gallons}$$

9.41 What area (in sq. ft.) is needed for two bioretention cells used to collect rainwater coming from a household roof? The roof has dimensions of 30 ft. × 40 ft. It drains to two downspouts, each of which will be routed to a bioretention cell. Assume the soil surrounding the home is silty and the cell will be dug to a depth of 6 in.

Solution:

$$\begin{bmatrix}\text{Area of residential}\\ \text{bioretention cell}\end{bmatrix}=\begin{bmatrix}\text{nonpermeable}\\ \text{area}\end{bmatrix}\times\begin{bmatrix}\text{size}\\ \text{factor}\end{bmatrix}$$

Using size factor provided in Table 8-9,

$$30\ ft\times 40\ \ ft\times 0.25=300\ ft^2$$

Since there are two cells, <u>each will have an area of 150 ft^2 with a depth of 6 in</u>.

9.42 A 1-acre paved parking lot measures 50 ft. × 20 ft. What volume of bioretention cell is required (in cu. Ft.) that can handle a first flush from the nonpermeable pavement of 0.5 in.? Assume the soil porosity is 0.30.

Solution:

$$\begin{bmatrix}\text{The volume}\\ \text{of rainwater to}\\ \text{be stored}\end{bmatrix} = \begin{bmatrix}\text{first}\\ \text{flush}\end{bmatrix} \times \begin{bmatrix}\text{nonpermeable}\\ \text{area}\end{bmatrix}$$

$$= 0.5 \text{ in} \times 1 \text{ acre} \times 43{,}560 \text{ ft}^2/\text{acre} \times \text{ft}/12 \text{ in}$$

$$= 1{,}815 \text{ ft}^3$$

$$\begin{bmatrix}\text{The volume}\\ \text{of the}\\ \text{bioretention cell}\end{bmatrix} = \begin{bmatrix}\text{volume of}\\ \text{rainwater to}\\ \text{be stored}\end{bmatrix} \div \begin{bmatrix}\text{soil}\\ \text{porosity}\end{bmatrix}$$

$$= \frac{1{,}815 \text{ ft}^3}{0.30} = \boxed{6{,}050 \text{ ft}^3}$$

9.43 Select a specific location on your campus that has a building and associated parking lot. Redesign this area, incorporating at least three low-impact development techniques. Besides thinking about management of stormwater, also consider the movement of people and vehicles, and the use of native plant species.

Solution:

Students' responses will vary.

9.44 Size a rain garden for your current home, apartment, or dormitory to treat stormwater that originates from the roof.

Solution:

Students' responses will vary based on the area of their home, apartment, or dormitory. They should use equation 9.36 from the textbook (see below) with size factors from table 9.26.

$$[\text{area of residential bioretention cell}] = \text{nonpermeable area} \times \text{size factor}$$

An average home in the United States has roof dimensions of 40ft x 60ft. Let us assume we are designing at 8 inch deep bioretention cell in Florida with sandy soils.

$$[area\ of\ residential\ bioretention\ cell] = 40ft \times 60ft \times 0.08 = \mathbf{192\ ft^2}$$

9.45 The average cost of delivering an acre-foot of treated water in a water scarce region is \$5,900 and the cost of delivering an acre-foot of reclaimed water in the same region is \$6,400 (due to treatment and transport). Given that the following factors can be credited to reclaimed water, what is the range of cost of reclaimed water as compared to treated water as a percentage?

Increased potable water supply: \$300-\$1000/acre-foot

Water supply reliability: \$100-\$140/acre-foot

Effluent disposal savings: \$200-\$2000/acre-foot

Downstream effects: \$400-\$800/acre-foot

Energy conservation: \$0-\$240/acre-foot

Solution:

$$Min_{saving} = \$300 + \$100 + \$200 + \$400 + \$0 = \$1{,}000/acre - foot$$

$$Min_{saving} = \$1{,}000 + \$140 + \$2000 + \$800 + \$240 = \$4{,}180/acre - foot$$

$$Min_{cost\ of\ reclaimed\ water} = \$6{,}400 - \$4{,}180 = \$2{,}220$$

$$Max_{cost\ of\ reclaimed\ water} = \$6{,}400 - \$1{,}000 = \$5{,}400$$

$$\frac{\$2{,}220}{\$5{,}900} = 0.38 \times 100\% = 38\%$$

$$\frac{\$5{,}400}{\$5{,}900} = 0.92 \times 100\% = 92\%$$

The range of cost of reclaimed water as compared to treated water as percentage is between **38%-92%.**

9.46 Assume the energy requirements to treat wastewater using a mechanical process is 1 million kWhr per million gallons of water treated. According to eGRID, the carbon dioxide equivalent emission rate is 1,324.79 lb CO_2e/MWh in Florida and 727.26 lb CO_2e/MWh in California. Estimate the carbon footprint of treating 50 million gallons of wastewater Florida and California. Ignore line losses in your estimate (you may have to go back to Chapter 2 to review carbon footprints and eGRID).

Solution:

$$50\ million\ gallons \times \frac{1\ million\ kWhr}{1\ million\ gallons\ of\ H_2O} \times \frac{1\ MWh}{10^3 kWh} = 50{,}000\ MWh$$

For Florida:

$$50{,}000\ MWh \times \frac{1{,}324.79\text{lb CO}_2\text{e}}{MWh} = \mathbf{6.6 * 10^7 lb\ CO_2e}$$

For CA:

$$50{,}000\ MWh \times \frac{727.26\text{ lb CO}_2\text{e}}{MWh} = \mathbf{3.6 * 10^7 lb\ CO_2e}$$

Chapter 10. Solid Waste Management

10.1 A community with a population of 150,000 has a solid waste generation rate of 1.5 kg solid waste/day-person. Assume that yard waste makes up 15% of the total waste generated (by weight) and yard waste is banned by the state from being disposed of in a landfill, therefore, the community has set up a program to collect and compost yard waste. Assume the density of the loose solid waste is 140 kg/m^3 at the curb, is compacted to 340 kg/m^3 in the truck that collects the waste at the home, and is 220 kg/m^3 after the material is removed from the compacter truck at the landfill. (a) is this generation rate above or below the current value for a U.S. residential community? (b) What is the volume of waste that is discarded every day by the community at the source (m^3)? (c) What is the volume of waste that will removed from the compacter truck at the landfill (m^3)?

Solution:

a. From table 10.2, 0.74 Mg of waste is generated per person per year in 2010.

The community in the problem generates: $1.5\frac{kg}{person-day}\times\frac{365\ days}{year}\times\frac{1\ Mg}{10^3 kg}=0.55\frac{Mg}{person\ year}$

$$0.55\frac{Mg}{person\ year}<0.74\frac{Mg}{person\ year}$$
$$\therefore this\ generation\ rate\ is\ \boldsymbol{below}\ the\ current\ value\ for\ a\ US\ residential\ community$$

b. Calculate the amount of waste generate by the population per day (remember that the 15% that is yard waste is banned from being disposed in the landfill) then use the equation for density to solve for the volume of the waste discarded every day.

$$150{,}000\times\frac{1.5\ kg\ solid\ waste}{day-person}\times 0.85=191{,}250\frac{kg}{day}$$

$$\rho=\frac{m}{V}\ \therefore V=\frac{\rho}{V}=\frac{191{,}250\ kg/day}{140\ kg/m^3}=\boldsymbol{1370\ m^3}$$

c. Use the same method as in part b.

$$V=\frac{\rho}{V}=\frac{191{,}250\ kg/day}{220\ kg/m^3}=\boldsymbol{869\ m^3}$$

10.2 A new solid waste landfill site is being designed with a projected life of 10 years. The landfill will serve a population of 250,000 that generates 1 kg solid waste/day-person. Assume that yard waste makes up 15% of the total waste (by weight), paper makes up 40% of the total waste (by weight), and metals make up 10% of the waste (by weight). The municipality bans the placement of yardwaste in landfill and has a recycling program that collects one half of all discarded metals. (a) What is the volume of waste that is discarded by the community every day (assume a waste density at the curb of 140 kg/m^3).

Solution:

First calculate the percentage of waste that is discarded (subtract yard and metal waste percentages given in the problem).

$$\text{Percent of waste discarded} = 1 - 0.15 - 0.10(0.5) = 0.80$$

Next, calculate the amount of waste generate by the population per day then use the equation for density to solve for the volume of the waste discarded every day.

$$250{,}000\ people \times \frac{1\ kg\ solid\ waste}{day - person} \times 0.8 = 200{,}000\ kg$$

$$\rho = \frac{m}{V}\ \therefore V = \frac{\rho}{V} = \frac{200{,}000\ kg/day}{140\ kg/m^3} = \boldsymbol{1430\ m^3}$$

10.3 Design and safely perform a waste characterization on the solid waste at your residence and at an office at your university or college. (a) How does your waste characterization compare with the data in Figure 10.2? (b) Which of the following pollution prevention strategies (source reduction, reuse, recycle) would you implement to reduce the discard rate?

Solution:

Students' responses will vary.

10.4 Identify one source of solid waste on your campus that could readily be reduced, one source that could be reused, and one that could be recycled. What social, economic, and environmental benefits would come from implementing a plan to deal with the three items you identified?

Solution:

Students' responses will vary.

10.5 Research the energy and water savings associated with recycling 1,000 kg office paper. Which value do you consider the most reliable of the ones you found? Justify your choice, and provide a reference for your preferred source of information.

Solution:

Students' responses will vary.

10.6 Using the values provided in Example 10.2, estimate the low moisture content and typical moisture content for the waste as a whole.

Solution:

$$\frac{dry\ mass}{total\ mass} = \frac{100 - moisture\ content\ \%}{100}$$

$$\frac{578.9}{700} = \frac{100 - low\ moisture\ content\ \%}{100} \Rightarrow \boxed{low\ moisture\ content = 17.3\%}$$

$$\frac{578.9}{1{,}024.1} = \frac{100 - typical\ moisture\ content\ \%}{100} \Rightarrow \boxed{typical\ moisture\ content = 43.5\%}$$

10.7 Waste composition has been measured for two cities. The results are summarized in Table 10.19.

.

	City 1	City 2
Wet Weight Generation Rate		
(kg/person-day)	2.0	1.8
Wet Weight Composition (%)		
Food	15	10
Paper	30	40
Yard	20	15
Other	35	35
Moisture Content of Fractions (% on wet weight basis)		
Food	80	50
Paper	10	4
Yard	80	30
Other	5	4

(a) Which city generates more paper on a dry weight basis? (b) Find the percent moisture (wet weight basis) for city 1. (c) A nearby disposal site receives all of its MSW from cities 1 and 2. The average moisture content for MSW disposed of at the site is 20percent. What fraction of the dry weight refuse comes from city 1?

Solution:

a)

$$dry\ \ paper\ \ mass\ \ for\ city\ 1 = 2\frac{kg}{person \times day} \times 30\% \times \left(\frac{100-10}{100}\right) = \boxed{0.54\frac{kg}{person \times day}\ \ of\ \ dry\ \ paper\ \ from\ city\ 1}$$

$$dry\ \ paper\ \ mass\ \ for\ city\ \ 2 = 1.8\frac{kg}{person \times day} \times 40\% \times \left(\frac{100-4}{100}\right) = \boxed{0.69\frac{kg}{person \times day}\ \ of\ \ dry\ \ paper\ \ from\ city\ \ 2}$$

City 2 produce more paper on dry basis per person.

b) Determine the dry weight production:

Type of waste	Wet weight city 1 composition	Moisture content%	Moisture%	Wet weight city 2 composition	Moisture content%	Moisture%
Food	0.15	80	12	0.1	50	5
Paper	0.3	10	3	0.4	4	1.6
Yard	0.2	80	16	0.15	30	4.5
Other	0.35	5	1.8	0.35	4	1.4
Total	100%		***32.8***	100%		12.5

c) Let X be fraction of dry weight from city 1, moisture content of city 2 refuse (MC2) = 12.5%

Fraction of total weight of city 2 = 1-X

$$\text{Moisture of mix} = \frac{moisture\ of\ city\ 1 + moisture\ of\ city\ 2}{Total\ \ fraction\ of\ city\ 1 + Total\ \ fraction\ of\ city\ 2}$$

$$0.2 = \frac{MC_1 + MC_2(1-X)}{1}$$

$$0.2 = 0.328X + 0.125(1-X) \quad \Rightarrow \quad X = 0.37$$

Determine the dry waste from each city:

$$Dry\ waste\ 1 = Fraction\ of\ city\ 1 \times (1 - MC_1) = 0.37 \times (1 - 0.328) = 0.249$$

$$Dry\ waste\ 2 = 0.63 \times (1 - 0.125) = 0.551$$

$$Fraction\ of\ dry\ weight = \frac{0.249}{0.249 + 0.551} \times 100\% = \boxed{31.1\%}$$

10.8 What is the dry weight percent composition for the following combined waste?

Component	% Composition	% Moisture (wet weight)
Paper	40	6
Yard/Food	30	60
Other	30	3

Solution:

$$Dry\ weight\ \%_{paper} = 100\% - \%moisture = 100\% - 6\% = 94\%$$

$$Dry\ weight\ \%\ of\ total\ weight_{paper} = dry\ weight\ \% \times \%\ composition = 94\% \times 40\% = 38\%$$

Component	% Composition	% Composition (g)	% Moisture (wet weight)	% Moisture (grams)	Dry weight %	Dry weight (g)	**Dry weight % of total weight**
Paper	40	0.4	6	0.02	0.94	0.38	**38**
Yard/Food	30	0.3	60	0.18	0.4	0.12	**12**
Other	30	0.3	3	0.01	0.97	0.30	**30**
Total	100	1		0.21		0.80	

10.9 The mass composition of dry paper is 43 percent carbon, 6 percent hydrogen, 44 percent oxygen, and 7 percent other. Estimate the liters of air required to burn 1 kg dry paper. Assume carbon dioxide and water are the only products of combustion of carbon, hydrogen, and oxygen. Assume a temperature of 20°C and pressure of 1 atm.

Solution:

Assume that all 7% of (other) is ash, therefore no air or O_2 is required for that.

Element	Mass g/kg of paper	MW g/mole	No. of moles/kg of paper
Carbon	430	12	35.8
Hydrogen	60	1	60
Oxygen	440	16	27.5

$$\left(35.8\ moles\ C \times \frac{mole\ O_2}{mole\ C}\right) + \left(60\ moles\ H \times \frac{\frac{1}{4}\ mole\ O_2}{mole\ H}\right) - \left(27.5\ moles\ O \times \frac{\frac{1}{2}\ mole\ O_2}{mole\ O}\right) = 37\ moles\ O_2$$

$$PV = nRT$$

$$V = 37\ moles\ O_2 \times 0.082 \frac{L - atm}{mole - K} \times \frac{293\ K}{1\ atm} = 889\ L\ O_2$$

$$889\ L\ O_2 \times \frac{1\ L\ air}{0.207\ L\ O_2} = \boxed{4,295\ L\ air}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

10.10 Estimate the oxygen demand for composting mixed garden waste (units of kg of O_2 required per kg of dry raw waste). Assume 1,000 dry kg mixed garden waste has a composition of 513 g C, 60 g H, 405 g O, and 22 g N. Assume 25 percent of the nitrogen is lost to $NH_{3(g)}$ during composting. The final C:N ratio is 9.43. The final molecular composition is $C_{11}H_{14}O_4N$.

Solution:

First determine the final amount Nitrogen available for composting
22 g N x (100-25)/100 = 16.5 g of nitrogen is available

C:N final is 9.43, so 9.43 x 16.5 = 155.6 g C final

Determine C:N ratio
C:N = 513/16.5= 31.1 , this is between 40 and 20 so there is enough N for composting.

Theoretical oxygen demand for $C_{11}H_{14}O_4N$ can be determined from:

$$C_{11}H_{14}O_4N + 11.75\,O_2 \rightarrow 11CO_2 + 5.5H_2O + NH_3$$

Use the final molar composition to get H:N and O:N ratios.
C: 12 g/mole x 11 mole = 132 g
H: 1 g/mole x 14 mole = 14 g
O: 16 g/mole x 4 mole = 64 g
N: 14 g/mole x 1 mole = 14 g

H:N final = 14/14 x 16.5 = 16.5 g H
O:N final = 64/14 x 16.5 = 75.4 g O

The carbon is lost to CO_2 via respiration by $C + O_2 \rightarrow CO_2$

The hydrogen is lost to H_2O via respiration by $H + \frac{1}{4} O_2 \rightarrow H_2O$, but some H is lost to $H \rightarrow NH_3$

The amount lost is 22 x 0.25 = 5.5 g N, or
5.5 g N x 1 mole N/14 g N x 3 mole H/1 mole N x 1 g H/1 mole H = 1.2 g H

	Initial Dry Mass	Final Dry Mass	Mass Lost by Respiration	Moles Lost	Moles O_2 Required
C	513	155.6	357.4	29.78	29.78
H	60	16.5	42.3	42.3	10.58
O	405	75.4	329.6	20.6	-10.30
N	22	16.5	Assume no N oxidation		
Total	1000				30.06

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

Convert moles O_2 to mass:
30.06 mole O_2 x 32 g O_2/1 mole O_2 x 1 kg/1000 g = $\boxed{\text{0.96 kg } O_2\text{/kg dry initial waste}}$

10.11 Waste of the composition shown in the following table is disposed of at a rate of 100,000 Mg/yr for 2 yr in one section of a landfill. Assume that half of the waste is disposed of at $time = 0.5\ yr$, and half at a time of 1.5 yr. Assume that gas production follows the first-order relationship used in Equation 10.4, and use the additional information provided in the table. How long until 90 percent of the gas will be produced in this section?

	Initial Mass (Mg)	Half-life (years)
Slowly biodegrading	10,000	10
Rapidly biodegrading	40,000	3
Non-biodegrading	50,000	infinite

Solution:

k for slowly biodegrading = 0.693/10 = 0.0693 year^{-1}
k for rapidly biodegrading = 0.693/3 = 0.231 year^{-1}

Time to 90% decay for k for slowly biodegrading = Ln(0.1)/0.0693 = $\boxed{\text{33 years}}$
Time to 90% decay for k for rapidly biodegrading = Ln(0.1)/0.231 = $\boxed{\text{10 years}}$

10.12 Assume all the waste in one section of a landfill was added at the same time. After 5 yr, the gas production rate reached its peak. After 25 yr (20 yr after the peak), the production rate had decreased to 10 percent of the peak rate. Assume first-order decay in the gas production rate after reaching its peak. Assume no gas is produced prior to the peak of 5 years. (a) What percentage of the total gas production do you predict has occurred after 25 yr? (b) How long do you predict until 99 percent of the gas has been produced?

Solution:

$$Peak\ rate = P = T \times k \times e^{-\left(k(5-t_{lag})\right)}$$

$$10\%\ Peak\ rate = 0.1P = T \times k \times e^{-\left(k(25-t_{lag})\right)} \Rightarrow P = \frac{T \times k \times e^{-\left(k(25-t_{lag})\right)}}{0.1}$$

$$T \times k \times e^{-\left(k(5-t_{lag})\right)} = \frac{T \times k \times e^{-\left(k(25-t_{lag})\right)}}{0.1}$$

$$-\left(k(5-t_{lag})\right) = -\left(k(25-t_{lag})\right) - \ln 0.1$$

$$k = 0.115\ year^{-1}$$

a) Since the production after peak follows first-order decay

$$C_t = C_o \times e^{-kt}$$

$$x \times C_o = C_o \times e^{-0.115\times 25} \quad solve\ \ for\ \ x$$

$$x = 5.65\%\ of\ \ the\ gas\ remained$$

$$so\ \boxed{94.35\%\ of\ \ the\ gas\ has\ been\ produced}$$

b) For 99% of the gas produced 1% of the gas is left

$$0.01C_o = C_o \times e^{-(0.115\times t)} \rightarrow solve\ \ for\ t$$

$$\boxed{t = 40\ yr\ until\ 99\%\ of\ \ the\ gas\ is\ \ produced}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2^{nd} *Edition*
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

10.13 Equal amounts of two types of waste are disposed into a section of a landfill. They both start producing gas at t=0, and so there is no lag time. Assume first-order decay for gas production. Each type of waste can produce 150 L CH_4/kg of waste. Waste type A produces gas with a half-life of 6 years, and waste type B produces gas with a half-life of 3 years. How long (to the nearest year) until 90% of each gas has been produced?

Solution:

The total gas produced at any time, t, is the sum of the gas produced by waste type A and waste type B,

$$\text{Tot. Cumul. Gas (t)} = \text{Cumul Gas A (t)} * \text{Cumul Gas B (t)}$$

Applying equation 10.6 twice

$$\text{Tot. Cumul. Gas (t)} = V_A * (1 - \exp(-k_At)) + V_B * (1 - \exp(-k_Bt))$$

Let x be the kg of each waste type disposed, then 150*x is the total volume produced from each type of waste, then

$$\text{Tot. Cumul. Gas (t)} = 150x*(1 - \exp(-k_At)) + 150x * (1 - \exp(-k_Bt))$$

At the unknown time, T, the total cumul. Gas is 90% of the total. The total is eventually 150x+150x = 300x, so

$$0.9 * 300x = 150x*(1 - \exp(-k_AT)) + 150x * (1 - \exp(-k_BT))$$

We can use equation 10.7 to use half-lives instead of k values:

$$270 = 150*(1 - \exp(T*(0.693/6)) + 150*(1 - \exp(T*(0.693/3))$$

Or

$$0.2 = \exp(-T*0.693/6) + \exp(-T*0.693/3)$$

There is no closed-form solution. This can be solved easily by iteration. To the nearest year, T = **15 years**.

10.14 Determine whether your local (or regional) landfill produces energy from methane gas. If so, what is the mass of solid-waste disposed at the landfill on an annual basis, and what is the amount of CH_4 generated? Relate these numbers to a calculation you can perform with appropriate assumptions.

Solution:

Students' responses will vary.

10.15 (a) Calculate the volume of methane produced (m^3/year) due to landfilling for the years 1970 and 2010. Assuming the landfilled municipal solid waste produces gas in a similar fashion between the two years. The U.S. Census Bureau reports the U.S. population was 203,392,031 in 1970 and was 308,745,531 in 2010. Use the landfilling and composting rates provided in Table 10.2. Assume the three waste components that produce methane did not change over time and are food wastes (15 percent of total), mixed paper (30 percent of total), and yard wastes (15 percent of total). Assume that 60 percent of the food and paper wastes and 40 percent of the yard trimmings will decompose if placed in a landfill. (b) Determine the energy (in MW) of landfill gas produced in 1970 and 2010. Assume 1 MW of gas is produced for every 270 m^3/hr of CH_4 produced at the landfill

Solution: Recalculate table 10.15 in example 10.5 given the different waste components.

	Wet weight (g)	Moisture Content (%)	Dry Weight (g)	Carbon (% by dry mass)	Total Carbon (g)	Hydrogen (% by dry mass)	Total Hydrogen (g)	Oxygen (% by dry mass)	Total Oxygen (g)	N (% by dry mass)	Total N (g)
Food wastes	150	70	45	48.0	21.6	6.4	2.9	37.6	16.9	2.6	1.2
Paper (mixed)	300	10	270	43.4	117.2	5.8	15.7	44.3	119.6	0.3	0.8
Yard Wastes	150	60	60	46.0	27.6	6.0	3.6	38.0	22.8	3.4	2.0
Other	400	0									
Total	1000										

	Degradation rates (%)	Degraded Carbon (g)	Degraded Hydrogen (g)	Degraded Oxygen (g)	Degraded Nitrogen (g)	Decgraded Carbon (moles)	Degraded Hydrogen (moles)	Degraded Oxygen (moles)	Degraded Nitrogen (moles)
Food wastes	60	13.0	1.7	10.2	0.7	1.08	1.71	0.63	0.05
Paper (mixed)	60	70.3	9.4	71.8	0.5	5.85	9.32	4.49	0.03
Yard Wastes	40	11.0	1.4	9.1	0.8	0.92	1.43	0.57	0.06
Other		0							
Total						7.85	12.46	5.69	0.14

Calculate the moles of methane produced using equation 10.3 $(4a+b-2c-3d)/8$ where a=7.85, b=12.46, c=5.69, and d=0.14.

$$\frac{4(7.85) + 12.46 - 2(5.69) - 3(0.14)}{8} = 4.01\, moles$$

Using the ideal gas law, at 0^oC (273^oK), there are 22.4 L gas per mole or 0.0224 m^3 of gas per mole of gas. The volume of methane produced per kg waste is then:

$$4.01\, moles\, CH_4 \times 0.0224 \frac{m^3}{mol} = 0.0898 \frac{m^3}{kg}$$

From Table 10.2, the U.S. landfilling rate in 2010 was 0.40 Mg (or 400 kg) per person per year. Therefore, the gas production rate is:

$$0.0898 \frac{m^3}{kg} \times 420 \frac{kg}{person - yr} = 37.7 \frac{m^3 methane}{person - yr}$$

$$V_{CH_4\, 1970} = 37.7 \frac{m^3 methane}{person - yr} \times 203{,}392{,}031 = \boldsymbol{7.67 \times 10^9 \frac{m^3 CH_4}{yr}}$$

$$0.0898 \frac{m^3}{kg} \times 400 \frac{kg}{person - yr} = 35.9 \frac{m^3 methane}{person - yr}$$

$$V_{CH_4\, 2010} = 35.9 \frac{m^3 methane}{person - yr} \times 308{,}745{,}531 = \boldsymbol{1.11 \times 10^{10} \frac{m^3 CH_4}{yr}}$$

b. Use unit conversions given in the problem to convert the volume of methane produced in part a to electricity.

$$7.67 \times 10^9 \frac{m^3 CH_4}{yr} \times \frac{1\, yr}{365\, day} \times \frac{1\, day}{24\, hr} \times \frac{1\, MW}{270 \frac{m^3}{hr}} = \boldsymbol{3243\, MW}$$

$$1.11 \times 10^{10} \frac{m^3 CH_4}{yr} \times \frac{1\, yr}{365\, day} \times \frac{1\, day}{24\, hr} \times \frac{1\, MW}{270 \frac{m^3}{hr}} = \boldsymbol{4693\, MW}$$

10.17 Return to Example 10.6 in this chapter. The overall greenhouse gas effect of a landfill is sensitive to a number of parameters and assumptions. In Example 10.6, an assumption of 80% gas recovery is used and leads to an overall greenhouse gas benefit of 0. 10 metric tons CO_2e. Leaving all parameters and assumptions in place used to solve Example 10.6, what is the percentage of landfill gas collected that provides an overall benefit of reducing greenhouse gas emissions.

Let f = fraction of gas collected

The greenhouse gas effect from pathways 1, 2, and 5 will be found separately and then summed.

For pathway 1, the direct methane emission impact, start with the methane produced by the waste of one person over one year. This was found to be 38.7 m^3 at 0°C. This is reduced by the methane collected (f) and by the methane oxidised in the soil (20%) to give the methane emitted (after conversion to CO2 equivalents)

38.7 m3 CH4 produced * (1 - f) * (1 – 0.2) * (1000 L/1 m3) * (1 mole CH4/22.4 L CH4) * (16 g CH4/1 mole CH4) * (1 Mg/10^6 g) * (25 Mg CO_2 e/Mg CH4)= 0.553*(1-f) Mg CO_2e emitted

For pathway 2, subtract the mass of degraded carbon from the total mass of biogenic carbon to find the residual, non-degraded biogenic carbon.

(21.6 – 13.0) + (117.2 – 70.3) + (46.0 – 18.4) = 83.1 g sequestered carbon / kg of landfilled waste

This is then converted to CO2e by multiplying by the waste to landfill per person per year, and then converting from mass of carbon to mass of CO2equivalents

83.1 g C/kg landfilled * (400 kg landfilled) * (44 g CO_2e/12 g C) * (1 Mg/10^6 g) = 0.122 t CO_2e

For pathway 5, we start with the methane produced, multiply it by the collection efficiency to give the methane used for energy, and then apply the factor given for the CO2e per volume of methane

38.7 m3 CH4 produced* (f m3 CH4 combusted/1.0 m3 produced) * (0.003 Mg CO2e/m3 CH4) = 0.116*f Mg CO2e

Pathway 1 is a negative greenhouse gas impact while pathways 2 and 5 are positive. Summing these, gives a net effect per person per year of

Overall Effect =
$-0.553*(1-f) + 0.122 + 0.116*f = 0$

$f = (0.553 - 0.122)/(0.553 + 0.116)$

$\boldsymbol{f = 0.64}$

$\therefore$ landfill gas collected that provides an overall benefit of reducing greenhouse gas emissions $= \mathbf{64}\%$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

10.18 What percentage reduction in yard waste would be required to reduce the NH_4^+ released in landfill leachate by 1 kg per Mg of MSW? Assume only yard waste contributes to NH_4^+ in leachate. Assume the waste composition provided in Figure 10.2 and Table 10.5. Assume all N in yard waste is eventually released as NH_4^+.

Solution:

Type of waste	% of the waste	Moisture%	N% dry mass	N% of wet	%N of MSW
Yard trimmings	13.1	60	3.4	1.36	0.178

Reduction in 1 kg NH_4 requires a reduction of 14/18 kg of N; 0.178% of the waste weight is N

$$0.00178\frac{kg\ N_{yard\ waste}}{kg\ MSW}\times Mg\ MSW\times\frac{1000\ kg}{Mg}=1.78\ kg\ N\ \ from\ yard\ waste$$

$$1-\left(\frac{1.78-\frac{14}{18}}{1.78}\right)=\boxed{43.7\%\ reduction\ is\ required}$$

10.19 Daily cells for a landfill are operated so that the following conditions are maintained: thickness of daily cover = 0.2 m; slope (horizontal:vertical) = 3:1; working face for refuse = 30 m; height of refuse = 3 m; and volume of daily refuse = 1,800 m^3/day. The landfill is interested in reducing requirements for daily cover soil over its 20 yr life and is considering three options. Which option would be the best? Why?

Option 1: Increase height of refuse to 4 m.
Option 2: Increase daily refuse volume by 2000 m^3/day.
Option 3: Decrease working face to 20 m.

Solution:

The initial daily length is given by:

$V_r = H \times L \times W$
1,800 m^3/day = 3 m x L x 30 m
L = 20 m
$V_s/V_r = [(1 + 0.2/3)(1 + (3 \times 0.2)/20)(1 + (3 \times 0.2)/30)] - 1$
$= 0.121$

The other options will need to have a lower V_s/V_r to be better.

Option 1:

V_r = 1,800 m^3/day = 4 m x L x 30 m
L = 15 m
$\underline{V_s/V_r = 0.114}$ (better than current situation)

Option 2:

V_r = 2,000 m^3/day = 3 m x L x 30 m
L = 22.2 m
$\underline{V_s/V_r = 0.117}$ (better, but not as good as option 1)

Option 3:

V_r = 1,800 m^3/day = 3 m x L x 20 m
L = 30 m
$\underline{V_s/V_r = 0.121}$ (same as current situation)

<u>Option 1</u>, because the same 0.2 layer will be used to cover 4 m instead of 3 m and that gives 25% more refuse to cover ratio.

10.20 Estimate the landfill area required, in hectares, given the following specifications: daily cover thickness = 0.2 m; total final cover = 1.0 m (in addition to daily cover); height above ground before biodecay and settlement = 10 m; lift height = 3 to 5 m; depth below ground level that waste can begin to be placed = 5 m; landfill site area is square; MSW generation rate = 100,000 Mg/yr; side slopes at 3 horizontal:1 vertical for daily cells and external slopes; working face width = 8 m; open for disposal 360 days per year; 30 yr life; and in-place density of fresh $MSW = 700\ \ kg/m^3$.

Solution:

First determine the daily volume.

$$100{,}000\frac{Mg}{year}\times\frac{yr}{360day}=278\frac{Mg}{day}$$

$$278\frac{Mg}{day}\times\frac{1{,}000\ kg}{Mg}\times\frac{m^3}{700\ kg}=397\frac{m^3}{day}\ \text{the daily volume of refuse}$$

Total H = height + depth below ground - total final cover = 10 m + 5 m – 1 m = 14 m

Layer depth = (14 – 2 x 0.2)/3 = 4.53 m

$$V_{daily\ cell} = Vr\left(1+T/H\right)\left(1+G\times T/L\right)\left(1+G\times T/W\right)$$

$$V_{daily\ Cell} = 397\ m^3 \times \left(1+\frac{0.2}{4.53}\right)\times\left(1+\frac{3\times0.2}{L}\right)\times\left(1+\frac{3\times0.2}{8}\right)=$$

$$V_{daily\ Cell} = 445.62+\frac{267.4}{L}$$

$$Total\ landfill\ volume\ \ for\ 30\ years = (445.62+\frac{267.4}{L})\times365\times30 = 4{,}879{,}539+\frac{2{,}928{,}030}{L}$$

$$V = \frac{h}{3}\times\left\{[L_1\times W_1+(L_1-2Gh)(W_1-2Gh)]+\sqrt{L_1\times W_1\times(L_1-2Gh)(W_1-2Gh)}\right\} \qquad : L_1 = W_1$$

$$4{,}879{,}539+\frac{2{,}928{,}030}{L} = \frac{14}{3}\times\left(\left(L^2+(L-2\times3\times14)^2\right)+\sqrt{L^2\times(L-2\times3\times14)^2}\right)$$

$$4{,}879{,}539+\frac{2{,}928{,}030}{L} = \frac{14}{3}\times\left(\left(2\ L^2-168\ L+7{,}056\right)+L^2-84L\right)$$

$$4{,}879{,}539+\frac{2{,}928{,}030}{L} = 14\ L^2-1{,}176\ L+32{,}928$$

$$0 = 14\ L^3-1{,}176\ L^2-4{,}879{,}539\ L-2{,}928{,}030 \quad solve\ for\ L$$

$$L = 634.14\ m$$

$$Since\ W = L, the\ area = 634.14\ m\times634.14\ m = \boxed{402{,}137\ m^2}$$

10.21 You need to budget for a new transfer station in your district. A similar transfer station cost \$1 million, but that station was 50 percent larger than yours. How much money should you budget so that your local government will have enough money to pay for the new transfer station? Assume that the economy of scale factor for transfer stations is 0.9.

Solution:

A land fill 50% bigger has 90% of per ton price of waste.

$$\textit{Cost of the smaller station} = \frac{1{,}000{,}000}{0.9 \times 150\%} = \boxed{\$740{,}740}$$

10.22 Go the World Health Organization Web site (www.who.org). Learn about a disease that is transmitted through improper disposal of solid waste. What is the extent of the disease on a global level?

Solution:

Students' responses will vary.

10.23 Identify an engineering professional society that you could join as a student or after graduation that deals with issues of solid-waste management. What are the dues for joining this group? What benefits would you receive as a member while working in practice?

Solution:

Students' responses will vary.

Professional societies that deal with issues of solid-waste management that students and engineers may join, their dues, and benefits are listed in the table below:

Professional Association	**Dues**	**Benefits of joining**
International Solid Waste Management Association (ISWMA)	Student membership: 50 euros Online member: 60 euros Regular member: 200 euros	Exposure to the global waste management sector, networking opportunities, conferences, access to publications
Solid Waste Association of North America (SWANA)	Public sector: $195 Private sector: $364 Student: $62 Retired member: $72	Conferences, certifications, publications, technical training courses, networking, leadership opportunities
Air and Waste Management Association (AWMA)	Individual: $195 Young Professional: $98 Electronic: $25-$110 Student: $35	Networking, technical resources, professional training and development, online access to publications, career center, annual conference discount

10.24 Determine the number of students currently enrolled full time at your university or college. Then, using the information provided in Figure 10.2 and Tables 10.2 and 10.5, determine the energy content associated with a day's worth of solid waste that would be generated by this population.

Solution:

Students' responses will vary based on the number of students enrolled at their university or college. An example for the University of South Florida (USF) is provided below:

Around 47,000 students are enrolled at USF. According to Table 10.2 the waste generated per person per year in 2010 was 0.74 Mg.

$$\begin{aligned}&\mathit{Waste\ generated\ by\ USF\ student\ population}\\ &= 47{,}000\ \mathit{students} \times \frac{0.74\ Mg}{\mathit{student} - \mathit{year}} \times \frac{1\ \mathit{year}}{365\ \mathit{days}} \times \frac{1{,}000 kg}{1\ Mg}\\ &= 95{,}300\ kg/day\end{aligned}$$

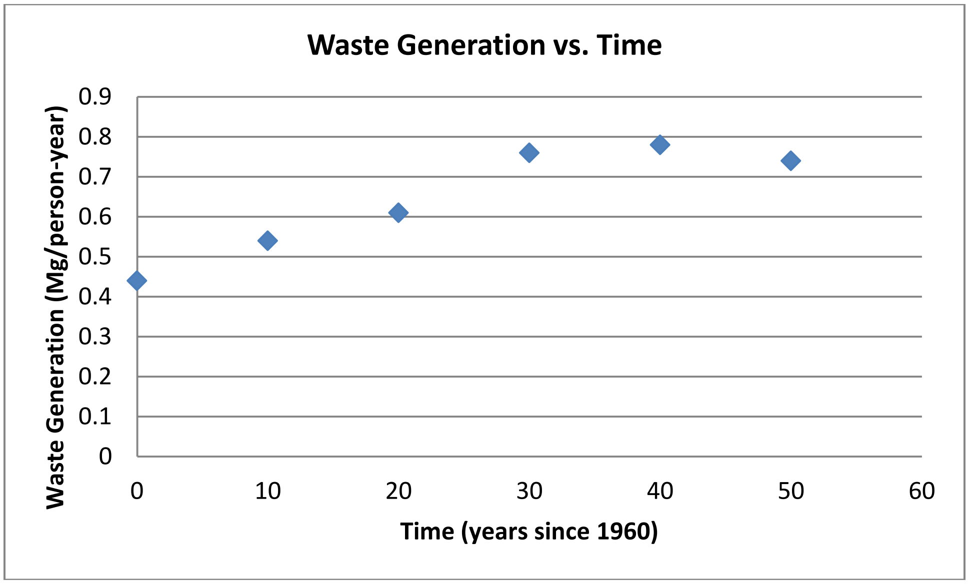
To characterize this waste, use the percentages in Figure 10.2 and then the energy values (MJ/kg) from Table 10.5 to calculate the energy content associated with a day's worth of solid waste generated by this population. Calculations are shown in the table below. Overall, a days worth of solid waste from students at USF generate **1,204 GJ** of energy.

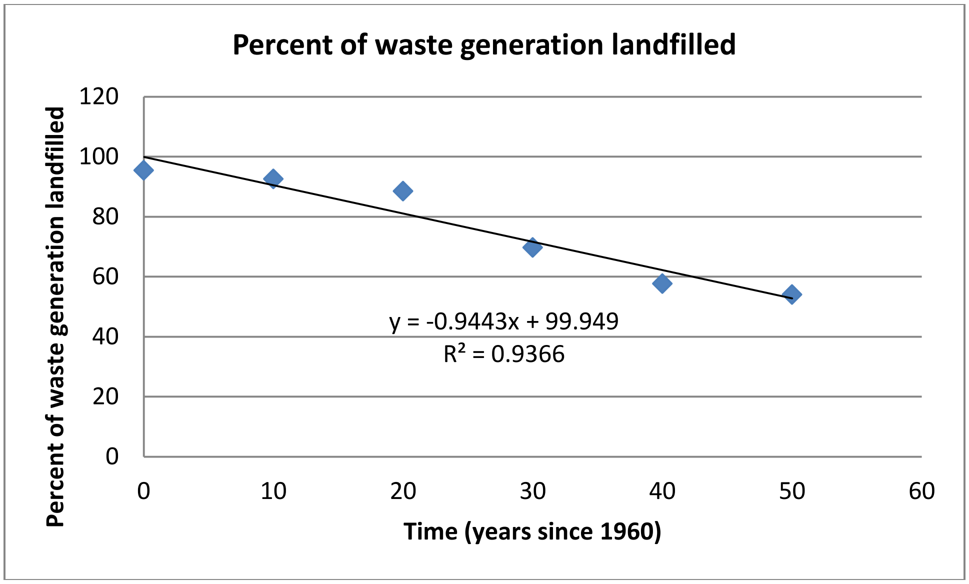
Waste	**Percentage of waste stream (table 10.2)**	**Waste amount (kg)**	**Energy Value (MJ/kg)**	**Energy Associated with waste (MJ)**
Paper and cardboard	28.5%	27,157	15.8	429,080
Glass	4.6%	4,383	0.2	877
Metals	9.0%	8,576	0.6	5,146
Plastics	12.4%	11,816	32.7	386,372
Rubber and leather	3.1%	2,954	21.4	63,066
Textiles	5.3%	5,050	18.5	93,430
Wood	6.4%	6,098	15.4	93,916
Food scraps	13.9%	13,245	4.2	55,629
Yard trimmings	13.4%	12,769	6.0	76,611
Other	3.5%	3,335		
TOTAL	**100%**	**95,383**		**1,204,126**

10.25 Assume the population of the United States will reach 420,000,000 in 2050. Estimate the annual mass of municipal solid waste that will be generated in the United States in 2050 and the annual amount that will require landfilling (both answers in metric tons). Use information provided in Table 10.2. Justify your assumptions on changes in solid-waste generation per person and landfill disposal per person from now until 2050. HINT: Graph waste generation versus time and also the percent of waste land filled versus. time and observe the trends. Make your own assumptions (e.g., waste generation will be the same in 2050 as 2010; waste generation will decrease back to 1960 levels; and/or the percent of landfill waste will decrease as recycling becomes more mainstream or it will remain the same).

Solution:

Graph table 10.2 as pictured below:





Students answers may vary but two potential answers may be:

It appears that the waste generated over time is following somewhat of a bell curve. If we continue this trend we can assume that by 2050 the waste generation per person reverts back to 1960 levels and the percent of waste generation landfilled follows the negative linear decline to 25%.

In the worst case scenario we may assume that the waste generation per person and percent of waste generation landfill remains the same in 2050 as 2010 (0.74 Mg per person per year and 54% is landfilled).

10.26 Non legume vegetable wastes have a moisture content of 80% and are 4% N (on a dry mass basis). The vegetable wastes are to be composted with readily available sawdust. The sawdust has a moisture content of 50% and is 0.1% N (on a dry mass basis) The desired C:N for the mixture is 20. The C:N ratio for vegetable wastes is 11, and the C:N ratio for sawdust is 500. Determine the kg of sawdust required per kilogram of vegetable waste that results in an initial C:N ratio of 20.

Solution:

Assume 1 kg of non legume vegetable waste dry mass. Let X = kg of sawdust on a dry mass basis. The mass of carbon and nitrogen obtained from each material in the mixture is given by:

Dry mass nitrogen from vegetable waste = 1 kg × (1 – 0.8) × 0.040 = 0.008 kg
Dry mass carbon from vegetable waste = 1 kg × (1 – 0.8) × 0.040 × 11 = 0.088 kg
Dry mass nitrogen from sawdust = $X \times (1 - 0.5) \times 0.001 = 0.0005 \times X$
Dry mass carbon from sawdust = $X \times (1 - 0.5) \times 0.001 \times 500 = 0.25 \times X$

The overall C:N ratio is given by

$$20 = \frac{(\text{mass carbon from vegetable waste} + \text{ mass carbon from grass clippings})}{\left(\text{mass nitrogen from vegetable waste } + \text{ mass nitrogen from grass clippings}\right)}$$

$$20 = \frac{(0.088 + 0.25 \times X)}{\left(0.008 + 0.0005 \times X\right)}, \quad \textit{Solve for } X$$

$$\boxed{X = 0.30\ kg}$$

Thus, for every 1 kg of vegetable wastes, we must add 0.30 kg of sawdust to obtain an optimal C:N ratio of 20. The vegetable waste is a better source of nitrogen, and the sawdust provides a better source of carbon.

10.27 A mixture of organic materials is to be composted. The mixture begins with 40% moisture and 80% of the solids are VS. Assume that 50% of the VS are lost through composting along with 70% of the moisture. What is the moisture content of the final compost?

Solution:

Assume 100 g of initial material. That is composed of:
40 g moisture and 60 g solids
Of the solids, 80% are volatile, so
12 g fixed solids, and 48 g volatile solids

Of the 40 g of moisture, 70% is lost, or 28 g, and so 12 g are left.

Of the fixed solids, none are lost so all 12 g remain.

Of the 48 g of volatile solids, 50% are lost, or 24 g, and so 24 g are left.

A total of 48 g remain, of which 12 g are moisture, so the **moisture content is 25%.**

	Initial (g/100 initial g)	Lost (g /100 initial g)	Remaining (g/100 initial g)	Remaining (%)
Moisture	40	28	12	25%
Fixed Solids	12	0	12	25%
Volatile Solids	48	24	24	50%

10.28 EPA provides five methods of composting at this web site: http://www.epa.gov/compost/types.htm Develop a table that lists the five methods in one column, and brief description of the method in a second column.

Solution:

Type	**Description**
Backyard or Onsite Composting	This composting can be implemented right outside your home, apartment, community or business for food scraps and yard trimmings. Little space or equipment is required but education is critical.
Vermicomposting	This composting uses red worms or garden filed worms to compost typical compost items (feed scraps, paper, plants, etc.) in bins. This type of compost is ideal for and often utilized at apartments, small offices, and schools.
Aerated (Turned) Windrow Composting	This larger scale (e.g. communities and businesses) form of composting is laid out in rows of long piles or "windrows". These winrows must be aerated mechanically or manual to aerate them. There are ideal dimensions for these piles. Different types of waste can be composted using this method such as grease, liquids, and animal byproducts in addition to the typical yard wastes and food scraps.
Aerated Static Pile Composting	This compost is formed into large piles with layers of bulking agents such as wood chips and shredded newspaper for better air circulation. This method is used for more homogenous mixes of organic waste such as food scraps, paper products, and yard trimmings often from larger communities, landscapers or farms. Air blowers may be required to better aerate the piles. This compost can be read in as little as 3 months.
In-Vessel Composting	In this method of composting, organic materials are stored in large vessels such as drums, silos, or concrete lined trenches. This uses less space than winrow composting. A diversity of wastes can be composted in these vessels including meat and animal manure. Some of these vessels can fit into restaurant or school kitchens or larger scale containers can be used by food processing plants.

10.29 Estimate the total landfill costs (in 2003 Euros) for a situation where you must landfill (a) 75,000 Mg of solid waste per year and (b) 1,000,000 Mg of solid waste per year.

Solution:

Use equation 10.11 to calculate the landfill costs.

$$total\ landfill\ cost = 5{,}040 \times X^{-0.3}$$

a.

$$total\ landfill\ cost = 5{,}040 \times X^{-0.3} = 5{,}040 \times 75{,}000^{-0.3} = 174\ euros/Mg$$

$$total\ cost = 174\frac{euros}{Mg} \times 75{,}000Mg = \mathbf{13,030,000}\ \boldsymbol{euros}$$

b.

$$total\ landfill\ cost = 5{,}040 \times X^{-0.3} = 5{,}040 \times 1{,}000{,}000^{-0.3} = 79.9\ euros/Mg$$

$$total\ cost = 79.9\frac{euros}{Mg} \times 1{,}000{,}000\ Mg = \mathbf{79,880,000}\ \boldsymbol{euros}$$

Chapter 11. Air Resources Engineering

11.1 Carbon monoxide (CO) is measured to have a concentration of 103 µg/m^3. What is the concentration in (a) ppm$_v$, (b) ppb$_v$, and, (c) percent by volume? Assume a temperature of 25°C and pressure of 1 atm.

Solution:

Refer to example 11.2 for this problem. Use equation 2.6.

a.

$$PV = \ nRT$$

$$\frac{n}{V} = \frac{P}{RT}$$

$$103\,\frac{\mu g}{m^3} \times \frac{1\ g}{10^6 \mu g} \times \frac{1\ mole\ CO}{28\ g\ CO} = \frac{3.68 \times 10^{-6} mole\ CO}{m^3 air} \times \frac{RT}{P}$$

$$= \frac{3.68 * 10^{-6} mole\ CO}{m^3 air} \times \frac{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(25 + 273K)}{1\ atm}$$

$$= \frac{8.99 * 10^{-8} m^3 CO}{m^3 air\ solution} = \mathbf{0.0899} = \boldsymbol{ppm_v}$$

b.

$$\frac{8.99 \times 10^{-8} m^3 CO}{m^3 air\ solution} = \frac{89.9\ m^3 CO}{10^9 m^3 air\ solution} = \mathbf{89.9}\ \boldsymbol{ppb_v}$$

c. Use equation 2.5

$$\text{ppm}_\text{v} = \frac{V_i}{V_\text{total}} \times 10^6$$

$$ppm_v = \ \mathbf{0.0899} \times \mathbf{10^6} \therefore \frac{V_i}{V_{total}} = \mathbf{0.0899} = \mathbf{8.99}\%$$

11.2 If the atmospheric mass concentrations of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are 90 and 120 μg/m^3, respectively, what is the NO_x concentration in ppb$_v$? Assume a temperature of 30ºC and pressure of 1 atmosphere.

Solution:

Refer to example 11.2 for this problem. Use equation 2.6.

$$PV = \ nRT$$

$$\frac{n}{V} = \frac{P}{RT}$$

$$90\,\frac{\mu g}{m^3} \times \frac{1\ g}{10^6 \mu g} \times \frac{1\ mole\ NO}{30.01\ g\ CO} = \frac{3.0 \times 10^{-6} mole\ NO}{m^3 air} \times \frac{RT}{P}$$

$$= \frac{3.0 * 10^{-6} mole\ NO}{m^3 air} \times \frac{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(303\ K)}{1\ atm}$$

$$= \frac{7.5 * 10^{-8} m^3 CO}{m^3 air\ solution} = \frac{75.0\ m^3 CO}{10^9 m^3 air\ solution} = \boldsymbol{75\ ppb_v\ NO}$$

$$120\,\frac{\mu g}{m^3} \times \frac{1\ g}{10^6 \mu g} \times \frac{1\ mole\ NO_2}{46.01\ g\ CO} = \frac{2.6 \times 10^{-6} mole\ NO_2}{m^3 air} \times \frac{RT}{P}$$

$$= \frac{2.6 * 10^{-6} mole\ NO_2}{m^3 air} \times \frac{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(303\ K)}{1\ atm}$$

$$= \frac{6.5 * 10^{-8} m^3 NO_2}{m^3 air\ solution} = \frac{65.0\ m^3 NO_2}{10^9 m^3 air\ solution} = \boldsymbol{65\ ppb_v\ NO_2}$$

11.3 If the mass concentration of particulate matter is 12,500 μg/m^3, report this concentration as the number concentration (# particles/cm^3). Assume spherical particles of 0.5 μm diameter with density of liquid water (1 g/cm^3).

Solution:

Use unit conversions from what is given in the problem.

$$12{,}500\,\frac{\mu g}{m^3} \times \frac{1\ g}{10^6 \mu g} \times \frac{1}{1\,\frac{g}{cm^3}} \times \frac{(10{,}000\mu m)^3}{(1\ cm)^3} \times \frac{\#\, particle}{\frac{4}{3}\pi\left(\frac{0.5\mu m}{2}\right)^3}$$

$$= 1.9 \times 10^{11}\,\frac{particles}{m^3} \times \frac{1\ m^3}{(100cm)^3} = \boldsymbol{190,000\ particles/cm^3}$$

11.4 Formaldehyde is commonly found in the indoor air of improperly designed and constructed buildings. If the concentration of formaldehyde in a home is 1.2 ppm_v and the inside volume is 600 m^3, what mass (in grams) of formaldehyde vapor is inside the home? Assume T = 298 K and P = 1 atm. The molecular weight of formaldehyde is 30.

Solution:

Follow example 2.4 and use equation 2.5.

$$\text{ppm}_\text{v} = \frac{V_i}{V_\text{total}} \times 10^6$$

$$V_{formaldehyde} \times 10^{-6} = ppm_v \times V_{total} \times 10^{-6} = 1.2\, ppm_v \times\ 600\, m^3$$

$$= .00072\, ppm_v formaldehyde$$

$$720\, ppm_v formaldehyde \times \frac{P}{RT}$$

$$= \frac{720 * 10^{-6} m^3 form}{m^3 air\ solution} \times \frac{1\, atm}{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(298\, K)}$$

$$= \frac{0.0294\, mol\ form}{m^3 air\ solution} \times \frac{30\ g\ form}{mole\ form} = \mathbf{0.883\ g}$$

11.5 The National Ambient Air Quality Standard (NAAQS) for sulfur dioxide (SO_2) is 0.14 ppm_v (24-hr average). (a) What is the concentration in μg/m^3 assuming an air temperature of 25°C? (b) What is the concentration in moles SO_2 per 10^6 moles of air?

Solution:

a. Refer to example 11.2 for this problem. Use equation 2.6.

$$PV = nRT$$

$$\frac{n}{V} = \frac{P}{RT}$$

$$0.14\ ppm_v\ SO_2 \times \frac{P}{RT} = \frac{0.14\ m^3 SO_2}{10^6 m^3 air\ solution} \times \frac{1\ atm}{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(298\ K)}$$

$$= \frac{5.7 \times 10^{-6}\ mol\ SO_2}{m^3 air\ solution} \times \frac{64.07\ g\ SO_2}{mole\ SO_2} \times \frac{10^6 \mu g}{g} = \boldsymbol{367\ \frac{\mu g}{m^3}}$$

b. Use equation 2.8

$$\text{ppm}_\text{v} = \frac{\text{moles}\, i}{\text{moles total}} \times 10^6$$

$$\frac{moles\ i}{moles\ total} = \frac{ppm_v}{10^6} = \boldsymbol{\frac{0.14\ moles\ SO_2}{10^6 moles\ air}}$$

11.6 Table 11.5 provided information that suggested “clean” air might have a sulfur dioxide (SO_2) concentration of < 30 ppb_v , while polluted air might have a concentration of 1 ppm_v. Convert these two concentrations to $\mu g/m^3$. Assume a temperature of 298 K. (note the difference units of concentrations, ppm_v versus ppb_v).

Solution:

Refer to example 11.2 for this problem. Use equation 2.6.

$$PV = nRT$$

$$\frac{n}{V} = \frac{P}{RT}$$

$$30\ ppb_v\ SO_2 \times \frac{P}{RT} = \frac{30\ m^3 SO_2}{10^9 m^3 air\ solution} \times \frac{1\ atm}{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(298\ K)}$$
$$= \frac{1.2 \times 10^{-6}\ mol\ SO_2}{m^3 air\ solution} \times \frac{64.07\ g\ SO_2}{mole\ SO_2} \times \frac{10^6 \mu g}{g} = \mathbf{79}\ \frac{\boldsymbol{\mu g}}{\mathbf{m^3\ air}}$$

$$1\ ppm_v\ SO_2 \times \frac{P}{RT} = \frac{1\ m^3 SO_2}{10^6 m^3 air\ solution} \times \frac{1\ atm}{\left(8.205 \times 10^{-5} \frac{m^3 - atm}{mol\ K}\right)(298\ K)}$$
$$= \frac{4.1 \times 10^{-5}\ mol\ SO_2}{m^3 air\ solution} \times \frac{64.07\ g\ SO_2}{mole\ SO_2} \times \frac{10^6 \mu g}{g} = \mathbf{2620}\ \frac{\boldsymbol{\mu g}}{\mathbf{m^3 air}}$$

11.7 Carbon monoxide (CO) affects the oxygen-carrying capacity of your lungs. Exposure to 50 ppm$_v$ CO for 90 minutes has been found to impair one's ability to discriminate stopping distance; therefore, motorists in heavily polluted areas may be more prone to accidents. Are motorists at a greater risk of accidents if the CO concentration is 65 mg/m^3? Assume a temperature of 298 K.

Solution:

Refer to example 11.2 for this problem. Use equation 2.6.

$$PV = nRT$$

$$\frac{n}{V} = \frac{P}{RT}$$

$$65\,\frac{\mu g}{m^3} \times \frac{1\ g}{10^6 \mu g} \times \frac{1\ mole\ CO}{30.01\ g\ CO} = \frac{2.3{\times}10^{-6} mole\ CO}{m^3 air} \times \frac{RT}{P} =$$

$$\frac{2.3{*}10^{-6} mole\ CO}{m^3 air} \times \frac{\left(8.205{\times}10^{-5}\frac{m^3-atm}{mol\ K}\right)(298\ K)}{1\ atm} = \frac{5.7{*}10^{-8} m^3 CO}{m^3 air\ solution} = \frac{0.0567\ m^3 CO}{10^6 m^3 air\ solution} =$$

$$0.0567\ ppm_v\ CO$$

$$0.0567\ ppm_v\ CO < 50 ppm_v\ CO\ \therefore \boldsymbol{No}, motorists\ are\ not\ at\ greater\ risk$$

11.8 Diesel engines emit very fine soot particles. In the atmosphere, these soot particles often agglomerate with other particles as they "age." Assume the agglomerated soot particles are initially suspended at a height of 2.2 m. They are spherical (diameter = 0.5 μm) and have a density of 1.1 g/cm^3. (a) Calculate the terminal settling velocity of the soot particles. (b) How many hours will the soot particles remain suspended before settling by gravity to the ground? The density of air is 1.2 kg/m^3 and its fluid viscosity is 1.72×10^{-4} g/cm-sec.

Solution:

Use the equation for Stoke's law (4.56) to solve this problem.

a.

$$v_s = \frac{g(\rho_P - \rho_f)}{18\mu} D_P^2$$

$$v_s = \frac{9.81\,\frac{m}{s^2} \times \frac{100\ cm}{1\ m} \times (1.1\,\frac{g}{cm^3} - 0.0012\,\frac{g}{cm^3})}{18 \times 1.72 \times 10^{-4}\,\frac{g}{cm - sec}} \times \left(0.5\mu m \times \frac{1\ m}{10^6 \mu m} \times \frac{100cm}{1\ m}\right)^2$$

$$= \mathbf{0.00087\,\frac{cm}{s}}$$

b. Velocity is equal to distance over time. Rearrange to solve for time.

$$v = \frac{D}{t} \therefore t = \frac{D}{v} = \frac{2.2\ m \times \frac{100\ cm}{1\ m}}{0.00087\,\frac{cm}{s}} \times \frac{1\ min}{60\ s} \times \frac{1\ hr}{60\ min} = \mathbf{70\ hr}$$

11.9 This problem allows you to think about how exposure impacts the concentration of air pollutants you are exposed to. (a) Maintain a diary for one full day and record all the locations you visit. Include the times of entry and exit for each location. Also record any interesting air quality information for each location. Calculate the percentage of time spent in each type of location. Summarize the data in a table. (b) In which location did you spend the most amount of time? The least? (c) Calculate the 24-hr time integrated average *exposure concentration* (units of µg/m^3) to airborne particles based on your recorded activity patterns, using the average airborne PM_{10} concentration for different locations provided below.

Location	**Average Airborne PM_{10} Concentration (µg/m^3)**
Home	90
Office-Factory	40
Bar-Restaurant	200
Other Indoor	20
In a Vehicle	45
Outdoors	35

(d) Now add a 35 µg/m^3 "proximity effect" to one of your locations above that we will assume is from exposure to cigarette smoking at that location. How does this change your 24-hr time integrated average *exposure concentration* (units of µg/m^3) to airborne particles?

Solution:

Students' answers may vary.

11.10 (a) Define NAAQS and (b) identify the NAAQS pollutants.

Solution:

NAAQS is described in section 11.4.

a. NAAQS- **National Ambient Air Quality Standards (NAAQS).** Major regulatory program created by the Clean Air Act. Air quality standard have been set at the National level for Ambient Air or NAAQs.

b. NAAQs are set for the six criteria air pollutants: **particular matter (PM_{10}, $PM_{2.5}$), Carbon Monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), Ozone (O_3), and Lead (Pb).**

11.11 On January 12, 2013 the AQI in Beijing (China) the AQI was determined to be 775. In contrast, on January 11' 2013, Salt Lake City (Utah) has a reported AQI of 142 compared to a value of 67 in San Francisco's and a value of 23 in Las Vegas. Develop a table with three columns. List the four cities, the AQI reported above, and the third column should provide the level of health concern related to an AQI for general and sensitive populations.

Solution:

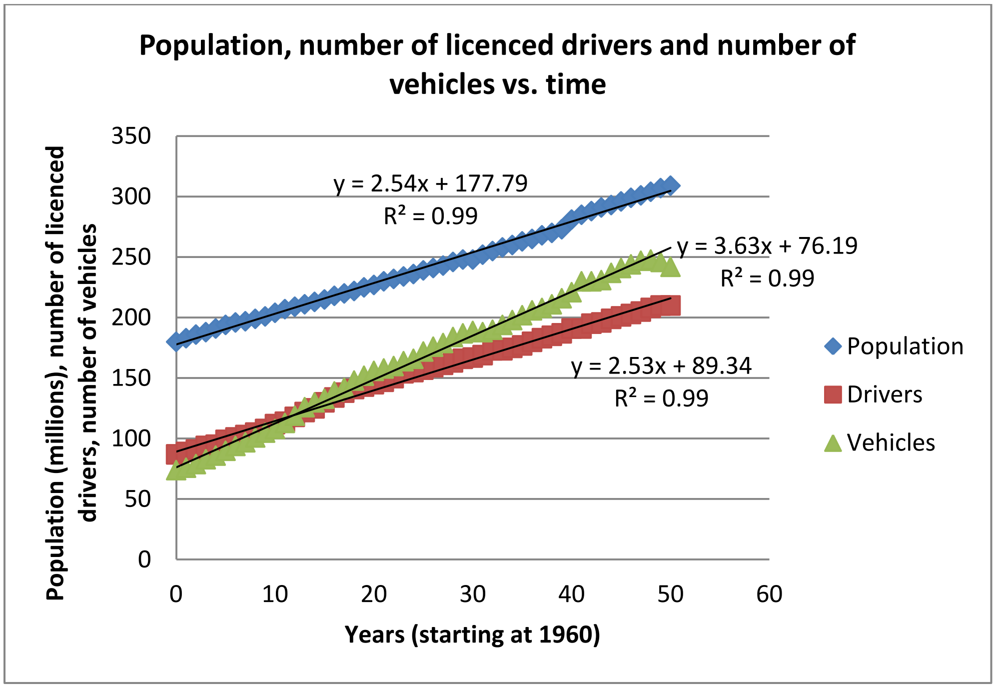
Level of health concern ranges are listed in table 11.11.

City	**Report AQI**	**Level of Health Concern**
Beijing	775	Beyond hazardous range (301-500)
Salt Lake City	142	Unhealthy for sensitive groups (101-150)
San Francisco	67	Moderate (51-100)
Las Vegas	23	Good (0-50)

11.12 The following data on U.S. population, number of licenses drivers, and number of vehicles was obtained from the U.S. Department of Transportation, Federal Highway Administration (http://www.fhwa.dot.gov/policyinformation/statistics/2010/dv1c.cfm). (a) Determine the rate of growth (on a per year basis) for the population, number of licensed drivers, and number of vehicles. (b) Are the rates of growth similar or different?

Solution:

Plot the population, driver, and vehicle data vs. time in excel and fit trendlines to determine their respective growth rates.



From the slope of the trendlines in the graph, the rates are as follows:

$$R_{pop} = \frac{2.54}{year};\ R_{vehicle} = \frac{3.63}{year};\ R_{drivers} = \frac{2.53}{year}$$

b. The rates of growth are **similar**. All rates are positive and the growth rate of population and drivers are the same (~2.53/year) while the rate of vehicular car growth is larger than the other two. More people are owning vehicles or even multiple vehicles.

11.13 A travel demand management action is planned that will add parking spaces to an existing park-and-ride facility that is served by transit. The plan will add 120 parking spaces. Assume the new spaces will have a 95 percent estimated utilization rate and these individuals will use the available light rail and bus service. Also assume that the average commute that will be eliminated is 42 miles roundtrip (distance from lot to destination and return), and there are 250 operating days per year. (a) What is the annual reduction in vehicle miles traveled from implementation of the park and transit ride facility? (b) if the emission factor for reactive hydrocarbons is 0.23 grams/mile driven and for $\mathrm{NO_x}$ is 0.40 grams per mile driven, what is the estimated reduction in air emissions for both of these air pollutants over the year?

Solution:

a. $120\ spaces \times 0.95\ utilization \times 42 \frac{miles}{roundtrip} \times 250 \frac{days}{year} = \mathbf{1.20 \times 10^6 \frac{miles}{yr}}$

b. $1.20 \times 10^6 \frac{miles}{yr} \times 0.23 \frac{grams\ hydrocarbon}{year} = \mathbf{275,000\ grams\ hydrocarbon\ reduced}$

$$1.20 \times 10^6 \frac{miles}{yr} \times 0.40 \frac{grams\ NO_x}{mile\ driven} = \mathbf{479,000\ grams\ NO_x\ reduced}$$

11.14 True or False? Compared to a baghouse with a high pressure drop, a baghouse with a low pressure drop would need a large fan and require more energy to move the gas through the baghouse.

Solution:

False, a baghouse with a low pressure drop needs LESS energy to move the exhaust gas than a baghouse with a high pressure drop.

11.15 A baghouse that employs a shaker collection method is being designed to remove 99.75 percent of an incoming stream of sawdust particles originating from a sawmill plant. What fabric area is required for the baghouse if it treats 15,000 ft^3/min of polluted air? How many bags are required if the bags are cylindrical and are 6 inches in diameter and 15 ft long? Assume the filter manufacturer has specified a woven fabric.

Solution:

The problem is similar to example 11.5. The proper gas-to-cloth ratio from table 11.21 for sawdust is 3.5 ft/min.

$$total\ fabric\ area = \frac{inlet\ flow\ rate}{gas - to - cloth\ ratio} = \frac{15{,}000\ ft^3/min}{3.5\ ft/min} = \mathbf{4290\ ft^2}$$

$$n_{cylindrical\ bags} = \frac{total\ filter\ area\ required}{\pi \times D \times h} = \frac{4290\ ft^2}{\pi \times 0.5\ ft \times 15\ ft} = \mathbf{182\ bags}$$

11.16 You are assigned to determine the number of filter bags required for an 8-compartment baghouse that uses pulse-jetting as the method to remove particulate matter from the bags. The following information is known: process gas exhaust rate is 100,000 ft^3/min and the recommended air-to-cloth ratio is 4 ft/min. The bags specified by the manufacturer have a diameter of 6 inches and height of 10 ft. (a) what is the total required fabric area? (ft^2)? (b) What number of bags is required? (c) How many bags are in each compartment?

Solution:

The problem is similar to example 11.5.

a.

$$total\ fabric\ area = \frac{inlet\ flow\ rate}{gas - to - cloth\ ratio} = \frac{100{,}000\ ft^3/min}{4\ ft/min} = \mathbf{25,000\ ft^2}$$

b.

$$\#\ of\ cylindrical\ bags = \frac{total\ filter\ area\ required}{\pi \times D \times h} = \frac{25{,}000\ ft^2}{\pi \times 0.5\ ft \times 10\ ft} = \mathbf{1592\ bags}$$

c.

$$\frac{1592\ bags}{8\ compartments} = \mathbf{199\ bags/compartment}$$

11.17 A thermal oxidizer incinerator operates as a plug flow reactor at a temperature of 250°C and has a gas residence time of 0.3 seconds (a) If the pollutant (vinyl chloride) enters the incinerator at a flow rate of 3,000 m^3/min and it is desired to remove 99.99% of the pollutant, what should the length of the incinerator be? (b) What is the length of the incinerator if the desired removal is increased to 99.99995? The first order rate constant for vinyl chloride removal is 45/sec at 250°C and the inside diameter of the incinerator (which is shaped like a cylinder) is 1 m.

Solution:

This problem is similar to example 11.7. Use the equation to describe pollutant removal in a plug flow reactor and solve for time/gas residence time (V/Q).

a.

$$\frac{C_{\text{out}}}{C_{\text{in}}} = \exp\left(-\frac{kV}{Q}\right)$$

$$\ln\left(\frac{1-0.9999}{1}\right) = \ln\left(e^{-\frac{45}{\text{sec}}\times t}\right)$$

$$t = \frac{\ln\left(\frac{1-0.9999}{1}\right)}{-45/sec} = 0.205\ sec$$

Time is equal to the gas residence time (V/Q). Solve for volume.

$$V = Q \times t = 3{,}000\frac{m^3}{min} \times \frac{1\ min}{60s} \times 0.205sec = 10.25\ m^3$$

Use the equation for the volume of a cylinder and solve for the incinerator length.

$$V = \pi\frac{D^2}{4}l, \therefore\ l = \frac{V}{\pi\frac{D^2}{4}} = \frac{10.25\ m^3}{\pi\frac{1m^2}{4}} = \mathbf{13\ m}$$

b. Use the same method in part a

$$t = \frac{\ln\left(\frac{1-0.99995}{1}\right)}{-45/sec} = 0.220\ sec$$

Time is equal to the gas residence time (V/Q). Solve for volume.

$$V = Q \times t = 3{,}000\frac{m^3}{min} \times \frac{1\ min}{60s} \times 0.220 sec = 11\ m^3$$

$$V = \pi\frac{D^2}{4}l, \therefore\ l = \frac{V}{\pi\frac{D^2}{4}} = \frac{11\ m^3}{\pi\frac{(1m)^2}{4}} = \mathbf{14\ m}$$

11.18 A tubular thermal oxidizer is operated at 225°C to remove toluene (C_6H_7) from a polluted airstream. The residence time for the gas is 1 sec. (a) Write the balanced reaction for theoretical oxidation of toluene to carbon dioxide and water. (b) If the toluene enters the incinerator at a flow rate of 2,500 ft^3/min and the reaction rate constant is 7.2/sec at this temperature, what percentage of the toluene is removed? (c) What is the length required for the oxidizer if the inside diameter is 4 feet?

Solution:

a. $\boldsymbol{2C_6H_7 + 15.5O_2 \rightarrow 12CO_2 + 7H_2O}$

b. Time is equal to the gas residence time (V/Q). Solve for volume.

$$V = Q \times t = 2{,}500\frac{ft^3}{min} \times 1sec \times \frac{1\ min}{60s} = 41.7\ ft^3$$

Use the equation to describe pollutant removal in a plug flow reactor from example 11.17 and chapter 4.

$$\frac{C_{\text{out}}}{C_{\text{in}}} = \exp\left(-\frac{kV}{Q}\right)$$

$$\frac{C_{out}}{C_{in}} = e^{\frac{-kV}{Q}} = e^{\frac{-\left(\frac{7.2}{\sec}\right)(41.7m^3)}{2{,}500ft^3/min \times 1min/60s}} = 0.00075$$

$$\frac{1 - 0.00075}{1} \times 100 = \boldsymbol{99.9\%\ removal}$$

c. Solve for the oxidizer length using the equation for the volume of the cylinder and the volume calculated in part b.

$$V = \pi\frac{D^2}{4}l, \therefore l = \frac{V}{\pi\frac{D^2}{4}} = \frac{41.7\ ft^3}{\pi\frac{(4ft)^2}{4}} = \boldsymbol{3.3\ ft}$$

11.19 A biofilter design uses a media that consists of a mixture of wood chips and compost at a ratio of 1 to 3 parts wood chips to municipal compost. The biofilter has the following dimensions, L = 8 m, W = 4.8 m, Depth = 0.35 m, and the air flow rate is 2.6 m^3/s. (a) What is the empty bed residence time (sec)? (b) Using the Table provided in the chapter that relates empty bed residence time to application, what application(s) might this biofilter be appropriate for?

Solution:

a. Use equation 11.24

$$\text{EBRT} = \frac{V}{Q} = \frac{8m \times 4.8m \times 0.35m}{2.6\ m^3/s} = \boldsymbol{52\ s}$$

b. From table 11.23, **composting** is the application this biofilter may be used for.

11.20 Calculate the (a) stack emissions and (b) fugitive emissions if some process equipment that is associated with a hood system generates 220 kg/hr of VOCs, the hood capture efficiency is 87%, and the collection efficiency of the air pollution control technology used to treat the captured air emissions is 95%.

Solution:

a. Use equation 11.26:

Stack emissions = {Emissions captured by the hood} × $\frac{100\% - \eta}{100\%}$

$$Stack\ emissions = 220\frac{kg}{hr} \times 0.87 \times \frac{100\% - 95\%}{100\%} = \mathbf{9.6\ kg/hr}$$

b. Use equation 11.25:

Fugitive emissions = {total emissions} – {emissions captured by a hood}

$$Fugitive\ emissions = 220\frac{kg}{hr} - \left(0.87 \times 220\frac{kg}{hr}\right) = \mathbf{29\ kg/hr}$$

11.21 A manufacturing plant converts sulfur trioxide (SO_3 to sulfuric acid (H_2SO_4) at 97.5% efficiency. The plant produces 350 metric tons of sulfuric acid at 100% purity every day. A wet scrubbing system is installed to reduce the SO_2 emissions and has a removal efficiency of 97%. The emission factor for this process equals 17 kg SO_2/metric ton of raw material processed. (a) What are the daily emissions of SO_2 from the manufacturing facility prior to treatment? (b) What are the daily emissions of SO_2 from the manufacturing facility after treatment?

Solution:

This problem is similar to example 11.10.

a. The emission factor for SO_2 air emissions from this process is related to the efficiency of the conversion process. AP-42 states the emission factor (in units of kg SO_2/metric ton processed) is determined as:

EF = 682 – [6.82 × % conversion efficiency of SO_3 to H_2SO_4)

In our case, EF = 682 – [6.82 × 97.5] = 682 – 665 = 17 kg $SO_2/10^6$ gram processed

The emissions then can be estimated as:

E = A × F = 350 x 10^6 gram/day x 17 kg$SO_2/10^6$ gram = **5,950 kg SO_2/day**.

b.

$$daily\ emissions\ of\ \mathrm{SO_2}\ from\ the\ manufac.facility\ after\ treatment$$
$$= 5{,}950\ \mathrm{kg}\frac{\mathrm{SO_2}}{\mathrm{day}} \times 0.03 = \mathbf{179\ kg\frac{SO_2}{day}}$$

Solutions Manual prepared by: Colleen Naughton, Ziad Katirji, and Heather E. Wright Wendel
Environmental Engineering: Fundamentals, Sustainability, Design, 2nd Edition
James R. Mihelcic and Julie Beth Zimmerman, John Wiley & Sons, New York, 2014.

11.22 Assume the emissions factor for release of mercury from a solid waste incinerator is 0.107 lb per ton incinerated and for dioxin is 2.13×10^{-5} lb per ton solid waste incinerated. Estimate the daily emission rates (lb pollutant/day) and annual emissions rates (lb/yr) of each of these hazardous air pollutants. Assume the incinerator processes 2.88×10^{6} lbs of solid waste per year.

Solution:

Use equation 11.28 to calculate the emissions factors:

E = A × EF

$$E_{Hg} = 2.88\times10^{6}\,\frac{lb}{yr}\times\frac{1\ ton}{2{,}000\ lbs}\times\frac{0.107\ lb}{ton} = \boldsymbol{154\ lbs/yr}$$

$$E_{Hg} = 154\,\frac{lbs}{yr}\times\frac{1\ yr}{365\ days} = \boldsymbol{0.422\ lb/day}$$

$$E_{dioxin} = 2.88\times10^{6}\,\frac{lb}{yr}\times\frac{1\ ton}{2{,}000\ lbs}\times\frac{2.13\times10^{-5}\ lb}{ton} = \boldsymbol{0.0307\ lbs/yr}$$

$$E_{dioxin} = 0.0307\,\frac{lbs}{yr}\times\frac{1\ yr}{365\ days} = \boldsymbol{8.40\times10^{-5}\ lb/day}$$

11.23 Acetone is released from combustion of 100,000 metric tons of wood waste per year. The wood waste has an average heat content of 0.05 MM BTU/lb. The reported emission factor for acetone emitted from a waste bark fired boiler with no emissions control is 9.5×10^{-3} kg/metric ton of wood burned. What are the annual emissions of acetone from this facility (metric tons per year)?

Solution:

Use equation 11.28 to calculate the emissions factor:

E = A × EF

$$E_{acetone} = 100{,}000\ metric\ tons\ wood\ waste \times 9.5 \times 10^{-3}\,\frac{kg}{ton} \times \frac{1\ ton}{907.185\ kg}$$

$$= \boldsymbol{1.05\ tons}$$

11.24 A company annually applies 25,000 liters of a surface coating to their product. The surface coating contains the VOC, acetone. The emissions are collected and an emissions control technology is installed that reduces the VOC emissions by 80%. The company is required to report their emissions to the atmosphere if they exceed 3,500 kg/year. For this coating process operation, there is no loss of the coating compound to the coating equipment and no loss to the system's liquid or solid waste streams. All the VOC applied is captured by the collection system prior to treatment. The Material Safety Data Sheet reports that the surface coating product contains 25% by weight acetone and the specific gravity of the material is 1.35 kg/L. Use a mass balance approach to estimate if the company must report their air emissions to the state regulatory agency.

Solution:

This problem is similar to example 11.11

$$25{,}000\,\frac{liter}{yr} \times 0.25\ weight\ acetone \times 1.35\,\frac{kg}{L} = 8438\,\frac{kg}{yr} \times 0.2 = 1688\,\frac{kg\ acetone}{yr}$$

$$1688\,\frac{kg\ acetone}{yr} < 3{,}500\,\frac{kg}{yr} \therefore \boldsymbol{Do\ not\ need\ to\ report}$$

11.25 A company applies 21,000 liters of a coating every year that contains three VOCs; 0.26 kg xylene per liter of coating, 0.040 kg n-butyl alcohol per liter of coating, and 0.13 kg ethyl benzene per liter of coating. (a) What is the total mass of VOC in the coating (kg VOC/liter of coating)? (b) Estimate the total mass of VOCs released to the atmosphere every year (kg/year) assuming no collection or treatment of the VOCs takes place. (c) What is the total mass of VOCs released to the atmosphere assuming that 8% of the applied VOC is retained in a liquid wastestream and is discharged to the wastewater treatment plant and the company installs some control technology which captures and degrades 60% of the collected air emissions?

Solution:

a. $m_{total\ VOC} = 0.40\frac{kg}{L} n - butyl\ alcohol + 0.13\frac{kg}{L} ethyl\ benzene + 0.26\frac{kg}{L} xylene = \mathbf{0.79\frac{kg}{L} VOC}$

b. $total\ mass\ of\ VOCs = 21{,}000\frac{L}{yr} \times 0.79\frac{kg\ VOC}{L} = \mathbf{16,590\frac{kg}{yr}}$

c. $total\ mass\ of\ VOCs\ released\ to\ the\ atmostphere =\ 16{,}590\frac{kg}{yr} \times 0.92 \times 0.40 = \mathbf{6105\frac{kg}{yr}}$

11.26 A company performs measurements that show the VOC xylene is present in the stack gas and the gas flow rate is 2,200 m^3/min. The concentration of xylene was measured exiting the stack on a weekly basis and averaged 0.62 kg/hr. The manufacturing process runs 6,700 hours every year. If the reporting threshold for the xylene is 3,200 kg/year, use the source measurements to determine if the company exceeds the annual reporting threshold.

Solution:

$$0.62\ \frac{kg\ xylene}{hr} \times \frac{6{,}700\ hrs}{yr} = 4{,}154\frac{kg}{yr} > 3{,}200\frac{kg}{yr}$$

$$\therefore \boldsymbol{company\ exceeds\ annnual\ reporting\ threshold}$$

11.27 Between 1980 and 2000, the average CO emission factor of the vehicle fleet in Hillsborough County, Florida, dropped by almost half, from about 65 to 34 grams of CO per vehicle-mile driven. However, the total miles driven in the county by all vehicles increased by 60 percent during this same time period. (a) Did countywide emissions of CO go up or down, and by how much between 1980 and 2000? (b) Vehicle exhaust is getting cleaner through a combination of engine improvements, emission control technologies, auto re-design, and fuel reformation. What are five transportation demand management strategies you can use to reduce emissions of air pollutants in an urban area?

Solution:

a. $\frac{(65-34\ g\ CO)}{65\ g\ CO} \times 100 = 48\%\ reduction\ in\ CO$

But with a 60% increase in miles driven during this same period, **emissions would still go up** since this is greater than the 48% reduction.

b. From table 11.7, five transportation demand management strategies are:

(1) park-and-ride facilities

(2) regional rideshare programs

(3) new/expanded bus/rail service

(4) bicycle and pedestrian projects/programs

(5) vanpool programs

11.28 Investigate sources of hazardous air pollutants emitted near your community. Go to Scorecard (www.scorecard.org) to gather data about air pollutant emissions. The Scorecard site makes the Toxics Release Inventory easily searchable; by entering your zip code, you can find a list of major air polluters in your area. (a) For your area, identify the top three five polluters and their total emissions. (b) Plot total environmental release for data from the top emitting company over the years of available data. (c) Describe the overall trend of emissions over time.

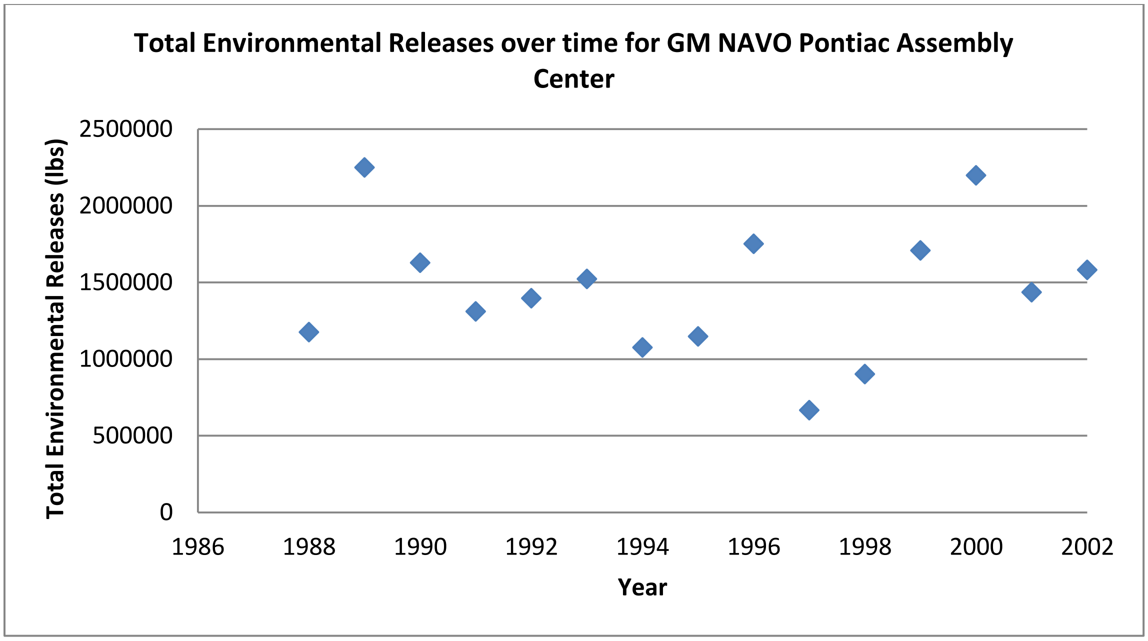
Solution:

Students answers may vary based on the location they choose but here an example for Detroit, MI:

a. The top five polluters and their emissions in Detroit, MI are shown in the table below:

Rank	**Facility**	**Emissions (lb)**
1	GM NAVO Pontiac Assembly Center	1582541
2	GM MCG Orion Assembly Center	430284
3	Ford Wixom Assembly Plant	254816
4	LDM TECHS. New Hudson	100066
5	Precision Coatings, Inc.	70600

b. The plot for the total environmental release data for BM NAVO Pontiac Assembly Center is shown in the figure on the next page.



c. It appears there was a general decrease of emissions from 1989 through 1998 (with lowest total environmental releases in 1997 and 1998) but followed by a sharp increase in 1999 and 2000 with another drop in 2001 and 2002.

11.29 At the wet adiabatic lapse rate, the cooling rate of the air parcel is usually: (a) slower than the dry adiabatic lapse rate, (b) the same as the dry adiabatic lapse rate, or, (c) faster than the dry adiabatic lapse rate?

Solution:

(a) slower than the dry adiabatic lapse rate

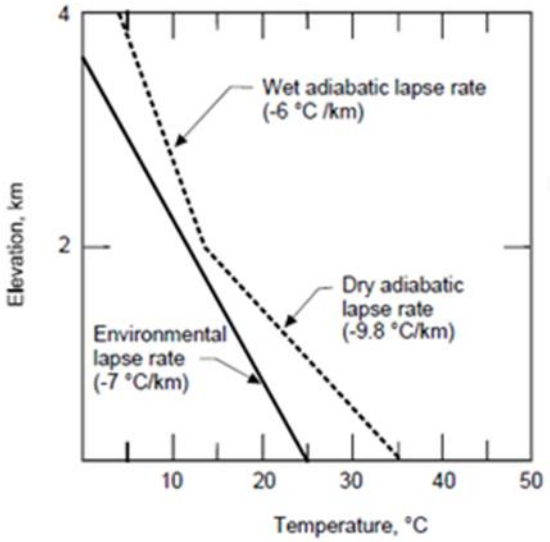
Since from table 11.25:

$$wet\ adiabatic\ lapse\ rate = 6/7℃/km$$

$$dry\ adiabatic\ lapse\ rate = 9.8℃/km$$

$$6/7℃/km < 9.8℃/km \therefore wetadiabatic\ lapse\ rate < dry\ adiabatic\ lapse\ rate$$

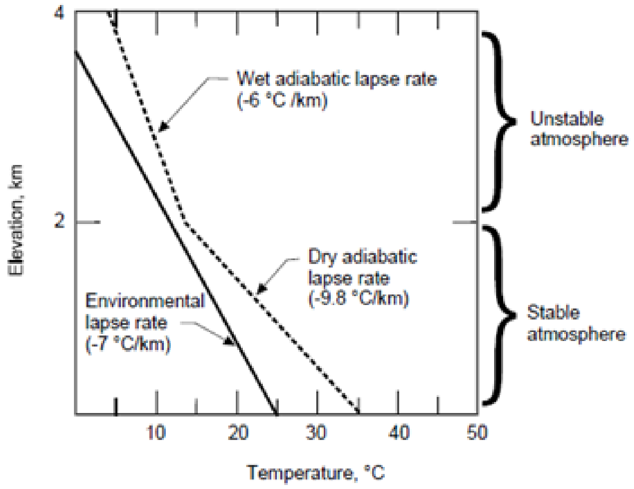
11.30 In the following figure, an air parcel is displaced and becomes saturated at an elevation of 2 km. Which of the following stability conditions does the diagram depict? (a) stable only below 1 km, (b) stable only above 1 km, (c) unstable above 2 km? (problem from EPA, 2012h).



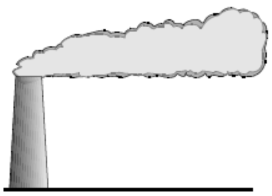
Solution:

See figure 11.27 for definitions of atmospheric stability conditions and apply them to the figure given in the problem statement. See figure below for the stability conditions:

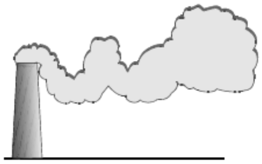
(c) Unstable above 2 km



11.31 (a) Name the following three plume types. (b) sketch a graph of elevation on the y-axis and air temperature on the x-axis that would describe the environmental lapse rate and the lapse rate of an air parcel being emitted from the stack for each of these three plume types.



a.



b.

c.

Solution:

a. See figure 11.28 for plume types

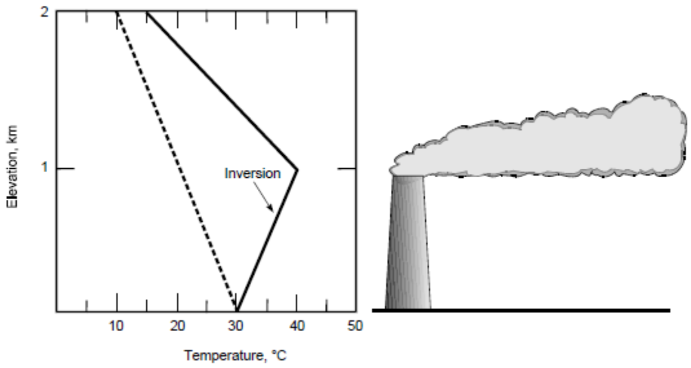
a. Lofting

b. Looping

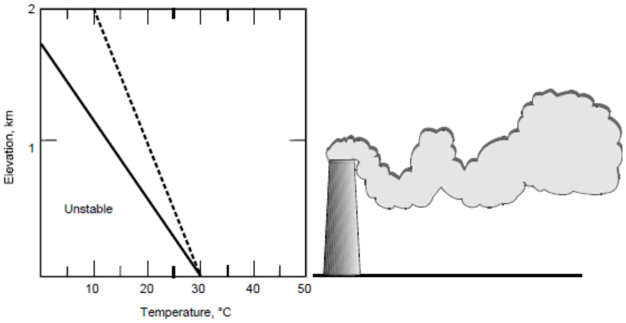
c. Fumigation

b.

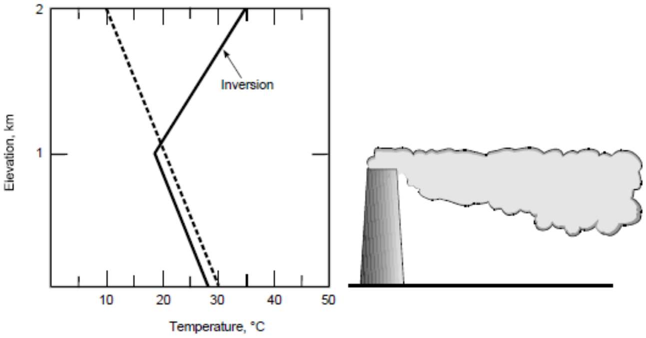
a. Lofting



b. Looping



c. Fumigation



11.32 A fanning plume will occur when atmospheric conditions are generally (a) stable, (b) highly unstable, or, (c) neutral?

Solution:

According to figure 11.28, fanning occurs under “very stable conditions” **(a)**

11.33 For extremely unstable atmospheric stability conditions, what are values for the dispersion coefficient in the y and z directions 1,000 meters downstream in an urban area from the point of the pollutant release? Estimate your values using two methods, (a) the correct Briggs equation, and (b) a graphical method that allows you to estimate the dispersion coefficients from established figures.

Solution:

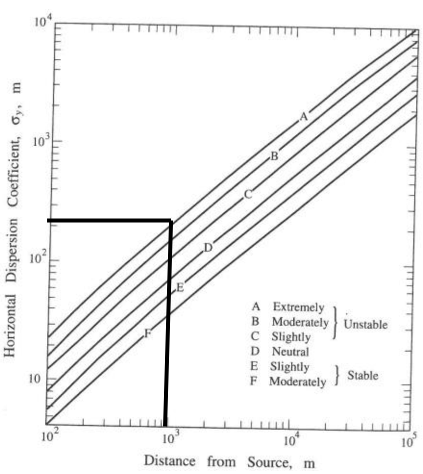
a. See table 11.27

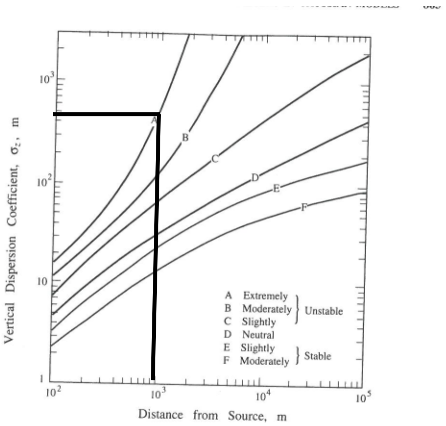
For extremely unstable (A) in urban conditions:

$$\sigma_y = 0.32x(1+0.0004x)^{-\frac{1}{2}} = 0.32(1{,}000m)(1+0.0004(1{,}000m))^{-\frac{1}{2}} = \mathbf{270m}$$

$$\sigma_z = 0.24x(1+0.001x)^{-\frac{1}{2}} = 0.24(1{,}000m)(1+0.001(1{,}000m))^{-\frac{1}{2}} = \mathbf{339m}$$

b.





$From\ the\ graphs$: $\sigma_y \approx \mathbf{220m}, \sigma_z \approx \mathbf{350m}$

11.34 For neutral atmospheric stability conditions, what are values for the dispersion coefficient in the y and z directions 5 km meters downstream in a rural area from the point of the pollutant release? Estimate your values using two methods, (a) the correct Briggs equation, and (b) a graphical method that allows you to estimate the dispersion coefficients from established figures.

Solution:

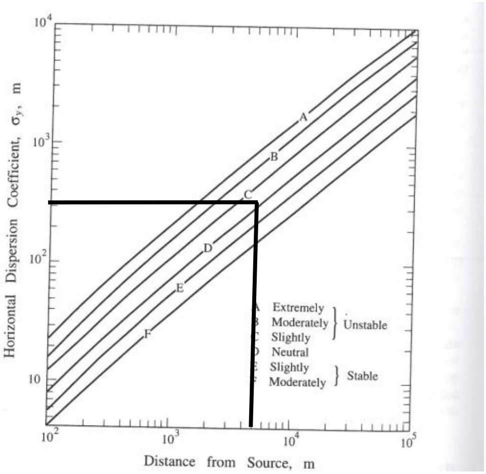
a. See table 11.27

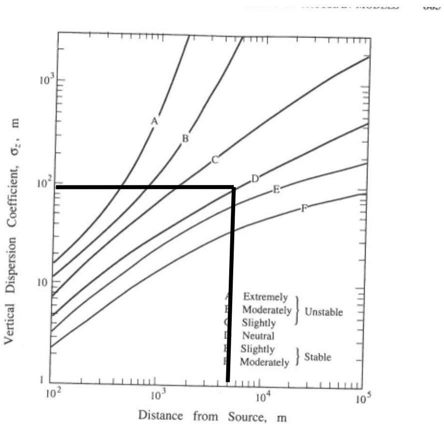
For neutral (D) in rural conditions:

$$\sigma_y = 0.08x(1+0.0001x)^{-\frac{1}{2}} = 0.08(5{,}000m)(1+0.0001(5{,}000m))^{-\frac{1}{2}} = \mathbf{327m}$$

$$\sigma_z = 0.06x(1+0.0015x)^{-\frac{1}{2}} = 0.06(5{,}000m)(1+0.0015(5{,}000m))^{-\frac{1}{2}} = \mathbf{103m}$$

b.





$From\ the\ graphs: \sigma_y \approx \mathbf{315m}, \sigma_z \approx \mathbf{95m}$

11.35 For slightly unstable atmospheric conditions, what are the values the dispersion coefficients, σ_y and σ_z, 3 km downstream in a rural area? Provide your values for (a) the correct Briggs formula and (b) a graphical method that allows you to estimate the dispersion coefficients from established figures. (c) How do these values change if the atmosphere is moderately stable?

Solution:

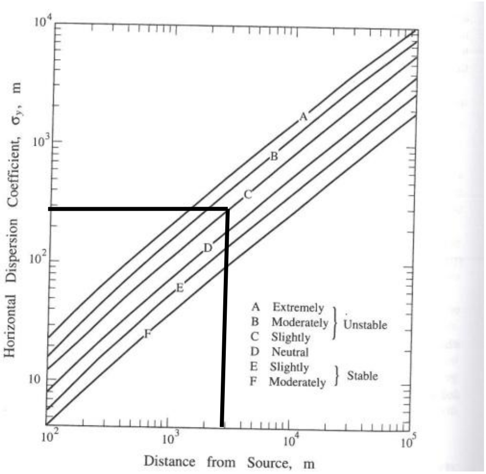
a. See table 11.27

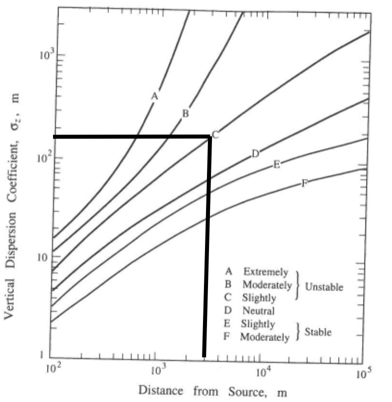
For slightly stable(C) in rural conditions, the dispersion coefficients are calculated using the equations below:

$$\sigma_y = 0.11x(1+0.0001x)^{-\frac{1}{2}} = 0.11(3{,}000m)(1+0.0001(3{,}000m))^{-\frac{1}{2}} = \mathbf{289m}$$

$$\sigma_z = 0.08x(1+0.0002x)^{-\frac{1}{2}} = 0.08(3{,}000m)(1+0.0002(3{,}000m))^{-\frac{1}{2}} = \mathbf{190m}$$

b.





$\textit{From the graphs}: \sigma_y \approx \mathbf{290m}, \sigma_z \approx \mathbf{200m}$

11.36 Wind is measured at 10 m above the ground surface at 2 m/sec. Estimate the wind speed at an effective stack height of a 40 m in (a) smooth rural terrain for unstable atmospheric conditions and (b) for rough urban terrain for the most stable atmospheric conditions.

Solution:

Use equation 11.32:

$u = u_0\,(H/z_0)^p$

a. From section 11.8.2, P=0.07 for smooth, rural terrain

$$u = \left(2\frac{m}{s}\right)\left(\frac{40m}{10m}\right)^{0.07} = 2.2\frac{m}{s}$$

b. From section 11.8.2, P=0.6 for rough, urban terrain

$$u = \left(2\frac{m}{s}\right)\left(\frac{40m}{10m}\right)^{0.6} = 4.6\frac{m}{s}$$

11.37 What is the estimated wind speed at a 45 m effective stack height located in the country side? Assume there are very unstable atmospheric conditions near the stack and wind measurements made close to the stack location showed the wind speed was 3 m/sec at a height of 5 m.

Solution:

Use equation 11.32:

$u = u_0\,(H/z_0)^P$

a. From section 11.8.2, P=0.07 for smooth, rural terrain

$$u = \left(3\frac{m}{s}\right)\left(\frac{45m}{5m}\right)^{0.07} = 3.5\frac{m}{s}$$

11.38 What is the ground level concentration of a pollutant (μg/m^3) 250, 500, 750, and 1,000 meters downwind for a stack release along the centerline of the plume? The pollutant is released from a 45-m tall stack at a rate of 8.5 grams per second in an urban area. The plume rises an additional 10 meters. The wind speed is 3 m/sec and there are slightly unstable atmospheric stability conditions.

Solution:

Use equation 11.34 for the concentration of an air pollutant at ground level.

$$C(x,y,0) = \frac{S}{\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

At 250m from table 11.27, the dispersion coefficients for slightly unstable (C), urban conditions are calculated as follows:

$$\sigma_y = 0.22x(1+0.0004x)^{-\frac{1}{2}} = 0.22(250m)(1+0.0001(250m)^{-\frac{1}{2}} = \boldsymbol{52m}$$

$$\sigma_z = 0.2x = 0.2(250m) = \boldsymbol{50m}$$

$$C(250{,}0{,}0) = \frac{8.5\ g/s}{\pi \times 3m/s \times 52m \times 50m} e^{\frac{-0^2}{2(100m)^2}} e^{\frac{-(4.5+10m)^2}{2(100m)^2}} \times \frac{10^6 \mu g}{g} = \boldsymbol{332\mu g/m^3}$$

At 500m:

$$\sigma_y = 0.22(500m)(1+0.0004(500m)^{-\frac{1}{2}} = \boldsymbol{100m}$$

$$\sigma_z = 0.2x = 0.2(500m) = \boldsymbol{100m}$$

$$C(500{,}0{,}0) = \frac{8.5\ g/s}{\pi \times 3m/s \times 100m \times 100m} e^{\frac{-0^2}{2(100m)^2}} e^{\frac{-(4.5+10m)^2}{2(100m)^2}} \times \frac{10^6 \mu g}{g}$$

$$= \boldsymbol{89\mu g/m^3}$$

At 750m:

$$\sigma_y = 0.22(750m)(1+0.0004(750m)^{-\frac{1}{2}} = \boldsymbol{145m}$$

$$\sigma_z = 0.2x = 0.2(750m) = \boldsymbol{150m}$$

$$C(750{,}0{,}0) = \frac{8.5\ g/s}{\pi \times 3m/s \times 145m \times 150m} e^{\frac{-0^2}{2(145m)^2}} e^{\frac{-(4.5+10m)^2}{2(150m)^2}} \times \frac{10^6 \mu g}{g}$$

$$= \boldsymbol{41\mu g/m^3}$$

At 1,000m:

$$\sigma_y = 0.22(750m)(1 + 0.0004(1{,}000m)^{-\frac{1}{2}} = \mathbf{186}\boldsymbol{m}$$

$$\sigma_z = 0.2x = 0.2(1{,}000m) = \mathbf{200}\boldsymbol{m}$$

$$C(1{,}000{,}0{,}0) = \frac{8.5\ g/s}{\pi \times 3m/s \times 186m \times 200m} e^{\frac{-0^2}{2(186m)^2}} e^{\frac{-(4.5+10m)^2}{2(200m)^2}} \times \frac{10^6 \mu g}{g}$$

$$= \mathbf{24}\ \boldsymbol{\mu g/m^3}$$

11.39 NO_x is emitted from a 75-m high stack at a rate of 65 g/s. Calculate the ground level concentration of NO_x 90 m from the centerline. The plume rises 20 m and the wind speed is 5 m/sec. Assume $\sigma_y = 120$ m and $\sigma_z = 47$ m and there is reflection from the ground.

Solution:

Use equation 11.34 for the concentration of an air pollutant at ground level.

$$C(x,y,0) = \frac{S}{\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

$$C(90,0,0) = \frac{65\ g/s}{\pi \times 5m/s \times 120m \times 47m} e^{\frac{-0^2}{2(100m)^2}} e^{\frac{-(75m+20m)^2}{2(47m)^2}} \times \frac{10^6 \mu g}{g} = \mathbf{95\ \mu g/m^3}$$

11.40 Estimate the downwind distance (x) at which the maximum pollutant concentration would occur at the ground surface for an emission that occurs from a stack that is 60 m high? Assume the pollutant is SO_2, it is emitted at a rate of 3,000 g/sec, the wind speed is 4 m/s, the plume rises an additional 14 m after being emitted, and there are slightly unstable atmospheric conditions in this urban area. Calculate your value using two methods, equations and curves provided in the chapter.

Solution:

Using equation 11.35, calculate the vertical dispersion coefficient given the stack height.

$\sigma_z = H/\sqrt{2}$

$$\sigma_z = \frac{60m + 14m}{\sqrt{2}} = 52.3\ m$$

In table 11.27 at slightly unstable (C) in urban conditions the vertical dispersion coefficient is equal to:

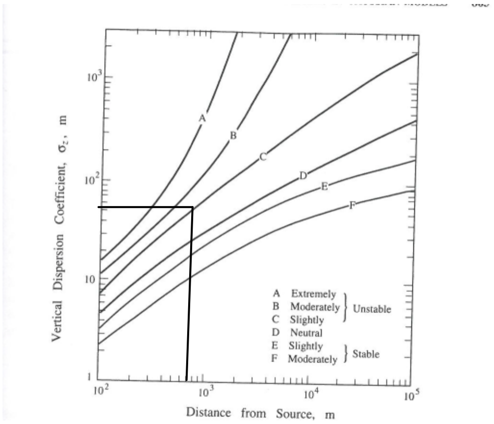
$$\sigma_z = 0.2x$$

Now solve for downwind distance

$$x = \frac{\sigma_z}{0.2} = \frac{52.3m}{0.2} = \boldsymbol{262m}$$

From the graph:

$$\boldsymbol{\sigma_z \approx 700m}$$



11.41 An air pollutant is released at a rate of 2 g/s from the top of a tall stack that is 110 m high. The plume initially rises upward an additional 10 m above the stack exit, after which it travels with a wind speed of 5 m/s. The atmosphere has moderately stable conditions in the open country. (a) What is the concentration of the pollutant (µg/m^3) in the very center of the plume 750 downwind of the stack and at the effective stack height? (b) What is the concentration of the pollutant (µg/m^3) at ground level 750 downwind of the stack? (c) At what distance downwind does the maximum ground level concentration occur? (d) What is the concentration of the pollutant (µg/m^3) at this location you identify in part (c)?

Solution:

a. Use equation 11.33

$$C(x,y,z)=\frac{S}{2\pi u\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right\}$$

From table 11.27 at moderately stable (B) conditions in the open-country, the dispersion coefficients are calculated as follows:

$$\sigma_y = 0.16x(1+0.0001x)^{-\frac{1}{2}} = 0.16(750m)(1+0.0001(750m)^{-\frac{1}{2}} = 116m$$

$$\sigma_z = 0.12x = 0.12(750m) = 90m$$

$$C(750,0,100) = \frac{2\ g/s \times \frac{10^6 \mu g}{1\ g}}{2\pi \times 116m \times 90m} e^{\frac{-0^2}{2(116m)^2}} \left\{ e^{\frac{-(110m-120m)^2}{2(90m)^2}} + e^{\frac{-(110m+120m)^2}{2(90m)^2}} \right\}$$

$$= \mathbf{32 \mu g/m^3}$$

b. Use equation 11.34 for the concentration of an air pollutant at ground level.

$$C(x,y,0) = \frac{S}{\pi u\sigma_y\sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

$$C(750,0,0) = \frac{2\ g/s \times \frac{10^6 \mu g}{1\ g}}{\pi \times 5m/s \times 116m \times 90m} e^{\frac{-0^2}{2(100m)^2}} e^{\frac{-(120m)^2}{2(90m)^2}} = \mathbf{5.0\ \mu g/m^3}$$

c. Using equation 11.35, calculate the vertical dispersion coefficient given the stack height.

$\sigma_z = H/\sqrt{2}$

$$\sigma_z = \frac{120m}{\sqrt{2}} = 85\ m$$

In table 11.27 at slightly unstable (C) in urban conditions the vertical dispersion coefficient is equal to:

$$\sigma_z = 0.12x$$

Now solve for downwind distance

$$x = \frac{\sigma_z}{0.12} = \frac{85m}{0.12} = \mathbf{707m}$$

d. Recalculate the dispersion coefficients as in part a and the pollutant concentration in part b with the maximum distance in part c.

$$\sigma_y = 0.16x(1 + 0.0001x)^{-\frac{1}{2}} = 0.16(707m)(1 + 0.0001(707m)^{-\frac{1}{2}} = 109m$$

$$\sigma_z = 0.12x = 0.12(707m) = 84m$$

$$C(707,0,0) = \frac{2\ g/s \times \frac{10^6 \mu g}{1\ g}}{\pi \times 5m/s \times 109m \times 84m} e^{\frac{-0^2}{2(109m)^2}} e^{\frac{-(120m)^2}{2(84m)^2}} = \mathbf{5.0\ \mu g/m^3}$$

11.42 An air pollutant is released at a rate of 0.72 g/s 4 meters above ground level. The wind speed is 2 m/s. What is the maximum ground level concentration 1 km downwind? Assume that

$\sigma_y = 45$ m and $\sigma_z = 26$ m.

Solution:

Use equation 11.34 for the concentration of an air pollutant at ground level.

$$C(x,y,0) = \frac{S}{\pi u \sigma_y \sigma_z} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

$$C(750,0,0) = \frac{0.72\ g/s \times \frac{10^6 \mu g}{1\ g}}{\pi \times 2m/s \times 45m \times 26m} e^{\frac{-0^2}{2(45m)^2}} e^{\frac{-(4m)^2}{2(26m)^2}} = \mathbf{97\ \mu g/m^3}$$