Handbook of Water Quality for the Singapore Secondary 1 Geography Curriculum

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Chapter 1

Water in the Singapore Context

This Handbook is intended to be a companion resource for the National Institute of Education Sustainability Learning Lab video series on water quality (www.SLL.com). The video series is meant to delivers an accessible media format for a broader audience, while this Handbook provides more detailed information and a deeper discussion about the water quality analytical methods, data presentation and interpretation, example water quality investigations, and a Glossary of Terms. Other helpful water quality resource books are available, and in particular, this Handbook builds on the substantial foundation provided by M.K. Mitchell and W.B. Stapp (1995) *Field Manual for Water Quality Monitoring, An Environmental Education Program for Schools*, Thomson-Shore, Inc., MI, which was written predominantly for a North American audience. A more locally-relevant reference has been written by C.K. Ko (2011) *Your First Guide to Water Quality Monitoring in Singapore* and is available free at waterqualityinsingapore.blogspot.co. This Guide provides useful practical advice on developing a water quality monitoring programme and a discussion of some of the water quality parameters presented in this Handbook (as well as some others not discussed in this Handbook, such as alkalinity and hardness).

Water is essential for all life and it is a matter of national security in Singapore. Because of its small catchment area relative to its dense population, Singapore has become a world leader in innovative and effective water management. A great deal has been written about Singapore's approach to water management (e.g. Goh, 2005; Khoo, 2009; Ong, 2010; Tortajada and Probre, 2011; Bennett, 2011; Chew et al., 2011; Joshi et al., 2012; Tortajada and Joshi, 2013; Irvine et al., 2014; 2015; Chang and Irvine, 2014) and the PUB website (www.pub.gov.sg/) provides an extensive catalogue of resources. It is not the intent of this Handbook to thoroughly review this broader waterscape context; the reader simply is referred to these afore-mentioned references. However, a quick overview of the PUB water management philosophy is warranted.

Singapore takes a holistic approach to managing its water resources, essentially overseeing the entire hydrologic cycle through one agency, the PUB. The PUB has termed this approach "closing the loop" and the philosophy is summarized in Figure 1.1. The core element of the "closing the loop" philosophy is the "Four National Taps", or the four water supply sources for Singapore: i) imported water from Malaysia; ii) NEWater (recycled water); iii) water desalination; and iv) local catchments (i.e. stormwater runoff) and reservoirs.

1.1. The Four National Taps

1.1.1. Water Imports from Malaysia

Two water agreements between Malaysia and Singapore were signed in 1961 and 1962, the first of which expired in 2011 and the second which will expire in 2061. The current (second) agreement still provides up to 250 mgd (946,00 cubic meters per day (10.95 m^3s^{-1})). This water enters Singapore via pipeline at the Causeway between Singapore and Johor, Malaysia.

Singapore and Malaysia have a long history of water import agreements that stretches back to 1927 and a new round of water negotiations began in 1998 that were linked to economic packages focusing on recovery from the Asian financial crisis (Tortajada and Pobre, 2011). By 2003, Singapore had begun to look seriously for alternative water sources, including import from Indonesia, and ultimately the negotiations with Malaysia ended without agreement (Tortajada and Pobre, 2011). With the expiry date of 2061 for the second agreement looming, this has become the de facto planning horizon for

Singapore to advance and diversify its technologies as it moves towards the goal of water self-sufficiency.

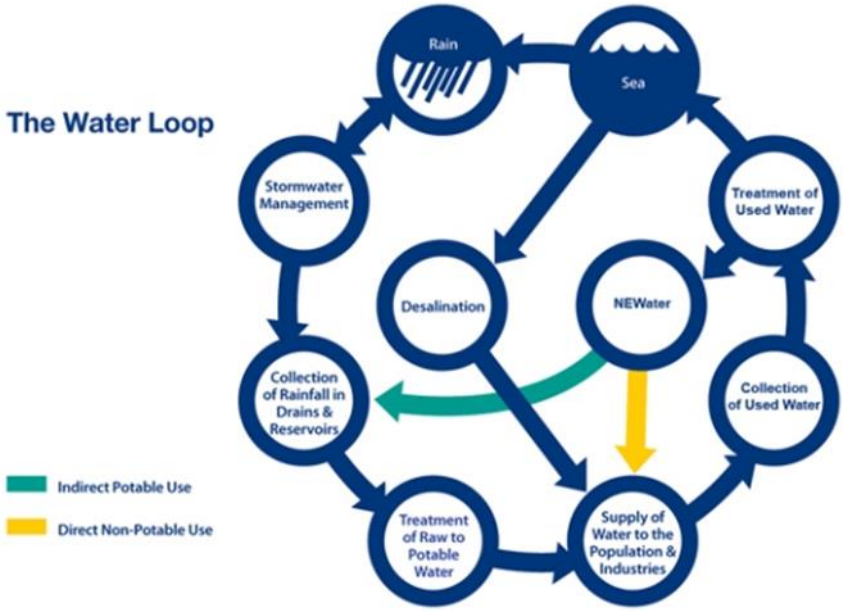


Figure 1.1 The PUB approach to closing the water loop (from http://www.pub.gov.sg/water/Pages/default.aspx).

1.1.2. NEWater

Five NEWater plants now provide 190 mgd (863,757 cubic meters per day) which meets 40% of Singapore's water demands and the PUB expects that by 2060 NEWater will meet 50% of Singapore's demand (http://www.pub.gov.sg/water/newater/Pages/default.aspx; http://www.todayonline.com/singapore/fifth-newater-plant-changi-opens). The NEWater plants accept treated wastewater and then further treat the wastewater using a three-stage process that includes ***microfiltration***, ***reverse osmosis***, and ***ultraviolet disinfection*** to produce water that meets U.S. EPA and WHO drinking water standards (Bennett, 2011). NEWater is used primarily as a replacement for potable water in industrial processing, including microelectronics and wafer fabrication, although a small percentage also is blended into reservoirs for indirect potable use. The NEWater plants are an outstanding example of innovative research and development that resulted from combined efforts of government and the private sector (Chew et al., 2011). The NEWater Visitor Centre provides daily guided tours of the plant and includes scale models of the processes and educational opportunities (http://www.pub.gov.sg/water/newater/visitors/Pages/default.aspx).

1.1.3. Desalination

Once considered a costly last option for water scarce countries, desalination technology has advanced dramatically over the past decade and while the costs vary by location, desalination increasingly is supplying water demand throughout the world (Karagiannis and Soldatos, 2008; Greenlee et al., 2009; Ghaffour et al., 2013). Singapore currently has two seawater reverse-osmosis plants that produce 100 mgd (454,609 cubic meters per day) and meets about 25% of Singapore's water needs

(http://www.pub.gov.sg/water/Pages/DesalinatedWater.aspx). By 2060, desalinated water is expected to meet 30% of Singapore's demand.

1.1.4. Runoff from Local Catchments

Stormwater runoff is now captured from two-thirds of Singapore's land area and stored in 17 reservoirs throughout the island for subsequent use. Furthermore, all the major estuaries have been dammed to create reservoirs, and the PUB intends to capture water from remaining streams near the shoreline, which will increase Singapore's water catchment area to 90% by 2060 (http://www.pub.gov.sg/water/Pages/LocalCatchment.aspx). One of the most recent additions to reservoir capacity is the Marina Barrage, which collects runoff from a 10,000 ha area having a population of around 1 million people (Kamer et al., 2008). A 350 m wide dam separates Marina Bay from the sea, while the bay receives freshwater discharges from the Singapore River, Stamford Canal, Rochor Canal, Sungei Whampoa, Kallang River, Geylang River, and Pelton Canal. The barrage also provides flood control for local low-lying areas. Construction of the barrage was completed in 2008 and by 2010 the impoundment had been successfully flushed of seawater and converted to a freshwater reservoir.

Clearly, it is important, to the extent possible, to maintain stormwater runoff quality and thereby keep treatment costs for drinking water to a minimum. Water quality issues also must be balanced with local flooding issues and therefore stormwater management is of primary concern to the PUB. The reservoirs receive discharge from approximately 7,000 km of drains and canals. Khoo (2009) noted that traditionally the canals and drains were covered, and when above ground, were simply concrete conduits which resulted in a sense of detachment between people and the waterways. As such, the PUB initiated its Active, Beautiful, and Clean (ABC) Programme in 2006 to re-connect Singapore's population to its water. The ABC Programme includes water-based nature areas, but also has supported extensive research and demonstration projects related to stormwater runoff management and ***Low Impact Development*** (LID) technologies (e.g. PUB, 2011).

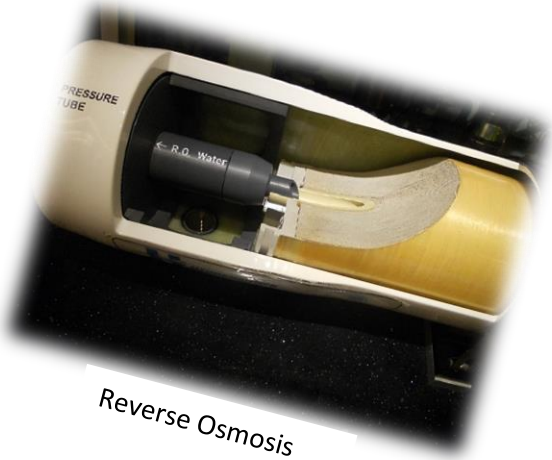
1.2. Water Quality and the Secondary 1 Geography Curriculum

The new syllabuses for geography place an emphasis on geographical investigations (GI) as a means to give students opportunities to appreciate real world application of geographical knowledge and skills as well as help them acquire 21st century competencies. Under the lower secondary school geography syllabus topic of water shortage, students conduct a GI into the water quality of a selected water body, as well as how human activities affect the water quality in that location. Clearly, this is an important issue with respect to the Runoff from Local Catchments tap. Singapore's storm drains receive runoff from a mix of land uses, so it is imperative to manage runoff in a way that both minimizes flooding *and* water pollution. We each can do our part, for example, through best housekeeping practices around our HDBs (e.g. picking up after pet dogs, maintaining proper waste disposal, avoiding automobile maintenance or cleaning in the car parks). The PUB and URA play very important roles too, in implementing LID to reduce localized flooding and improve water quality, for example, as well as maximizing Singapore's green space. Some of these connections between urban planning and water quality are not always clear and it is the goal of the Sustainability Learning Lab to provide support in making such connections. Some of these concepts will be scafolded throughout secondary and up to A-level geography where the *influence of land use on infiltration rates* is explored as a GI, as is *liveability of urban neighbourhoods*. Green space, LID, and innovative water management all have a role in *Improving Liveability in Cities* (e.g. Irvine et al., 2016).

Typically, the GI for water quality involves fieldwork to collect and analyse samples, but also may involve post-fieldwork efforts such as library research to place data results in context. The intent here is for students to organize and analyse the data using sound reasoning skills, making appropriate connections between their field observations, data, and secondary information, thereby constructing new knowledge. Essentially, these become the steps of inquiry-based learning. There are many different water quality questions and approaches to water quality evaluations that could be employed and the intent of this Handbook is to provide support to teachers and students for collecting and analysing samples and evaluating the data to draw appropriate conclusions.

AAG333 Visit to the NEWater plant, 2012

Micro-filtration



Reverse Osmosis

Ultraviolet

Chapter 2
Water Quality Parameters

2.1. Introduction

A number of different water quality parameters could be assessed and general categories of pollutants are summarized in Table 2.1. Although Table 2.1 is helpful in categorizing the different types of pollutants and their sources, it would not be feasible (time-wise, technically, budget-wise) for schools to examine such a broad list. So, the question becomes, what pollutants to assess? In some areas, specific contaminants are very important with respect to human health, for example, arsenic contamination of groundwater used for drinking in parts of south and southeast Asia (Charlet and Polya, 2006; Feldman et al., 2007; Berg et al., 2007; Sampson et al., 2008; Phan et al., 2010; Chea et al., 2016). In such cases, very directed sampling programs might be developed to address a specific problem. However, sometimes we want to get a general indication of ecosystem health and track changes in health over time. The question then becomes, what are the best overall indicators of water quality?

Table 2.1 Major Categories of Water Pollutants

Category	Examples	Sources
A. Causes Health Problems		
1. Infectious agents	Bacteria, viruses, parasites	Human and animal excreta
2. Organic chemicals	Pesticides, plastics, detergents, oil, gasoline	Industrial, household, and farm use
3. Inorganic chemicals	Metals, salts	Industrial effluents, household cleansers, surface runoff
4. Radioactive materials	Uranium, thorium, cesium, iodine, radon	Mining and processing or ores, power plants, weapons production, natural sources
B. Causes Ecosystem Disruption		
1. Sediment	Soil, silt	Land erosion
2. Plant nutrients	Nitrates, Phosphates	Agricultural and urban fertilizers, sewage, manure
3. Oxygen-demanding wastes	Animal manure, plant residues	Sewage, agricultural runoff, paper mills, food processing
4. Thermal	Heat	Power plants, industrial cooling

A variety of water quality monitoring approaches and programmes have been developed in different countries over the years, but a Water Quality Index (WQI) approach has become popular, particularly with government agency-citizen not-for-profit partnerships, and the WQI approach has been applied to countries throughout the world (Dunnette, 1979; Bhargava, 1983; House and Ellis, 1987; House, 1990; Smith, 1990; Palupi et al., 1995; Wills and Irvine, 1996; Pesce et al., 2000; Bordalo et al., 2001; 2006; Cude, 2001; Liou et al., 2004; Debels et al., 2005; Kannel et al., 2007; Sanchez et al., 2007; Boyacioglu, 2010; Cordoba et al., 2010; Sharma and Kansal, 2011; Gazzaz et al., 2012; Akkoyunlu and Akiner, 2012). There are a number of advantages to using a WQI. WQIs generally synthesize results

for multiple water quality parameters into a single value between 0 and 100, with values closer to 100 representing better water quality. This single value representation facilitates the communication of complicated water quality data to politicians and the general public. Tracking changes in a single value also is more straightforward, but at the same time, the full data set behind the single values is retained, so if a more detailed investigation is required, this also can be done.

2.2. Which WQI?

In this Handbook, we will use the WQI originally developed for the National Sanitation Foundation (NSF)(Brown et al., 1970) but which subsequently has been applied globally. Mitchell and Stapp (1995) provided a clear and concise set of steps to applying the NSF WQI that we will build on in this Handbook. The original NSF WQI (Brown et al., 1970) was constructed using a Delphi approach and this has been summarized by Wills and Irvine (1996) and Kumar and Alappat (2008). In essence, Brown et al. (1970) assembled a panel of 142 persons throughout the U.S.A. with known expertise in water quality management. Three questionnaires were mailed to each panelist. In the first, the panelists were asked to consider 35 analytes for possible inclusion in a WQI and to add any other analytes they felt should be included. The panelists also were asked to rate the analytes that they would include on a scale from 1, (highest significance), to 5, (lowest significance). The results from the first survey were included with the second questionnaire and the panelists were asked to review their original response. The purpose of the second questionnaire was to obtain a closer consensus on the significance of each analyte. Also included was a list of nine new analytes that had been added by some respondents in the first questionnaire. For the second questionnaire, the panelists were asked to list no more than 15 most important analytes for inclusion from the new total of 44.

From these first two responses, Brown et al. (1970) derived nine analytes for inclusion in the WQi. In the third questionnaire, the panelists were asked to draw a rating curve for each of the nine analytes on blank graphs provided. Brown et al (1970) then averaged all the curves to produce a single line for each analyte. Statistical analysis of the ratings enabled Brown et al (1970) to assign weights to each analyte, where the sum of the weights was equal to 1. The nine analytes and their corresponding weights are listed in Table 2.2. The WQ value for each analyte then is calculated as the product of the rating curve value (also known as the Q-value) and the WQI weight. Greater weights in Table 2.2 indicate a consensus by water quality experts that those parameters are a better general indicator of water quality than others and as such should have more importance or influence in the calculation of the WQI. More detail will be provided about the application of the NSF WQI in Chapters 3 and 4.

An interesting alternative to the NSF WQI was developed under the auspice of the Canadian Council of Ministers of the Environment and instead of using a Delphi expert opinion approach, it is based on the water quality standards of the particular country. Any parameter of interest for which there is a standard can be included in this WQI. Kahn et al. (2004; 2005) summarize this WQI very nicely, but the basis of the calculation lies in three factors (F):

F1 (Scope) - represents the % of variables that do not meet their objectives at least once during the time period of consideration, relative to the total number of variables measured.

F2 (Frequency) - represents the % of individual tests that do not meet objectives (i.e. failed tests)

F3 (Amplitude) - the amount by which the failed tests do not meet their objectives.

It should be noted that the use of indices is not without its detractors (Chapman, 2011; 2016; Green and Chapman, 2011) and most certainly interpretation of indices must be done with care. Irvine and

Murphy (2009) used a weight-of-evidence approach that included several indices to assess degradation of phytoplankton communities in the Buffalo River Area of Concern, while Greer et al. (2002) found that benthic macroinvertebrate indices were in general agreement with NSF WQI values for seven sites on Cazenovia Creek, NY, suggesting a slightly impacted status. The approach of using multiple indices may aid with environmental interpretation. Kumar and Alappat (2009) more recently suggested that while the NSF WQI has been extensively utilized by state and interstate water pollution control agencies in the U.S., a reassessment of the included parameters might be considered, particularly in light of evolving analytical methodologies, water quality concerns, and the general Delphi technique used by Brown et al. (1970) in the first place. Despite shortcomings identified with an index approach, I would argue that an index evaluation also has pedagogical value. As we will see, the NSF WQI, for example, requires students to apply basic calculation and graphing skills, interpret data, and to think critically about what parameters seem to have the greatest influence on water quality in their watershed, and in fact debate whether the index is a useful tool.

Table 2.2 NSF WQI Analytes and Weights

Analyte	WQI Weight
Dissolved Oxygen	0.17
Fecal Coliform	0.15
pH	0.12
BOD_5	0.10
Nitrates	0.10
Phosphates	0.10
$\Delta t\ ^oC$	0.10
Turbidity	0.08
Total Solids	0.08

2.3. NSF WQI Water Quality Parameters

2.3.1. Dissolved Oxygen (DO)

The first question we might ask is “why is dissolved oxygen important?” Well….. just as we need oxygen to survive, so do most aquatic organisms. However, rather than breathing air directly, these organisms obtain their oxygen from the gas that is dissolved in the water.

But, HOW MUCH DISSOLVED OXYGEN DO WE NEED IN THE WATER?

Many countries use a “beneficial use” approach in developing water quality guidelines. For example, the beneficial use categories in Thailand, India, and New York State (NY), U.S.A. are shown in Table 2.3. Very often these beneficial use categories consider the protection of aquatic organisms, human health, and human economic activities.

Table 2.3 Beneficial Use Categories for Surface Waters

Thailand (http://www.pcd.go.th/info_serv/en_reg_std_water05.html#s3)	
Class 1	Extra clean fresh surface water resources used for: (1) conservation, not necessary to pass through water treatment processes and requires only ordinary processes for pathogenic destruction; (2) ecosystem conservation where basic organisms can bread naturally.

Class 2	Very clean fresh surface water resources used for: (1) consumption which requires ordinary water treatment processes before use; (2) conservation of aquatic organisms; (3) fisheries; (4) recreation.
Class 3	Medium clean fresh surface water resources used for: (1) consumption, but passing through an ordinary treatment process before use; (2) agriculture.
Class 4	Fairly clean fresh surface water resources used for: (1) consumption, but requires special water treatment processes before use.
Class 5	The sources which do not fall under classes 1-4, and used for navigation.
India (http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.485.3428)	
Class A	Waters for use as drinking water source without conventional treatment but after disinfection.
Class B	Waters for use for organised outdoor bathing.
Class C	Waters for use as drinking water source with conventional treatment followed by disinfection.
Class D	Waters to maintain aquatic life (i.e. propagation of wildlife and fisheries).
Class E	Waters for use for irrigation, industrial cooling and controlled waste disposal.
New York State, U.S.A. (https://govt.westlaw.com/nycrr/Browse/Home/NewYork/NewYorkCodesRulesandRegulations?guid=I06849fe0b5a111dda0a4e17826ebc834&originationContext=documenttoc&transitionType=Default&contextData=(sc.Default))	
Class n	(a) The best usages of Class N waters are the enjoyment of water in its natural condition and, where compatible, as a source of water for drinking or culinary purposes, bathing, fishing, fish propagation, and recreation. The waters shall be suitable for shellfish and wildlife propagation and survival and fish survival. (b) There shall be no discharge of sewage, industrial wastes, or other wastes, waste effluents or any sewage effluents not having had filtration resulting from at least 200 feet of lateral travel through unconsolidated earth. A greater distance may be required if inspection shows that, due to peculiar geologic conditions, this distance is inadequate to protect the water from pollution. (c) These waters shall contain no deleterious substances, hydrocarbons or substances that would contribute to ***eutrophication***, nor shall they receive surface runoff containing any such substance. (d) There shall be no alteration to flow that will impair the waters for their best usages.
Class AA-Special	(a) The best usages of Class AA-S waters are: a source of water supply for drinking, culinary or food processing purposes; primary and secondary contact recreation; and fishing. The waters shall be suitable for fish, shellfish and wildlife propagation and survival. (b) These waters shall contain no floating solids, settleable solids, oil, sludge deposits, toxic wastes, deleterious substances, colored or other wastes or heated liquids attributable to sewage, industrial wastes or other wastes. (c) There shall be no discharge or disposal of sewage, industrial wastes or other wastes into these waters. (d) These waters shall contain no phosphorus and nitrogen in amounts that will result in growths of algae, weeds and slimes that will impair the waters for their best usages. (e) There shall be no alteration to flow that will impair the waters for their best usages.

	(f) There shall be no increase in turbidity that will cause a substantial visible contrast to natural conditions.
Class A-Special	(a) The best usages of Class A-S waters are: a source of water supply for drinking, culinary or food processing purposes; primary and secondary contact recreation; and fishing. The waters shall be suitable for fish, shellfish and wildlife propagation and survival. (b) This classification may be given to those international boundary waters that, if subjected to approved treatment, equal to coagulation, sedimentation, filtration and disinfection with additional treatment, if necessary, to reduce naturally present impurities, meet or will meet New York State Department of Health drinking water standards and are or will be considered safe and satisfactory for drinking water purposes.
Class AA	(a) The best usages of Class AA waters are: a source of water supply for drinking, culinary or food processing purposes; primary and secondary contact recreation; and fishing. The waters shall be suitable for fish, shellfish and wildlife propagation and survival. (b) This classification may be given to those waters that, if subjected to approved disinfection treatment, with additional treatment if necessary to remove naturally present impurities, meet or will meet New York State Department of Health drinking water standards and are or will be considered safe and satisfactory for drinking water purposes.
Class A	(a) The best usages of Class A waters are: a source of water supply for drinking, culinary or food processing purposes; primary and secondary contact recreation; and fishing. The waters shall be suitable for fish, shellfish and wildlife propagation and survival. (b) This classification may be given to those waters that, if subjected to approved treatment equal to coagulation, sedimentation, filtration and disinfection, with additional treatment if necessary to reduce naturally present impurities, meet or will meet New York State Department of Health drinking water standards and are or will be considered safe and satisfactory for drinking water purposes.
Class B	The best usages of Class B waters are primary and secondary contact recreation and fishing. These waters shall be suitable for fish, shellfish and wildlife propagation and survival.
Class C	The best usage of Class C waters is fishing. These waters shall be suitable for fish, shellfish and wildlife propagation and survival. The water quality shall be suitable for primary and secondary contact recreation, although other factors may limit the use for these purposes.
Class D	The best usage of Class D waters is fishing. Due to such natural conditions as intermittency of flow, water conditions not conducive to propagation of game fishery, or stream bed conditions, the waters will not support fish propagation. These waters shall be suitable for fish, shellfish and wildlife survival. The water quality shall be suitable for primary and secondary contact recreation, although other factors may limit the use for these purposes.

Singapore does not have the same type of system, but does have water quality guidelines for “Highly Efficient Water Pollution”; “Allowable Limits for Trade Effluent Discharge to Sewer/ Watercourse/ Controlled Watercourse”; and “Recreational Water Quality”. Singapore does not have a specific guideline for dissolved oxygen in surface waters, but the guidelines for Thailand and New York State are provided in Table 2.4.

Table 2.4 Surface Water Quality Standards for Dissolved Oxygen, mg/L

Thailand	
Class 1	N*
Class 2	6.0
Class 3	4.0
Class 4	2.0
Class 5	N
New York State, U.S.A	
Class A-Special	In rivers and upper waters of lakes, not less than 6.0 mg/L at any time. In ***hypolimnetic*** waters, it should not be less than necessary for the support of fishlife, particularly cold water species.
Classes AA, A, B, C, AA-Special	For ***trout*** spawning waters (TS) the DO concentration shall not be less than 7.0 mg/L from other than natural conditions. For trout waters (T), the minimum daily average shall not be less than 6.0 mg/L, and at no time shall the concentration be less than 5.0 mg/L. For nontrout waters, the minimum daily average shall not be less than 5.0 mg/L, and at no time shall the DO concentration be less than 4.0 mg/ L.
Class D	Shall not be less than 3.0 mg/L at any time.

*Natural level for that waterbody

The required level of dissolved oxygen also will vary according to the type of fish or aquatic organism and we might note that there are no trout or cold water fisheries in Singapore. Tilapia commonly are raised and harvested because they can survive in water with dissolved oxygen levels of 1 mg/L or less, although the optimum level is at least 3 mg/L (http://pubstorage.sdstate.edu/AgBio_Publications/articles/fs963-02.pdf). Freshwater prawns require higher levels of dissolved oxygen, preferably >4 mg/L (New, 2002).

WHERE DOES THE DISSOLVED OXYGEN COME FROM?

Air mixing with the water is the primary external source of oxygen. Air mixing is enhanced by moving water and turbulence. Faster flowing streams exhibit greater turbulence than still water, such as lakes and ponds, and therefore tend to have higher dissolved oxygen levels than the still waterbodies.

Within a waterbody, the process of photosynthesis by green plants and algae also produces oxygen as a by-product:

$$6CO_2 + 6H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2 \qquad [2.1]$$

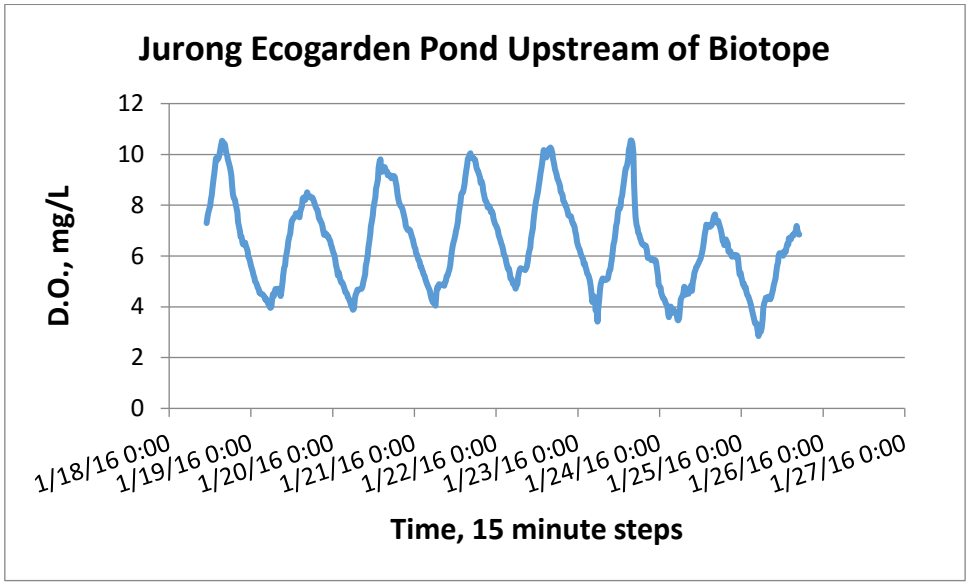
where the $C_6H_{12}O_6$ is glucose, which can be converted into chemicals, such as cellulose, needed for development of plant cells, can combine with nutrients such as nitrogen, phosphorus, and sulfur, to build complex molecules such as proteins and nucleic acids, can be converted into starch, a storage molecule, that can be converted back to glucose when the plant requires, or can be broken down during the process of respiration, which releases energy stored in the glucose ***molecules***.

Because photosynthesis requires sunlight (shortwave radiation energy), it will occur only during daylight hours. Of course, when the sun sets photosynthesis stops, but the aquatic organisms do not stop their activity. They carry on with respiration, a biological process that consumes oxygen and also results in the production of CO_2:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{heat} \qquad [2.2]$$

Therefore, as we see in Figure 2.1, dissolved oxygen levels in a waterbody may be greatest near solar noon, while just before sunrise, the dissolved oxygen can be quite low (see also, Odum, 1956; Ansa-Asare et al., 1999; Williams et al., 2000; McBride and Chapra, 2005; Price et al., 2011).

a



b

Figure 2.1 (a) Dissolved oxygen levels logged at 15 minute time steps using a YSI 6920 datasonde in the Jurong Ecogarden pond upstream of the biotope; and (b) NIE students manual sampling with the YSI 6920 datasonde at the location where it was installed upstream of the biotope for the data logging.

Through the data then, we see a clear daily cycle of photosynthesis and respiration affecting dissolved oxygen levels in a waterbody. This can be considered part of the waterbody metabolism (after McBride and Chapra, 2005):

$$\frac{dD}{dt} + k_a D = R - P(t) \qquad [2.3]$$

where D is the dissolved oxygen deficit, mg/L, calculated as C_{sat} – C, with C being the D.O. concentration (mg/L) and C_s its saturated value; t is time (day); k_a is the first–order stream reaeration coefficient (per day); R is the respiration rate (mgO/L/day); and P(t) is the time-varying plant primary production (photosynthesis) rate (mgO/L/day).

WHAT FACTORS AFFECT DO LEVEL?

Other factors in addition to photosynthesis and respiration affect DO, with two important factors being water temperature and presence of organic pollution.

Warmer water has less capacity to hold oxygen than colder water and therefore DO levels in warmer water tend to be lower, as illustrated in Figure 2.2. This occurs because as the water molecules heat up and gain kinetic energy, they move or vibrate more quickly, creating greater gap space between the molecules, thereby allowing the gas phase of O_2 to be released more readily to the atmosphere. Looking at it in another way, this is why it is better to keep carbonated soda pop in a refrigerator if you are to be away for a period of time. Warmer carbonated soda pop will become "flat" more quickly as the CO_2 gas releases more quickly than chilled soda pop.

If there is a lot of organic pollution in the water (e.g. presence of wastewater) then the decay of the organic material will consume oxygen and reduce DO levels. So, low levels of DO can be an indicator of the presence of organic pollution. For example, as we see in Figure 2.3, the dissolved oxygen may "sag" or be reduced in a river when a ***combined sewer overflow*** discharges to it. This process also is well-illustrated in the Boeng Cheung Ek wetland of Phnom Penh, Cambodia (Figure 2.4). The Boeng Cheung Ek wetland receives wastewater from the south part of the city for treatment purposes before it discharges to the Bassac River (a distributary of the Mekong River). During the dry season (November through May), when mostly wastewater enters the wetland the dissolved oxygen levels decrease (Figure 2.4). During the rainy season (June through October) when a freshwater pulse enters the wetland from the Bassac River due to high water levels, this freshwater mixes with the wastewater and the dissolved oxygen levels increase (Figure 2.4).

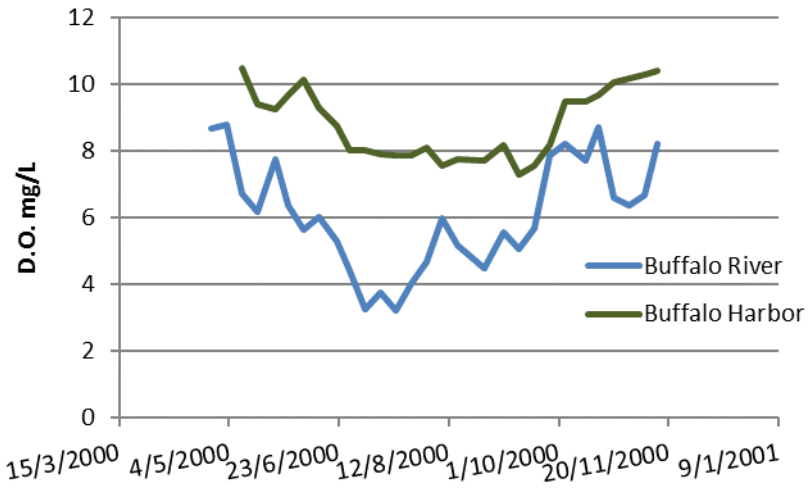


Figure 2.2 Weekly mean dissolved oxygen (D.O., based on measurements made every 15 minutes by Hydrolab Datasonde 4a's) for the Buffalo River and Buffalo Harbor, NY. The river dissolved oxygen is lower, primarily because of the hydraulics of the river, while the harbor is more reflective of dissolved oxygen at the eastern end of Lake Erie. In general, we see that both sites have lower dissolved oxygen levels in the July through September period when water temperatures are higher (from Irvine, 2013).

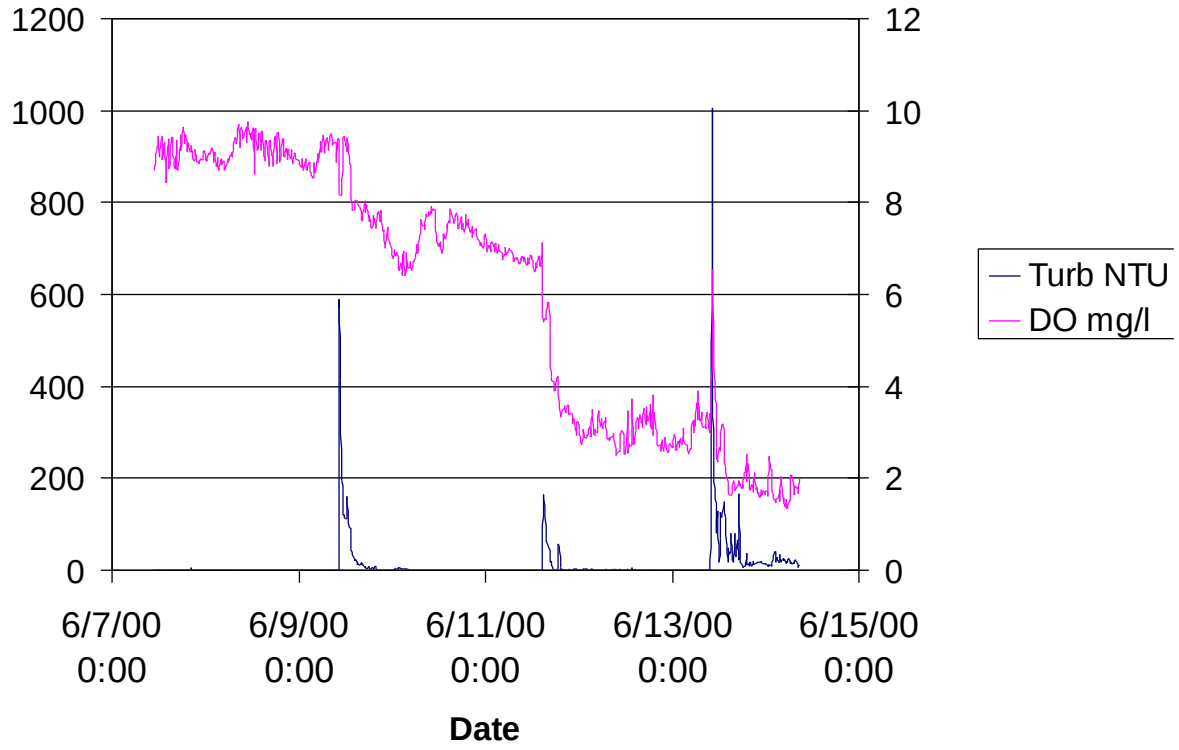


Figure 2.3 Turbidity and dissolved oxygen monitoring in the Black Rock Canal, Buffalo, NY. The monitoring site was adjacent to a combined sewer outfall and the spikes in turbidity are indicative of a combined sewer discharge into the canal. A corresponding reduction (sag) in dissolved oxygen also is observed (after Irvine et al. 2005a).

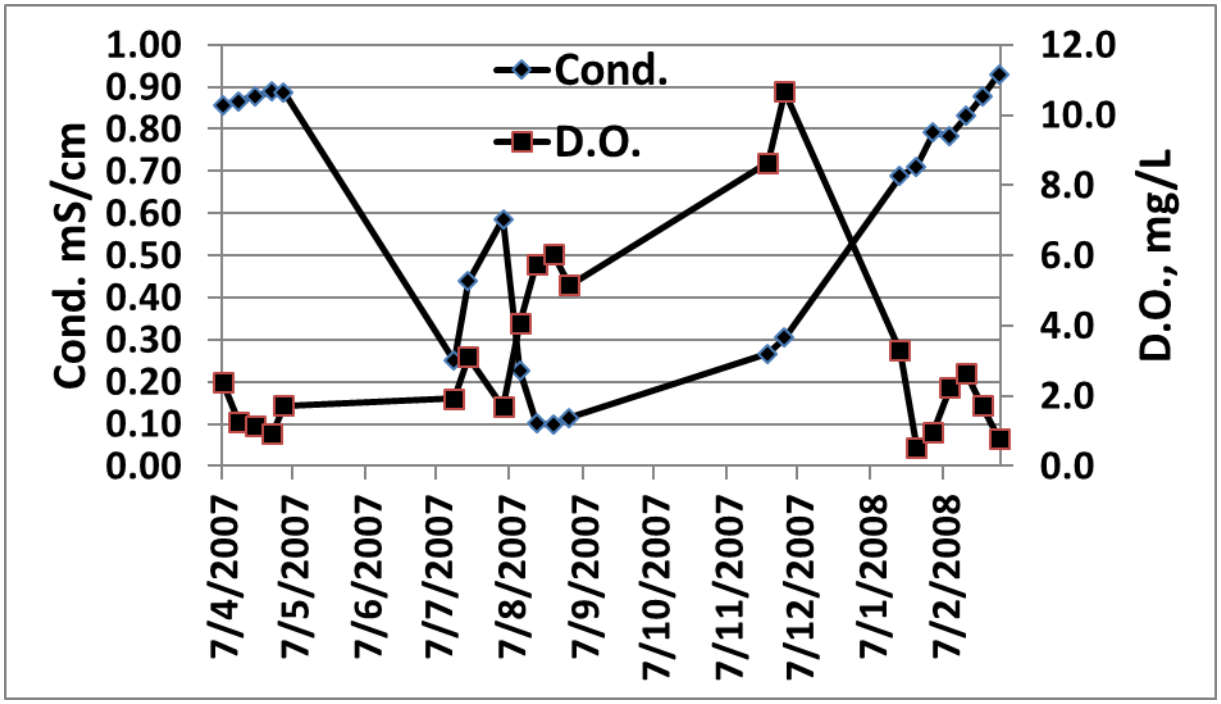


Figure 2.4 Weekly mean conductivity and dissolved oxygen levels in the Boeng Cheung Ek wetland, Phnom Penh, Cambodia. Note that dissolved oxygen is high and conductivity is low in the rainy season due to flushing and dilution by freshwater inflow from the Bassac River, whereas conductivity is high and dissolved oxygen is low during the dry season when most of the water entering the wetland is municipal sewage from Phnom Penh (after Visoth et al., 2010).

2.3.2. Indicator Bacteria

WHAT ARE INDICATOR BACTERIA?

There are many different bacteria species that are ***pathogenic*** and may result in waterborne illness, including ***Salmonella typhi***, ***Shigella***, ***Campylobacter***, ***Vibrio cholera***, ***Legionella***, ***Pseudomonas***, and some strains of Escherichia coli (E. coli)(Cabral, 2010; Centers for Disease Control and Prevention, 2010,http://www.hip.fhi360.org/file/28138/FactSheet%20on%20Microbiological%20Indicator%20Testing.pdf). Often these waterborne illnesses can be sourced to poor sanitation, but it is both difficult and costly to measure individual pathogens in surface waters and drinking water on a routine monitoring basis and as a result health organizations generally take an "indicator" approach to monitoring. An indicator approach relies upon the identification of a particular group of bacteria that generally are not harmful in and of themselves, but indicate the presence of fecal contamination and the *potential* for pathogenic species to be present. The most commonly tested fecal bacteria indicators are total coliforms, fecal coliforms, Escherichia coli, fecal streptococci, and enterococci. These indicators may be used to test the quality of surface water (e.g. at swimming areas) and drinking water. Ashbolt et al. (2001) and Griffen et al. (2001) provide summaries of the historical development of indicator approaches to assess water quality that date back to at least the early 1900's.

Francey et al. (1993) noted that following an extensive epidemiological study in which E. coli concentration was shown to be a better predictor of swimming-associated gastrointestinal illness than fecal coliform concentration, the United States Protection Agency (U.S. EPA) recommended in 1986 that E. coli was preferrable for recreational water standards than fecal coliform. Fecal coliform had

replaced total coliform as the preferred water quality standard in the U.S. in 1972. E. coli is part of the fecal coliform group and both are found in the intestines of warm-blooded animals (including humans), thereby indicating the presence of fecal contamination in water.

Griffin et al. (2001) also noted that in the 1980's, the U.S. EPA and concluded that while E. coli was the preferred indicator for freshwater quality standards, enterococci (a subgroup of fecal streptococcus) also could be used for freshwater as well as saltwater, a recommendation that recently was reiterated (U.S. EPA, 2012). In this Handbook we will focus primarily on E. coli.

WHAT INDICATOR TO USE AND HOW?

Generally, indicator use for freshwater contact is based on epidemiological studies at beaches, which results in the recommendation of some safe guideline or threshold value. For example, the U.S. EPA (2012) recommends a recreational water quality criteria for E. coli of 126 cfu/100 mL for freshwater contact (based on a 30 day geometric mean and illness rate of 36 per 1,000 recreators). The U.S. EPA also recommends a level of 35 cfu/100 mL (based on a 30 day geometric mean and illness rate of 36 per 1,000 recreators) for enterococci in freshwater or marine waters. In Singapore, enterococci is used as the standard for recreational beaches and freshwater, where 95% of the time the enterococci counts should be less than or equal to 200 cfu/100 mL. For drinking water E. coli often is used as the standard and generally it is accepted the level should be 0 cfu/100 mL to minimize health risks.

There is ongoing study and debate regarding the applicability of indicator bacteria in developing water quality guidelines, as some studies report significant correlation between incidence of beachgoer illness and bacteria level, while others do not find a good correlation (e.g. Francey et al., 1993; Ashbolt et al., 2001; Wade et al. (2003; 2006; 2010); Marion et al. (2010); Enns et al. (2012). In contrast to the U.S. EPA recommendations and the guidelines used in Singapore, a study for beaches in Hong Kong showed that E. coli was the best predictor of beachgoer illness (Cheung et al., 1990). Others (e.g. Kim and Grant, 2004; Boehm, 2007; Enns et al., 2012) have examined the variability of indicator bacteria within a waterbody and environmental variables that can play an important role in increasing variability. This uncertainty in indicator results has led some to explore a more risk-based approach rather than a strict single guideline value (e.g. Wong et al., 2008; Ashbolt et al. 2010).

WHERE DOES THE BACTERIA COME FROM?

Human activities can greatly increase the concentrations of pathogenic bacteria and sources that elevate indicator bacteria levels include stormwater runoff and nonpoint sources from urban and agricultural land uses, combined sewer overflows, poorly performing wastewater treatment plants, and failing or poorly designed septic systems (Irvine and Pettibone, 1993; Hrudey et al., 2003; Borchardt et al., 2003; Irvine et al., 2005b; Thurston Enriques et al., 2005; Selvakumar and Borst, 2006; Harmel et al., 2010; Irvine et al., 2011a; Passerat et al., 2011).

It is relatively straightforward to sample and analyse water samples for indicator bacteria levels such as E. coli and throughout the world, health agencies routinely monitor water quality at beaches and in source waters used for drinking. However, it is interesting to note that river bed sediment can be a reservoir for bacteria. Bacteria will attach and enhance settling of suspended sediment (Liss et al., 2004), eventually inoculating the bed sediment. The bed sediment provides a protective environment that can facilitate growth of bacteria so that eventually concentrations in bed sediment may be several orders of magnitude higher than the overlying water (Goyal et al., 1977; Stephenson and Rychert, 1982; Sherer et al., 1992; Irvine and Pettibone, 1993; Davies et al., 1995). The bacteria in the bed sediment may re-suspend during storm events or other disturbances and negatively impact quality of the overlying water (Pettibone et al., 1996; Muirhead et al., 2004; Kim et al. 2010). In a similar train of

thought, investigations have shown that beach sands can harbour bacteria, thereby posing a health risk to those digging or playing in the sand (Beversdorf et al., 2007; Halliday and Gast, 2010; Whitman et al., 2014), but beach sand is not part of the routine monitoring.

One of the limitations of the indicator bacteria assessment is that it does not tell us the precise source of the bacteria. For example, E. coli can be found in the intestines of humans as well as other warm-blooded animals and even watersheds unaffected by human activity may detectable levels of E. coli due to natural wildlife (Irvine and Pettibone, 1996; Donnison et al., 2004). One of the early methods to try and distinguish the sources of bacteria was the simple fecal colifirm:fecal streptococci ratio where a ratio of 4 or greater indicates bacteria predominantly are from human sources, ratios of 0.6 or less suggest warm blooded animals other than humans are the predominant source of bacteria, and ratios between 0.7 and 3 are indeterminant, representing a differential die off rate of the organisms. While the FC:FS ratio has been used successfully when careful consideration is made of the die off rate (e.g. Geldreich, 1972; Baxter-Potter and Gilliand, 1988; Irvine and Pettibone, 1996), Ashbolt et al. (2001) note that the use of this ratio is not recommended unless very recent faecal pollution is being monitored. More recently, higher tech approaches such community level physiological profiling and next-generation gene sequencing have been used to identify sources (e.g. Layton et al., 2006; Mieskin et al., 2009; Yergeau et al., 2012; Staley et al., 2015), but such techniques still tend to be in the research stage rather in applications of routine monitoring.

2.3.3. pH

WHAT IS pH?

There is some debate, but “pH” can be thought of as an acronym for “potential hydrogen”, or some people say “power of hydrogen”. When we measure the pH of a waterbody we really are measuring the relative concentration of H^+ ***ions*** to OH^- ions in the water. For example, if we dissolve carbon dioxide gas (a component of our atmosphere) into water we get a weak form of carbonic acid:

$$CO_2 + H_2O = H_2CO_3 \qquad [2.4]$$

The H_2CO_3 can further break down or dissociate in water, however, because other water molecules will attract the 2 hydrogens through hydrogen bonding, pulling the carbonic acid molecule apart:

$$H_2CO_3 = HCO_3^- \text{ (hydrogen carbonate) and } H^+ \qquad [2.5]$$

So, pH here is reflecting the higher concentration of H^+.

The pH scale ranges between values of 0 and 14, with 7 being neutral. If there are more H^+ ions, then the pH will be less than 7 and the water is called acidic. If there are more OH^- ions, then the pH will be greater than 7 and the water is called basic. The pH levels of common liquids used in everyday activities and some foods are shown in Figure 2.5.

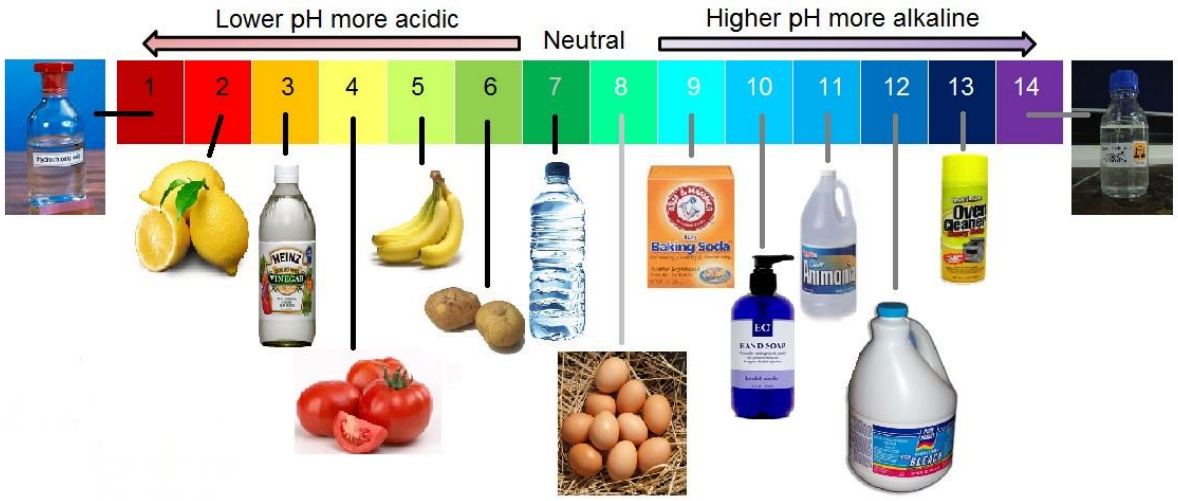


Figure 2.5 The pH of common liquids and foods.

It is important to note that the pH scale is logarithmic, or nonlinear, so if we go from a pH of 6 to a pH of 5, we have increased acidity by 10 times. If we go from a pH of 6 to a pH of 4, we have increased the acidity (or concentration of H^+) ions by 100 times.

Most people are surprised to find out that rainwater, even in a pristine environment, is slightly acidic, with a pH of around 5.6. This is because of the composition of our atmosphere that naturally contains sulfur oxides, nitrogen oxides, and carbon dioxide which mix with the cloud droplets and rainfall. Of course human activities such as burning fossil fuels can increase the acidity of the rain (Boubel et al., 1994; Botkin and Keller, 1998).

WHAT FACTORS CAN AFFECT pH IN THE ENVIRONMENT?

The pH of a waterbody can be affected by a number of factors and the pH can vary both temporally and spatially. The pH in a pond or lake, for example, may vary through the day (Figure 2.6). The pH may decrease at night because the green algae and plant respiration will release carbon dioxide and the reactions will occur as we see in equations [2.4] and [2.5], above.

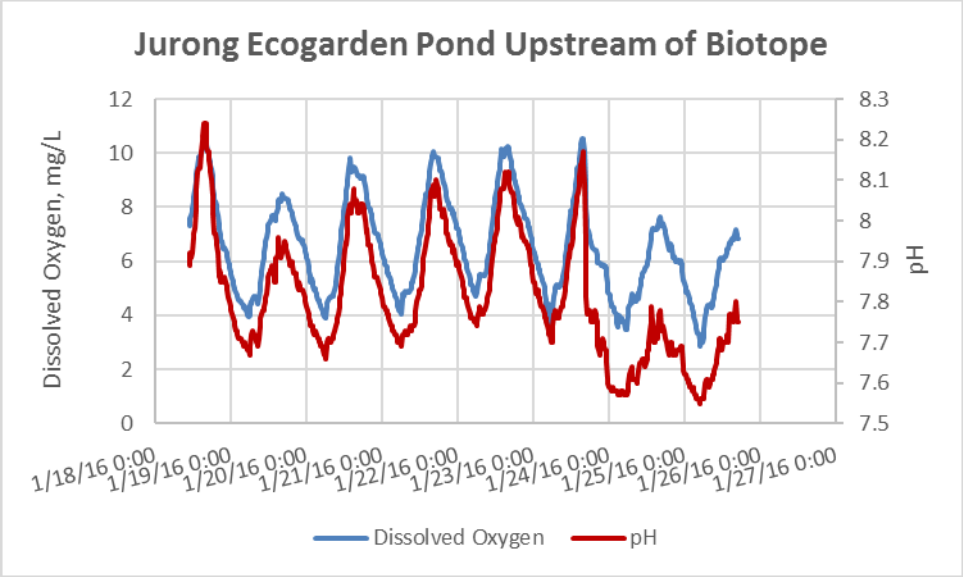


Figure 2.6 Relationship between dissolved oxygen and pH at Jurong Ecogarden. Both peak around solar noon with maximum photosynthesis and are lowest at night when photosynthesis stops and the respiration process dominates.

The pH of a waterbody will be affected by rainfall pH as well as natural factors and human activities in the watershed. For example, if the bedrock is limestone or dolomite, there will be a natural buffering effect that will make the pH of lakes and streams higher or more basic (e.g. Cowell and Ford, 1980; Gunn and Keller, 1984). The peat swamp forests of Malaysia and Indonesia may have rivers with a natural pH as low as 2.6-3.8 due to high levels of organic and ***humic acids*** (Table 2.5). Ore and coal mining activities that expose rocks having iron pyrite (FeS_2) and other sulfur-bearing minerals can result in highly acidic runoff. Many metals occur chiefly as sulfide ores (e.g., zinc in sphalerite), and these tend to be associated with pyrite, which is the most abundant sulphide mineral on the planet. Coal deposits also contain variable (generally 1–20%) amounts of "pyritic-sulfur" as well as organic sulfur, and can result in ***acid mine drainage*** problems (Johnson and Hallberg, 2005). A generalized equation for pyrite oxidation shows that the end result is an elevated level of H^+ ions:

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \qquad [2.6]$$

Low pH can negatively affect water quality as metals that are attached to sediment in the bottom of a pond or river may be released to the water and become more bioavailable (Warren and Haack, 2001; Hatje et al., 2003; Atkinson et al., 2007). The greater bioavailability of metals can affect aquatic organisms, but pH can have other health effects too. For example, a low pH can affect the balance of salts in fish tissue and this may lead to poorer reproduction. Of course different aquatic organisms will have different tolerance ranges. As we see in Figure 2.7, for example, snails and clams are less successful in acidic water than frogs and ***perch***.

Table 2.5 Selected Water Quality Values for Black Water Locations in Malaysia

Study	Turbidity, NTU	pH	Dissolved Oxygen, mg/L	Conductivity, ms/cm	Temperature, C	Ammonia, mg/L
Beamish et al. (2003)[1]	1.0-53.4	3.4-5.5	2.2-6.1	0.022-0.168	26-28	0-0.29
Yule and Gomez (2009)[2]	Not determined	2.6-3.8	1.8-16	Not determined	25-32	Not determined
Rahim et al. (2009)[3]	Not determined	4.55	1.15	0.021	26.6	0.81
Gasim et al. (2007)[4]	1.5-17.2	3.53-4.55	0.5-1.76	0.053-0.062	26.2-28.9	Not determined
Irvine et al., 2013[5]	1.2	3.63	0.31	0.083	27.3	Not determined

[1] multiple sites, North Selangor peat forest, including an irrigation ditch
[2]multiple sites, North Selangor peat forest
[3]black water habitats, Batang Kerang floodplain, Balai Ringin, Serian, Sarawak
[4]multiple sites, Bebar River, Pahang
[5]Mean of recorded readings every 15 minutes, 21/5-24/5/2011, North Selangor peat forest

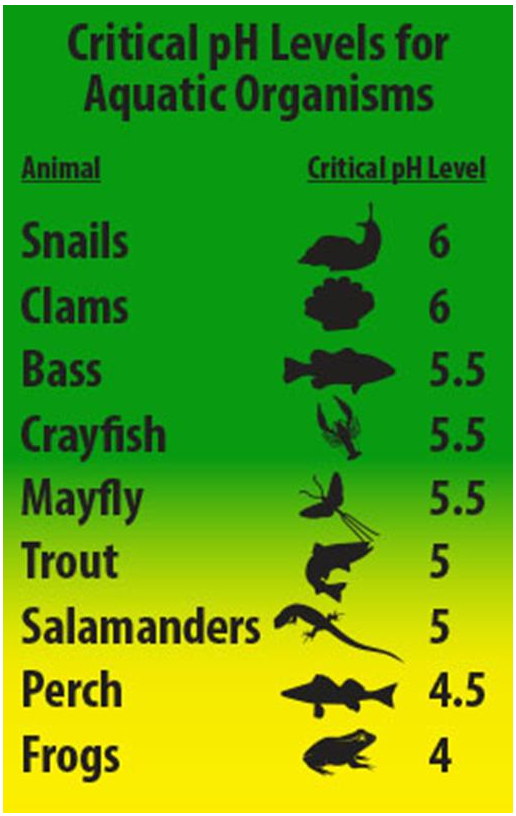


Figure 2.7 Critical pH levels for aquatic organisms (from https://www.epa.gov/acidrain/effects-acid-rain).

The pH guidelines for Thailand, New York State (U.S.), and Singapore are shown in Table 2.6.

Table 2.6 pH Guidelines

Country	Water Class	pH
Singapore	Allowable Limits For Trade Effluent Discharge To Sewer/ Watercourse/ Controlled Watercourse	6-9
U.S./New York State	AA, A, B, C, AA-Special, A-Special, GA	6.5-8.5
U.S./New York State	D	6-9.5
Thailand	Class 1	Natural
Thailand	Class 2-Class 4	5-9
Thailand	Class 5	NS

NS – no standard

2.3.4. BOD_5

Biochemical oxygen demand (BOD) is a measure of the amount of dissolved oxygen utilized by microorganisms during the oxidation of organic components in the effluent can be an indicator of contamination by wastewater. The BOD test normally is standardized to a 5 day measurement time (at 20°C), hence the designation BOD_5. In essence, we are measuring the difference in the DO of the water at the time of sampling compared to the DO level 5 days later. Most relatively unpolluted streams have a BOD_5 that ranges from 1 to 8 mg/L. If the BOD_5 value of a sample is less than 7 mg/L, sample dilution is not needed in the analysis. A BOD_5 value greater than 7 mg/L requires sample dilution. Dilution is necessary when the amount of DO consumed by microorganisms is greater than the amount of DO available in the air-saturated BOD_5 sample. BOD_5 in raw domestic wastewater may range between 100 and 400 mg/L (http://www.doh.wa.gov/portals/1/documents/pubs/337-107.pdf), while BOD_5 in wastewater effluent from agro-industries may be as high as 2,700 mg/L for tapioca starch extraction, 25,000 mg/L for sugar milling and 8,900 mg/L for coconut cream extraction wastewaters (Ng and Tjan, 2006).

2.3.5. Macronutrients

Macronutrients are those nutrients, such as nitrogen, phosphorus, and potassium, that generally are abundantly available in nature and are key components for algae and plant growth. In this Handbook we will focus on phosphorus and nitrogen since these two macronutrients are more indicative of environmental problems, especially cultural eutrophication.

2.3.5.1. Phosphorus

Phosphorus is a component of ***nucleic acids***, ***phospholipids***, and ***adenosine triphosphate*** (ATP) and a mineral constituent of bones and teeth. The only biologically important inorganic form of phosphorus is phosphate (PO_4), which plants absorb and use to synthesize organic compounds. More specifically for plants, phosphorus plays a role in photosynthesis, respiration, energy storage and transfer, cell division, and promotes leaf growth and root expansion.

A major reservoir of phosphorus is sedimentary rocks of marine origin. Also, large quantities of phosphorus are found in soils, dissolved in the oceans, and in organisms. Weathering of rocks gradually adds phosphate to soil. Some phosphate leaches into groundwater and surface water and moves to the ocean. Phosphate may be taken up by ***primary producers*** and incorporated into organic

material. Phosphate is returned to soil or water through decomposition of biomass or excretion by ***consumers***. Reservoirs for phosphorus and phosphorus movement through the environment (i.e. the phosphorus cycle) are summarized in Figure 2.8.

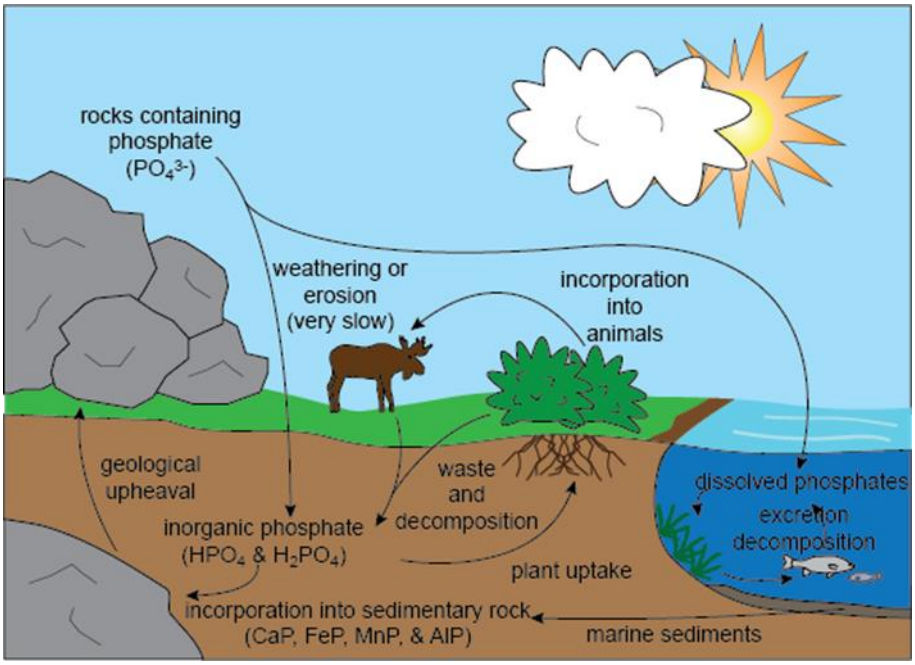


Figure 2.8 The phosphorus cycle (http://media1.shmoop.com/images/biology/biobook_eco_13.png).

2.3.5.2. Nitrogen

Nitrogen is a component of amino acids, proteins, and nucleic acids. Plants and algae can use nitrogen in the form of ammonium (NH_4) or nitrate (NO_3). Various bacteria can use NH_4, NO_3, or NO_2 (nitrite). Nitrogen is important in photosynthesis, promotes vigorous plant growth and produces a nice dark green color in the plant leaf.

The major reservoir of nitrogen is the atmosphere, which is 80% nitrogen gas (N2). Nitrogen also is found in soils and sediment of lakes, rivers, and oceans; is dissolved in surface water and groundwater; and is stored in living biomass. Nitrogen enters ecosystems primarily through bacterial nitrogen fixation. Ammonification by bacteria decomposes organic nitrogen. In nitrification, bacteria convert NH_4 to NO_3. In denitrification, bacteria use NO_3 for metabolism instead of O_2, releasing N_2. Reservoirs for nitrogen and nitrogen movement through the environment (i.e. the phosphorus cycle) are summarized in Figure 2.9.

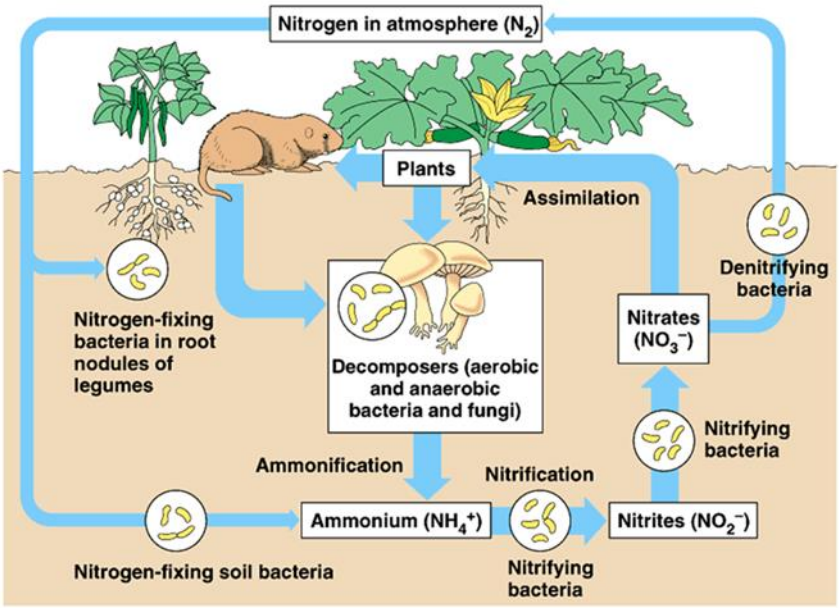


Figure 2.9 The nitrogen cycle.

2.3.5.3. Phosphorus and Nitrogen in the Environment

In agricultural areas, lawns, and parks, chemical fertilizers containing phosphorus and nitrogen often are spread to increase growth and productivity. However, too much of a good thing also can be a problem. Some of the additional phosphorus and nitrogen that is not taken up by the plants may be leached from the soil and transported to rivers, ponds, lakes and reservoirs. Once in the waterbodies algae will absorb the nutrients and happily grow.

The process of elevated nutrient levels due to human activities that leads to higher algae levels is known as cultural eutrophication and this can be bad news for a water body. First of all, uncontrolled algae growth, or an algae bloom, can result in a green scum or mat floating on the water surface. In addition to being unsightly, this mat reduces sunlight reaching aquatic plants below the water surface and these plants may die. Like all living organisms, the algae also will eventually die. The dead plants and algae will begin to decompose in the water and the decomposition process is fueled by the dissolved oxygen in the water. The decomposition therefore leads to lower dissolved oxygen levels in the water and as we saw in Section 2.3.1., most aquatic organisms, like fish, need good levels of dissolved oxygen to remain healthy. The classic work by Schindler and his colleagues in the freshwater experimental lakes of northwestern Ontario, Canada (Schindler, 1974; 2012; Schindler et al., 2008) elucidated this eutrophic relationship. In freshwater it seems that phosphorous is the ***limiting nutrient*** while in saline ocean waters, nitrogen may be more important (Granéli et al., 1990).

There is some discussion in the literature regarding the levels at which phosphorus and nitrogen may generate eutrophication problems and various proposed levels were summarized by Irvine and Murphy (2009; Table 2.7) for freshwater. It appears that threshold nutrient levels causing eutrophication problems can vary from waterbody to waterbody, depending on a complex interaction of physical, chemical, and biological factors. As a result, agencies frequently have not established numerical guidelines for nutrients. Singapore does not have a guideline for phosphorus, but for nitrate (as NO_3) the Allowable Limit for Trade Effluent to a Controlled Watercourse is 20 mg/L (http://www.nea.gov.sg/anti-pollution-radiation-protection/water-pollution-control/allowable-limits). In New York State, nutrient enrichment and eutrophication has been identified as one of the top 10 water quality issues facing the state. Currently the state uses a narrative water quality standard

rather than a numeric standard. As noted in previous sections, a numeric standard identifies a specific threshold value, while the narrative standard for phosphorus and nitrogen in New York State is: *None in amounts that result in the growths of algae, weeds and slimes that will impair the waters for their best usages* (http://www.dec.ny.gov/chemical/77704.html). In the North American (Laurentian) Great Lakes (Figure 2.10), the goals for phosphorus control are to maintain an oligotrophic state in Lakes Superior, Huron, and Michigan; to maintain algal biomass below that of a nuisance condition in Lakes Erie and Ontario; and to eliminate algal nuisance growth in bays and in other areas where they occur (Environment Canada and U.S. EPA, 2005). To meet these goals, total phosphorus guidelines are: Lake Superior – 5 µg/L; Lake Huron – 5 µg/L; Lake Michigan – 7 µg/L; Lake Erie (western basin) – 15 µg/L; Lake Erie (central basin) – 10 µg/L; Lake Erie (eastern basin) – 10 µg/L; Lake Ontario – 10 µg/L. These guidelines are non-regulatory and are used as guidance by agencies only.

Charlton et al. (1999) showed that summer total phosphorus levels declined in Lake Erie between the early 1970's and 1995, in response to phosphorus control measures (and in some way, by zebra mussel invasion), but levels increased between 1995 and 1999 in the eastern and central basins. The 1997 data reported by Charlton et al. (1999) indicated that the central and eastern basins of Lake Erie were meeting the 10 µg/L guideline, but the 15 µg/L guideline for the western basin was not being met. Makarewicz and Bertram (1991) concluded that the western basin of Lake Erie shifted from eutrophic to mesotrophic conditions between 1970 and 1985 and the eastern basin shifted from ***mesotrophic*** to ***oligotrophic*** during the same time. More recent data reported by Environment Canada and U.S. EPA (2005) shows that the western basin continues to not meet the 15 µg/L guideline. Generally, Lakes Superior, Huron, Michigan, and Ontario are meeting their open water guidelines (Environment Canada and U.S. EPA, 2005) although Makarewicz et al. (2006) reported that total phosphorus in Lake Ontario nearshore and embayment areas of New York State (41% of sample sites) did not meet the guideline in 2004. Charlton et al. (1999) also noted that nitrate/nitrite levels in Lake Erie have increased, while chlorophyll *a* levels have declined.

Table 2.7 Nutrient and ***Chlorophyll a*** Threshold Levels for Trophic Levels in Freshwater (from Irvine and Murphy, 2009)

TP, µg/L	TN, µg/L	Chlorophyll a, µg/L	Comment	Source[1]
42	300	8	Defines eutrophic boundary	Van Nieuwenhuyse and Jones, 1996 (quoted in U.S. EPA, 2000)
70		15	TP level based on experiments to keep Chlorophyll a <15 µg/L, a nuisance action level	State of Oregon guidelines (quoted in Walker et al., 2006)
25	70	10	Oligotrophic-mesotrophic boundary	Table 8, various sources (quoted in Walker et al., 2006)
75	1.5	30	Mesotrophic-eutrophic boundary	Table 8, various sources (quoted in Walker et al., 2006)
42	290	8	Nutrient levels to keep Chlorophyll a ≤8 µg/L,	Dodds and Welch, 2000

40	900		Median level from U.S. rivers	Dodds and Welch, 2000
20	300		Guideline set for Clark Fork Voluntary Nutrient Reduction Program, Montana	Dodds and Welch, 2000
50			Water quality guideline for Illinois	Quoted in Walker et al., 2006
100			Water quality guideline for New Jersey	Quoted in Walker et al., 2006
30	200		Water quality guidelines for Ohio, warmwater habitat for large rivers; nitrogen in nitrite/nitrate rather than TN	Quoted in Walker et al., 2006
		40	Water quality guideline for North Carolina, non-trout streams	Quoted in Walker et al., 2006
10-35 (annual mean)		Mean: 2.5-8; Max: 8-25	Mesotrophic lake characteristics	Vollenweider and Kerekes, 1982
35-100 (annual mean)		Mean: 8-25; Max: 25-75	Eutrophic lake characteristics	Vollenweider and Kerekes, 1982
20-35			Mesotrophic trigger range for lakes or rivers; conservative approach	Canadian Council of Ministers of the Environment, 2006
25-75			Mesotrophic trigger range for rivers and streams, suggested and depending on lake receiving water quality	Environment Canada, 2004
30			To avoid excessive plant growth in rivers	Ontario Ministry of Environment and Energy, 1999
50			Protection of freshwater aquatic life, guideline for Alberta	Environment Canada, 2004
50			Water quality guideline for Manitoba	Environment Canada, 2004

[1]See Irvine and Murphy (2009) for original references.

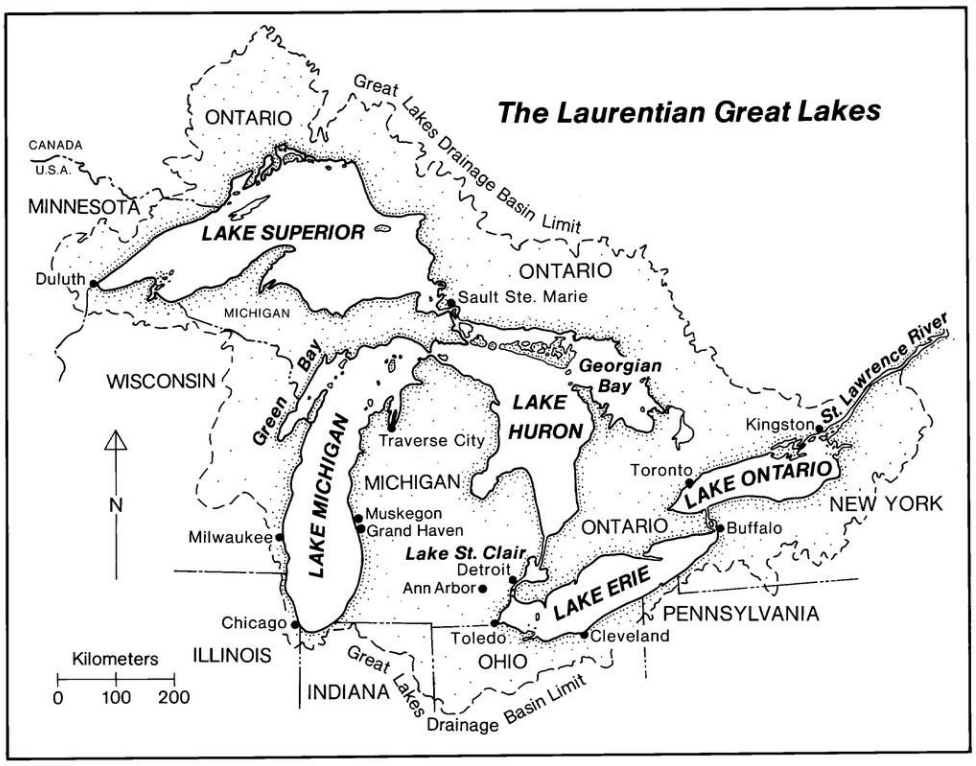


Figure 2.10 The North American (Laurentian) Great Lakes (from https://www.flickr.com/photos/noaa_glerl/4036841081)

The relationship between land use and nutrient levels in runoff is summarized in Table 2.8. This is a very generalized relationship for the United States and it should be noted that nutrient levels and loadings will vary between different events for the same watershed and between different watersheds having similar land uses. Nonetheless, it can be instructive to use Table 2.8 to explore how land use and change in land use might impact a waterbody.

Table 2.8 Nutrient Loading Rates by Land Cover/Use Types (from Marsh, 1991)

Cover Use	*Nitrogen (kg/km²/yr)*	*Phosphorus (kg/km²/yr)*
Forest	440	8.5
Mostly Forest	450	17.5
Mostly Urban	788	30.0
Mostly Agriculture	631	28.0
Agriculture	982	31.0
Mixed	552	18.5
Golf Course	1,500	41.0

2.3.6. Temperature

In its broadest sense, water temperature can have a number of impacts on aquatic organisms. For example, ***physiological*** factors such as metabolic and developmental rates and processes including photosynthesis and respiration may be impacted. As a result, the biogeographic distribution of aquatic organisms at a large spatial scale may be affected and the general concept is illustrated in Figure 2.11. Of course, the temperature tolerance range as shown in Figure 2.11 will vary from species to species. Andrews and McEwan (1987) note that the surface water temperature of the oceans ranges from about 27 °C in the tropics to about -3 °C in polar regions and for some aquatic organisms, such as reef-

building coral, there is a fairly small temperature tolerance range (in the case of the coral only about 18-20 °C).

Freshwater may be categorized as cold water fisheries or warm water fisheries, depending on water temperature, habitat, and fish species present. For example, brook trout (*Salvelinus fontinalis*) is a species that favours cold water in the U.S., while smallmouth bass (*Micropterus dolomieui*), largemouth bass (*Micropterus salmoides*), and chain pickerel (*Esox niger*) favour warm water. The state of Massachusetts in the U.S. formally defines cold water fisheries as those waters in which the maximum mean monthly temperature generally does not exceed 20 °C.

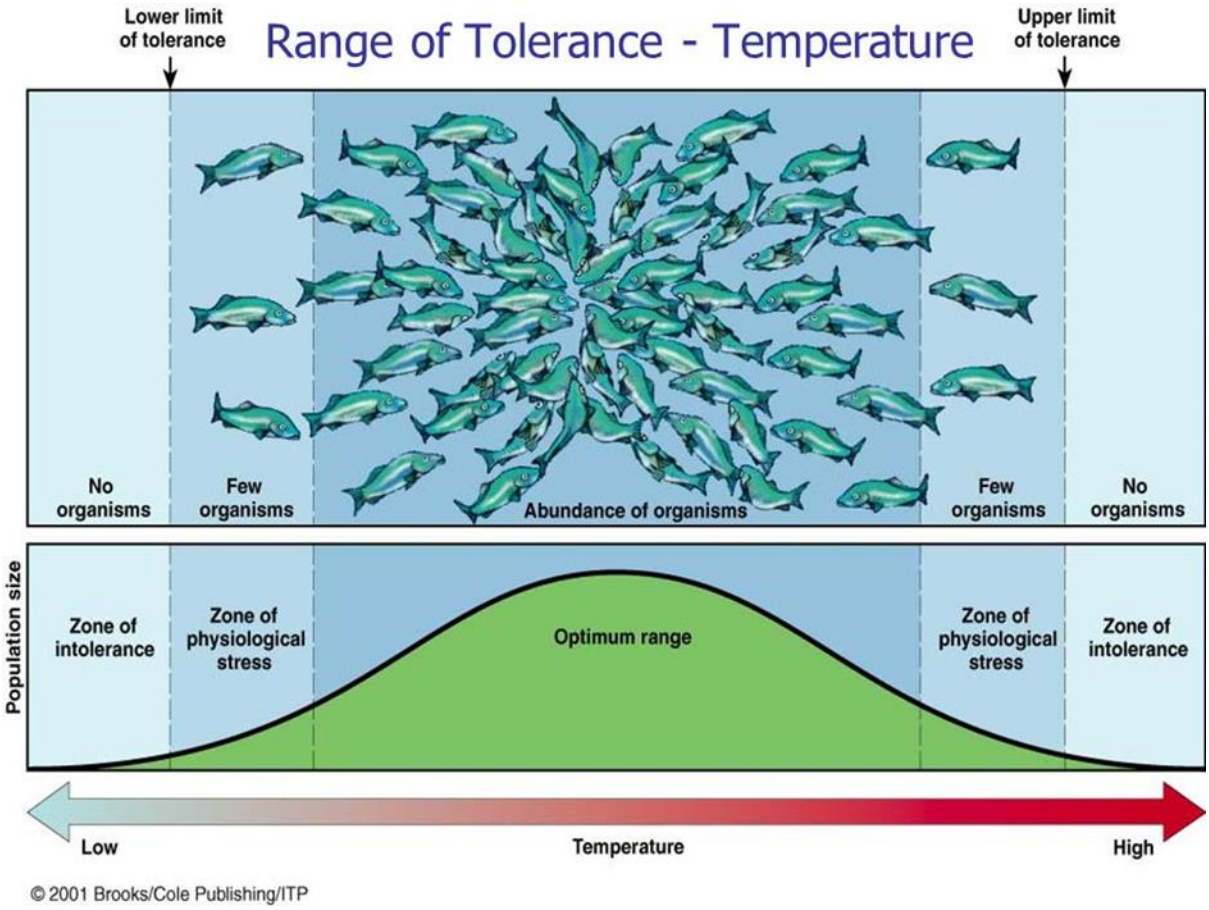


Figure 2.11 Illustration of the impact that thermal tolerance can have on aquatic biota.

A growing body of literature is examining the potential impact of climate change on aquatic organism distribution at large spatial and temporal scales (Hughes, 2000; Hoegh-Guldberg and Bruno, 2010; Doney et al., 2012), while Huegens et al. (2001) reviewed how organisms living under conditions close to their environmental tolerance limit tended to be more vulnerable to additional chemical stress such that increasing temperature and decreasing food availability resulted in increased chemical toxicity.

Cold water fisheries can be particularly vulnerable to sudden changes in water temperature. These sudden changes may come from industrial cooling water discharges or stormwater runoff from urban areas. For example, Xie and James (1994) found that thermal enrichment in the Speed River, Southern Ontario, Canada, was related to percent imperviousness. The type of urban surface can impact the runoff temperature, as James and Verspagen (1997) reported temperatures from permeable pavers being cooler by a factor of 2-4 °C as compared to asphalt, while Thompson et al. (2008) found

temperatures from sod plots on average were 9.5 °C cooler than asphalt plots. Herb et al. (2008) used a mathematical model to consider impacts of thermal enrichment from stormwater runoff on the Vermillion River, Minnesota, U.S.A. a designated trout stream. The modeled runoff from a 100 x 100 m asphalt plot was projected to increase the temperature of the stream between 0.13 and 4.23 °C, depending on the timing and size of the storm event and the flow in the river.

Thermal impacts from warm water discharges may produce both acute impacts such as thermal avoidance, increased vulnerability to predation due to thermal shock, or in the extreme, mortality, as well as longer term shifts in aquatic population characteristics, such as reduction in fish species richness due to impacts on benthic cover and reduced reproductive capability (Coutant, 1973; Jones et al., 1996; Beitinger et al., 2000; Lukšienė et al., 2000; Teixeira et al., 2009). However, to the contrary, in some locations that experience seasonally cooler water, elevated water temperature from discharges may attract some fish and marine mammals such as manatee, at least for periods of time (Spigarelli, 1975; Jones et al., 1996; Laist and Reynolds, 2005). Fish mortality also has been observed due to sudden drops and exposure to low temperature (Beitinger et al., 2000). In Singapore, the Allowable Limits for Effluent Discharge to a Controlled Watercourse is 45 °C (http://www.nea.gov.sg/anti-pollution-radiation-protection/water-pollution-control/allowable-limits).

2.3.7. Turbidity, Suspended Solids, and Total Solids

These three parameters are in some ways related and yet they represent different properties of water quality as well. Turbidity is an optical property that reflects the clarity of the water and can be measured in a couple of different ways, depending on your budget and the depth of the water. Most schools will opt to use some type of Secchi depth measurement. The standard Secchi disk is 20 cm in diameter and is divided into quarters with alternating black and white sections. The disk is lowered through the water column until it is no longer visible and this depth, then, is known as the Secchi depth (Figure 2.12). Clearer water will have a greater Secchi depth. If the water is too shallow for the disk we can use a Secchi tube. The Secchi disk in this system is smaller and is found at the bottom of the tube. The tube has a graduated scale with depth in cm. We collect a sample of water and pour the sample into the tube just to the point that we lose sight of the disk. Using the scale on the tube, we determine the Secchi depth (Figure 2.12). Turbidity also can be measured using some type of turbidity sensor in which the sensor emits a light beam into the water that is scattered by the sediment (Figure 2.13). With less sediment, there is less scatter.

Suspended solids concentration is determined by passing a known volume of sample water through a filter having a nominal pore size of 0.45-2 µm (see Appendix A for more detail). Although this is a fairly simple procedure, Pitt et al. (2017) provide a thorough review of a number of sampling and analytical factors that can influence results. This analysis is known as a ***gravimetric*** procedure and produces results in mg/L. The water that passes through the filter can be collected in a dish and evaporated in an oven. The residual material remaining in the dish after filtration is known as the dissolved solids (i.e. smaller than 0.45-2 µm) and like suspended solids are expressed as a concentration in mg/L. This is analogous to dissolving a sugar cube in coffee. The sugar starts as a visible solid (e.g. like rock or soil before weathering). The sugar cube is dropped in the coffee and dissolves, so that it is no longer visible (e.g. the rock or soil is chemically weathered, dissolves, and is not seen by the naked eye in the flowing water). Yet, the sugar (or rock/soil elements) are still there, just not visible. If you evaporate the coffee, the sugar again will be visible, so in essence the sugar for some period of time was the dissolved solid in coffee. Dissolved solids will be discussed further in the next section.

Figure 2.12 NIE student on overseas field course measuring the Secchi depth in the Buffalo River, New York (left) and NIE student using a Secchi tube at Jurong Ecogarden (right **THIS PHOTO WILL CHANGE!!!!!!!!**).

Figure 2.13 River Valley Secondary School student demonstrating how to clean the turbidity sensor of a YSI 6920 datasonde at Admiralty Park.

Turbidity and suspended solids are related in that as suspended solids increase in the water, turbidity also will increase (e.g. Figure 2.14). The turbidity-suspended solids relationship has been well documented for water bodies throughout the world (e.g. Walling, 1977; Lewis, 1996; Sun et al., 2001; Davies-Colley and Smith, 2001; Irvine et al., 2002; Pfannkuche and Schmidt, 2003; Stubblefield et al., 2007; Minella et al., 2008) and although this relationship can be strong, several environmental variables, including different particle size distribution, particle shape, particle composition, and presence of humic acids can produce scatter in the data. As such, Sun et al. (2001) concluded that suspended solids-turbidity relationships may be both site and time specific, so that a relationship may be unique for a particular catchment and within a particular period of time. Normally, the turbidity-suspended solids relationship is explored using the results of a turbidity meter (e.g. Figure 2.13) and suspended solids sampling. However, turbidity (NTU) and Secchi depth also are related and a general conversion between these two measures is provided in Table 2.9.

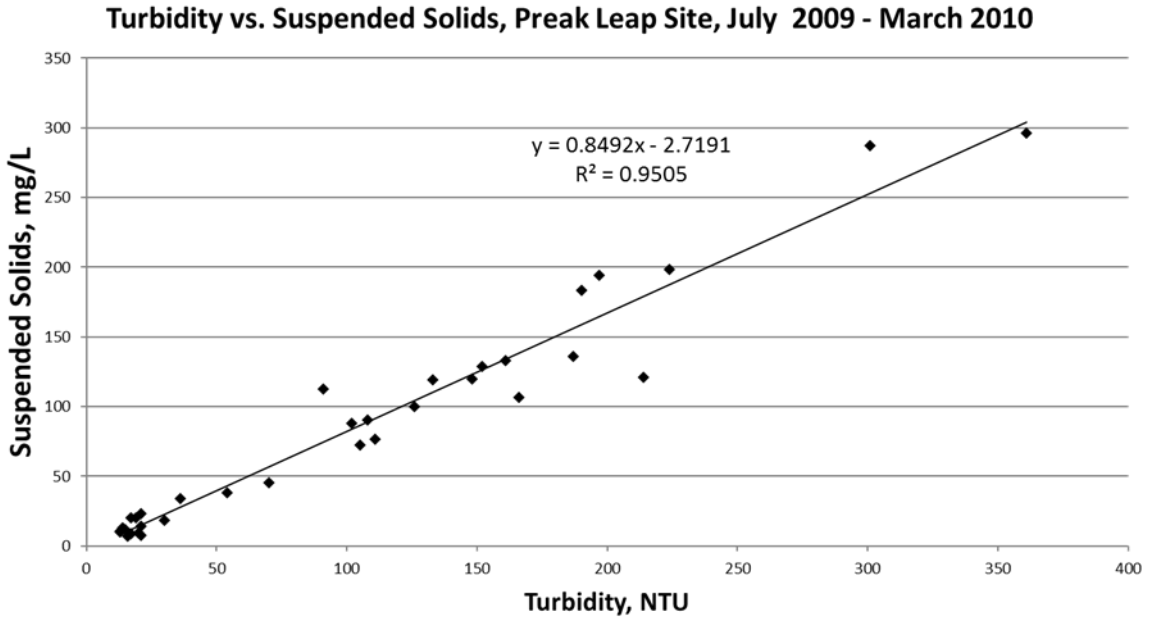


Figure 2.14 Relationship between turbidity and suspended solids concentration, Preak Leap site on the Mekong River, near Phnom Penh (after Irvine et al., 2011b).

Turbidity finds its applications more in ecological assessments. Higher turbidity appears to impact mating habits for some fish (Järvenpää and Lindström, 2004), can affect predator-prey relations for both visual feeders (predators) as well as prey that depend on visual detection of predators (Abrahams and Kattenfeld, 1997; Utne-Palm, 2002; Van de Meutter et al., 2005), and can reduce light penetration into the water which results in decreased production and abundance of plant material and algae (thereby also affecting higher order organisms) (Lloyd, 1987; Irvine and Murphy, 2009). For the state of Minnesota in the U.S.A., the guideline for turbidity is 25 NTU, while Lloyd (1987) noted that for fish and wildlife in Alaska, no more than 25 NTU above "natural" in streams and no more than 5 NTU above "natural" in lakes were appropriate standards. In contrast, the Mekong River is a highly productive fishery that generally experiences greater levels of turbidity. For example, upstream of Phnom Penh, Cambodia, turbidity for the Mekong River typically is in the 50-400 NTU range (Irvine et al., 2011b; Figure 2.15). It seems likely that organisms in these more turbid waters have adapted to and thrived

in such conditions (e.g. Wilbur and Clarke, 2001). Notwithstanding the optical impacts from turbidity on aquatic ecosystems, suspended solids also can have negative impacts related to physiology in some fish species, including reduced growth rates, gill damage, and interrupted gas exchange, (Wilbur and Clarke, 2001; Sutherland and Meyer, 2007; Kemp et al., 2011), as well as impact to fish egg viability through abrasion, smothering and reduced oxygen exchange (Greig et al., 2005; Kemp et al., 2011). Kjelland et al. (2015) provide a more thorough review of the potential impacts related to suspended sediment concentration.

Table 2.9 Relationship between Turbidity and Secchi Depth

Depth, cm	Turbidity, NTU	Depth, cm	Turbidity, NTU
<6.0	>240	31.1 to 34.0	21
6.1 to 7.0	240	34.1 to 36.0	19
7.1 to 8.0	185	36.1 to 39.0	17
8.1 to 9.0	150	39.1 to 41.0	15
9.1 to 10.0	120	41.1 to 44.0	14
10.1 to 12.0	100	44.1 to 46.0	13
12.1 to 14.0	84	46.1 to 49.0	12
14.1 to 16.0	60	49.1 to 51.0	11
16.1 to 19.0	48	51.1 to 54.0	10
19.1 to 21.0	40	54.1 to 57.0	9
21.1 to 24.0	35	57.1 to 60.0	8
24.1 to 26.0	30	60.1 to 70.0	7
26.1 to 29.0	27	70.1 to 85.0	6
29.1 to 31.0	24	>85	<5

2.3.7.1. Total Solids, Dissolved Solids, and Specific Conductivity

Operationally, total solids (mg/L) can be determined as:

Suspended Solids Concentration (mg/L) + Dissolved Solids Concentration (mg/L)

based on the sample filtration and evaporation procedure noted in the previous section. As an alternative to determining dissolved solids concentrations, which can be laborious due to the efforts needed for sample collection and laboratory analysis, it is possible to monitor the specific conductivity of the water. Specific conductivity can be determined using a conductivity meter and is a measure of how well water can conduct an electrical current (and is expressed in µm/cm or mS/cm). Conductivity is higher with greater concentrations of ions in the water. These ions, which come from the breakdown of compounds, conduct electricity because they are negatively or positively charged when dissolved in water. Therefore, specific conductivity is an indirect measure of the presence of dissolved solids such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, and iron, and can be used as an indicator of water pollution. It is important to note that specific conductivity does not tell us "what stuff" is dissolved in the water and it is important to understand your sample area to help give you clues about sources. For example, if your river is near the ocean, conductivity may be elevated during high tide periods due to the mixing with saline water. But et al. (2016) used specific conductivity to show that the wastewater collection system in the seaside town of Cha am, Thailand, was experiencing groundwater intrusions of brackish water that was sourced from the ocean.

A 27 week campaign to monitor conductivity in the Admiralty Park (Woodlands, Singapore) stormwater pond in 2014 showed that, on average, specific conductivity was slightly higher at the inlet to the pond (0.479 mS/cm) than the outlet (0.439 mS/cm) a trend most likely related to the settling of particulate matter and particle-associated elements such as iron (Figure 2.15). In relative terms, the mean conductivity presented in the pond was greater than some waters of Southeast Asia (e.g. Mekong, Irvine et al., 2011; Ping River upstream of Chiang Mai, Guigino et al., 2006; blackwater wetlands, Irvine et al., 2013); similar to some urban-impacted waters (e.g. Ping River in Chiang Mai, Guigino et al., 2006); and lower than some highly-impacted urban waters (e.g. Rangsit Canal upstream of Bangkok, Price et al., 2011). As has been observed frequently in other locations, the conductivity for the Admiralty Park pond dropped rapidly in association with storm events (Figure 2.16) due to a dilution effect of the dissolved material (e.g. Krueger et al., 2004; Irvine et al., 2005; Guigino et al., 2006).

Figure 2.15 Admiralty Park stormwater pond waters immediately after sampling (left) and after a two day hold time (right).

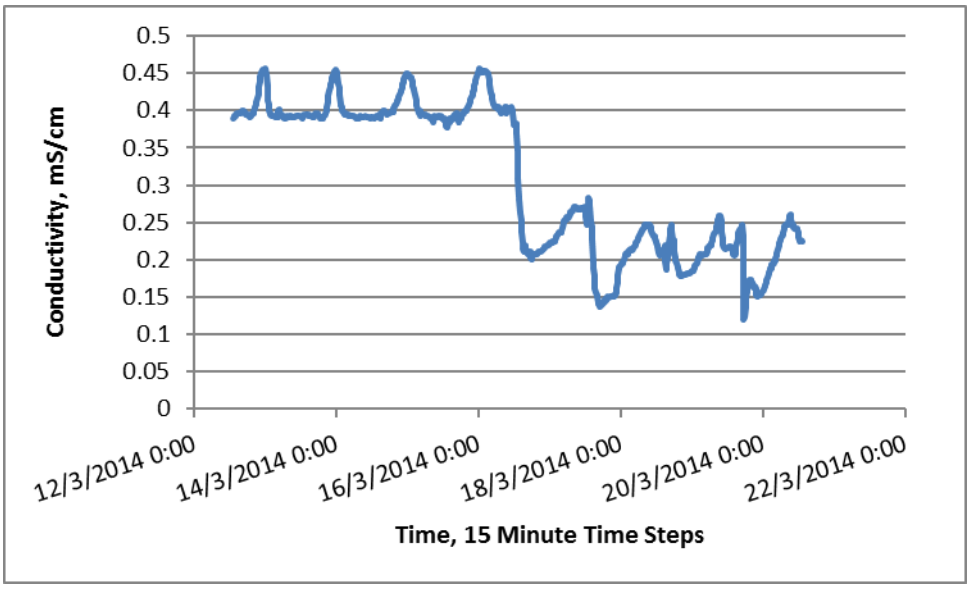


Figure 2.16 Conductivity at the Admiralty Park stormwater pond inlet site. Note the clear decrease in conductivity in association with the events of 17 and 19 March 2014.

The dissolved sediment load in rivers may originate from a variety of sources including chemical weathering and groundwater input, atmospheric deposition, runoff from agricultural areas, and urban inputs. For example, Roy et al. (1999) reported that for the Seine River near Paris, 2% of the dissolved load came from natural sources of atmospheric deposition, 7% from anthropogenic sources of atmospheric deposition, 6% from agriculture, 3% from communal inputs, and 82% from rock weathering. Milliman (2009) noted that dissolved load was influenced by the type of bedrock in the watershed as well as climate and reported typical suspended sediment and dissolved sediment concentrations for major rivers in the world (Table 2.10). The data in Table 2.10 show…….

Table 2.10 Comparison of Suspended and Dissolved Sediment Concentrations for Selected River (data compiled by Milliman (2009).

River	*Suspended Sediment Concentration, mg/L*	*Dissolved Sediment Concentration, mg/L*	*Ratio, Suspended:Dissolved Sediment Concentration*
Amazon	190	43	4.4:1
Yangtze	510	200	2.6:1
Ganges	950	130	7.3:1
Irrawaddy	600	230	2.6:1
Mississippi	820	280	2.9:1


CAROLINA


25
A25
A1
A27
Wildco

Chapter 3

Application of the National Sanitation Foundation Water Quality Index

The National Sanitation Foundation Water Quality Index (NSF WQI) has a long history and variations of it have been applied throughout the world. As noted in Section 2.2, the Delphi Method was used to determine the nine parameters to be considered in the NSF WQI as well as the relative weights for each parameter (Table 2.1). In other words, it was determined that dissolved oxygen, followed by fecal coliform, best reflected or were the most useful indicators of water quality, and therefore held the greatest weight in the NSF WQI calculation. In summary, the NSF WQI:

- Measures analytes often associated with eutrophication.
- Measures some analytes related to human health.
- Measures some indicators of sewage contamination.
- Does not measure toxic pollutants.

3.1. The General Steps in Applying the NSF WQI

Most of the parameters (dissolved oxygen, pH, nitrate, phosphate, Δtemperature, and turbidity) can be determined directly in the field. Total solids, E. coli, and BOD_5 will need to be determined in the lab after the water samples are collected and returned to the school. Ideally, samples are kept on ice for the E. coli and total solids analysis, but at the very least should be processed immediately upon returning to the school. Note here that we are replacing fecal coliform, the older bacteria indicator (used in the 1970's when the NSF WQI was first developed), with E. coli, the bacteria indicator that is now more commonly used to characterize fecal contamination.

Step 1: *Enter the test result for each parameter into Table 3.1.*

Step 2: *Determine the Q-value (quality value) for each parameter, based on the test result and enter the Q-value into Table 3.1. The Q-value for each parameter is determined from its specific parameter rating curve, two examples of which are shown in Figure 3.1. The full set of Q-value rating curves are found in the Water Quality section of the Sustainability Learning Lab website (www.xxx.xx.). Note that the different parameters have different Q-value rating curve shapes, depending on how the result reflects better or poorer water quality. As with the weighting factors, the Q-value rating curve shapes also were determined using the Delphi Method as reported by Brown et al. (1970).*

Step 3: *Multiply the Q-value by the weighting factor and enter the product in the last column (Sub-total) of Table 3.1.*

Step 4: *Sum all of the individual sub-total scores in the last column of Table 3.1 and enter the sum as the Overall Water Quality Index Score for that site.*

Step 5: *A qualitative ranking scheme has been proposed by Mitchell and Stapp (1995) and can be used to classify your results:*

Numerical Range	Descriptor Words
90-100	Excellent
70-90	Good
50-70	Medium
25-50	Bad
0-25	Very bad

Table 3.1 The NSF WQI Worksheet

Parameter	Test Result	Q-Value	Weighting Factor	Sub-Total
DO (% Saturation)			0.17	
E. Coli (#/100 mL)			0.16	
pH			0.11	
BOD_5 (mg/L)			0.11	
Temperature (Δ^oC)			0.1	
Phosphorus (mg/L)			0.1	
Nitrate (mg/L)			0.1	
Turbidity (NTU)			0.08	
Total Solids (mg/L)			0.07	

Overall Water Quality Index Score: _____

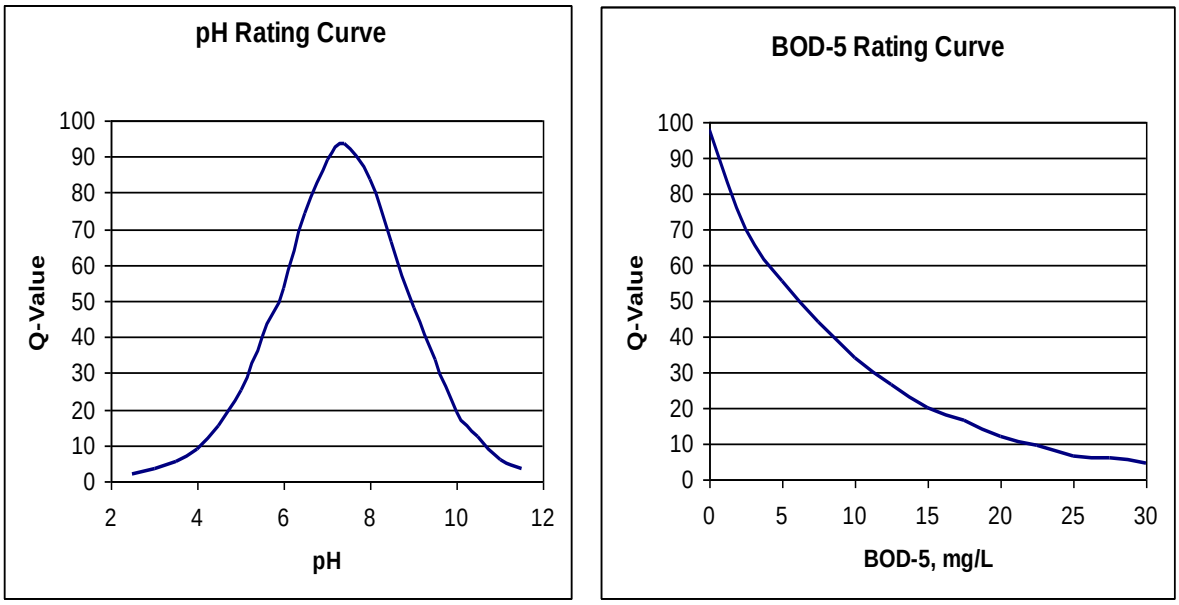


Figure 3.1 Example Q-value rating curves for pH (left graph) and BOD_5 (right graph).

There are several additional considerations when completing the NSF WQI calculation:

1. The dissolved oxygen entry for the NSF WQI requires a per cent saturation value rather than the normally reported concentration (mg/L) value. The conversion between per cent saturation and concentration for dissolved oxygen is found in Table 3.2.

2. Turbidity must be entered as an NTU value. If turbidity was measured using a Secchi depth, convert the depth to an NTU value using Table 2.9.

3. If a parameter value is missing, there are a couple of options. Stoner (1978) recommended estimating missing WQI data from available data collected at that site or a nearby site in the past. Alternatively, the weighting of the WQI could be modified per the following approach:

$$WQI_{modified} = \frac{\sum W_Y Q_Y}{\sum W_y} \qquad [3.1]$$

Where:

Y = available parameters
Q_y= Q-values of the available parameters
W_y = the weighting factors for the available parameters

4. If you would prefer to use a more automated approach to the NSF WQI, a spreadsheet to conduct the calculation is provided in the Water Quality section of the SLL website (www.xxx.xx). Alternatively, if you also would like to geocode your sites, synch and store your data with your classes, an app (WaterScope) was developed by Mr. Vernon Tan as part of his final year project (2014) in Geography at NIE and is available as a free download from the App store (limited to use on iPhones).

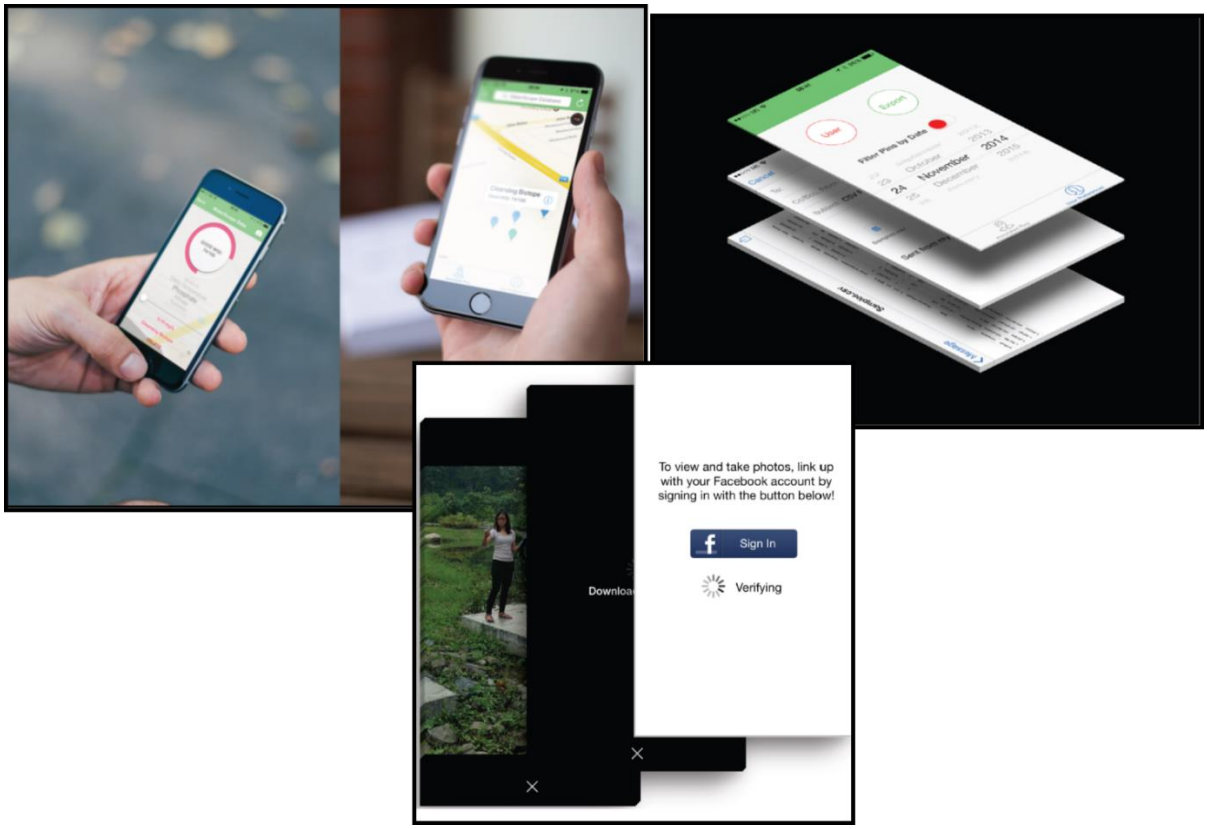
Table 3.2 Conversion of Dissolved Oxygen in mg/L to Per Cent Saturation[1]

Dissolved Oxygen Percent (%) Saturation Sheet

Temp	D.O. (mg/L)														
(C)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15*
0	7%	14%	21%	27%	34%	41%	48%	55%	62%	68%	75%	82%	89%	96%	103%
1	7%	14%	21%	28%	35%	42%	49%	56%	63%	70%	78%	85%	92%	99%	106%
2	7%	14%	22%	29%	36%	43%	51%	58%	65%	72%	80%	87%	94%	101%	109%
3	7%	15%	22%	30%	37%	45%	52%	60%	67%	74%	82%	89%	97%	104%	112%
4	8%	15%	23%	31%	38%	46%	53%	61%	69%	76%	84%	92%	99%	107%	115%
5	8%	16%	24%	31%	39%	47%	55%	63%	71%	78%	86%	94%	102%	110%	118%
6	8%	16%	24%	32%	40%	48%	56%	64%	72%	80%	88%	97%	105%	113%	121%
7	8%	17%	25%	33%	41%	50%	58%	66%	74%	83%	91%	99%	107%	116%	124%
8	8%	17%	25%	34%	42%	51%	59%	68%	76%	85%	93%	101%	110%	118%	127%
9	9%	17%	26%	35%	43%	52%	61%	69%	78%	87%	95%	104%	113%	121%	130%
10	9%	18%	27%	35%	44%	53%	62%	71%	80%	89%	98%	106%	115%	124%	133%
11	9%	18%	27%	36%	45%	54%	64%	73%	82%	91%	100%	109%	118%	127%	136%
12	9%	19%	28%	37%	46%	56%	65%	74%	84%	93%	102%	112%	121%	130%	139%
13	10%	19%	29%	38%	48%	57%	67%	76%	86%	95%	105%	114%	124%	133%	143%
14	10%	19%	29%	39%	49%	58%	68%	78%	87%	97%	107%	117%	126%	136%	146%
15	10%	20%	30%	40%	50%	60%	70%	79%	89%	99%	109%	119%	129%	139%	149%
16	10%	20%	30%	41%	51%	61%	71%	81%	91%	102%	112%	122%	132%	142%	152%
17	10%	21%	31%	41%	52%	62%	73%	83%	93%	104%	114%	124%	135%	145%	155%
18	11%	21%	32%	42%	53%	63%	74%	85%	95%	106%	116%	127%	138%	148%	159%
19	11%	22%	32%	43%	54%	65%	76%	86%	97%	108%	119%	130%	140%	151%	162%
20	11%	22%	33%	44%	55%	66%	77%	88%	99%	110%	121%	132%	143%	154%	165%
21	11%	22%	34%	45%	56%	67%	79%	90%	101%	112%	124%	135%	146%	157%	169%
22	11%	23%	34%	46%	57%	69%	80%	92%	103%	115%	126%	138%	149%	161%	172%
23	12%	23%	35%	47%	58%	70%	82%	93%	105%	117%	129%	140%	152%	164%	175%
24	12%	24%	36%	48%	60%	71%	83%	95%	107%	119%	131%	143%	155%	167%	179%
25	12%	24%	36%	49%	61%	73%	85%	97%	109%	121%	133%	146%	158%	170%	182%
26	12%	25%	37%	49%	62%	74%	87%	99%	111%	124%	136%	148%	161%	173%	185%
27	13%	25%	38%	50%	63%	75%	88%	101%	113%	126%	138%	151%	164%	176%	189%
28	13%	26%	38%	51%	64%	77%	90%	102%	115%	128%	141%	154%	166%	179%	192%
29	13%	26%	39%	52%	65%	78%	91%	104%	117%	130%	143%	156%	169%	183%	196%
30	13%	27%	40%	53%	66%	80%	93%	106%	119%	133%	146%	159%	172%	186%	199%
31	13%	27%	40%	54%	67%	81%	94%	108%	121%	135%	148%	162%	175%	189%	202%
32	14%	27%	41%	55%	69%	82%	96%	110%	124%	137%	151%	165%	179%	192%	206%
33	14%	28%	42%	56%	70%	84%	98%	112%	126%	140%	154%	168%	182%	196%	209%
34	14%	28%	43%	57%	71%	85%	99%	113%	128%	142%	156%	170%	184%	199%	213%
35	14%	29%	43%	58%	72%	87%	101%	115%	130%	144%	159%	173%	188%	202%	216%
36	15%	29%	44%	59%	73%	88%	103%	117%	132%	147%	161%	176%	191%	205%	220%
37	15%	30%	45%	60%	75%	89%	104%	119%	134%	149%	164%	179%	194%	209%	224%
38	15%	30%	45%	61%	76%	91%	106%	121%	136%	151%	166%	182%	197%	212%	227%
39	15%	31%	46%	61%	77%	92%	108%	123%	138%	154%	169%	184%	200%	215%	230%

[1]If the dissolved oxygen is >15 mg/L, calculate per cent saturation as:

$$\frac{Actual\ Dissolved\ Oxygen, mg/L}{Max. Oxygen\ Concentration\ at\ Water\ Temp.}$$



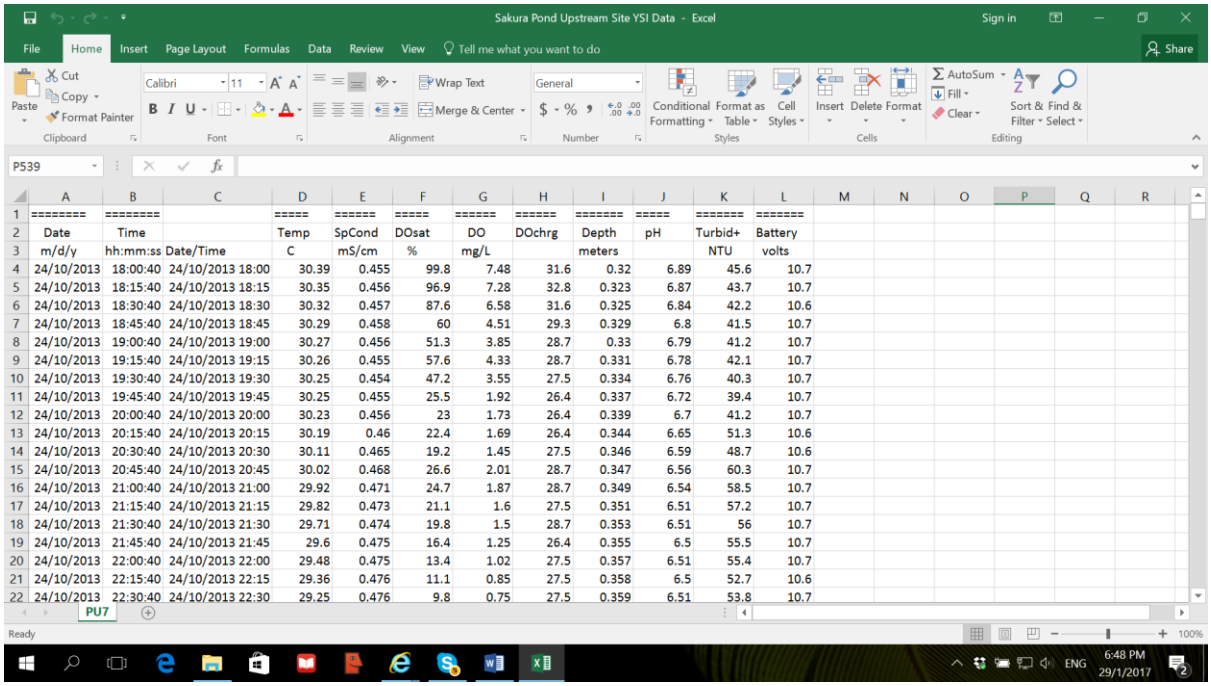
There's an app for that…….WaterScocpe

Chapter 4

We Have the Data – Now What?

4.1. Graphing

The first step in any data analysis should be: *Draw a Picture!!* The old adage that a picture is worth a thousand words rings true in data analysis. What we really mean here, of course, is that you should begin your analysis by graphing the data. Effective graphs can quickly allow you to visualize and understand complex data sets and relationships. Let me provide an example. When a YSI datasonde is deployed in a waterbody to monitor parameters at 15 minute time steps, the raw data look something like Figure 4.1. At first glance, you smile to yourself and say "awesome, so much data", but then the question is how to make sense of the data? Simply staring at the numbers does not help. Instead, draw a picture.



	A	B	C	D	E	F	G	H	I	J	K	L
1	========	========		=====	======	=====	======	======	=======	=====	=======	=======
2	Date	Time		Temp	SpCond	DOsat	DO	DOchrg	Depth	pH	Turbid+	Battery
3	m/d/y	hh:mm:ss	Date/Time	C	mS/cm	%	mg/L		meters		NTU	volts
4	24/10/2013	18:00:40	24/10/2013 18:00	30.39	0.455	99.8	7.48	31.6	0.32	6.89	45.6	10.7
5	24/10/2013	18:15:40	24/10/2013 18:15	30.35	0.456	96.9	7.28	32.8	0.323	6.87	43.7	10.7
6	24/10/2013	18:30:40	24/10/2013 18:30	30.32	0.457	87.6	6.58	31.6	0.325	6.84	42.2	10.6
7	24/10/2013	18:45:40	24/10/2013 18:45	30.29	0.458	60	4.51	29.3	0.329	6.8	41.5	10.7
8	24/10/2013	19:00:40	24/10/2013 19:00	30.27	0.456	51.3	3.85	28.7	0.33	6.79	41.2	10.7
9	24/10/2013	19:15:40	24/10/2013 19:15	30.26	0.455	57.6	4.33	28.7	0.331	6.78	42.1	10.7
10	24/10/2013	19:30:40	24/10/2013 19:30	30.25	0.454	47.2	3.55	27.5	0.334	6.76	40.3	10.7
11	24/10/2013	19:45:40	24/10/2013 19:45	30.25	0.455	25.5	1.92	26.4	0.337	6.72	39.4	10.7
12	24/10/2013	20:00:40	24/10/2013 20:00	30.23	0.456	23	1.73	26.4	0.339	6.7	41.2	10.7
13	24/10/2013	20:15:40	24/10/2013 20:15	30.19	0.46	22.4	1.69	26.4	0.344	6.65	51.3	10.6
14	24/10/2013	20:30:40	24/10/2013 20:30	30.11	0.465	19.2	1.45	27.5	0.346	6.59	48.7	10.6
15	24/10/2013	20:45:40	24/10/2013 20:45	30.02	0.468	26.6	2.01	28.7	0.347	6.56	60.3	10.7
16	24/10/2013	21:00:40	24/10/2013 21:00	29.92	0.471	24.7	1.87	28.7	0.349	6.54	58.5	10.7
17	24/10/2013	21:15:40	24/10/2013 21:15	29.82	0.473	21.1	1.6	27.5	0.351	6.51	57.2	10.7
18	24/10/2013	21:30:40	24/10/2013 21:30	29.71	0.474	19.8	1.5	28.7	0.353	6.51	56	10.7
19	24/10/2013	21:45:40	24/10/2013 21:45	29.6	0.475	16.4	1.25	26.4	0.355	6.5	55.5	10.7
20	24/10/2013	22:00:40	24/10/2013 22:00	29.48	0.475	13.4	1.02	27.5	0.357	6.51	55.4	10.7
21	24/10/2013	22:15:40	24/10/2013 22:15	29.36	0.476	11.1	0.85	27.5	0.358	6.5	52.7	10.6
22	24/10/2013	22:30:40	24/10/2013 22:30	29.25	0.476	9.8	0.75	27.5	0.359	6.51	53.8	10.7

Figure 4.1 YSI 6920 datasonde data for Admiralty Park stormwater pond.

Of course there are two important tricks that you need to consider: i) choose the right type of graph; and ii) make sure the graph has all of the elements it needs to convey an effective message. Most often you will use a spreadsheet to generate your graphs and it is beyond the scope of this Handbook to provide detailed step by step guidance to generate graphs in Excel. In fact, the Sustainability Learning Lab data portal will help by allowing you to select pre-formatted graphs. However, let's explore some key graphing points in this section.

Time series data in environmental analysis is quite common. Figure 4.1 is an example of time series data; i.e. data collected over a period of time. In Figure 4.1 temperature, specific conductivity, dissolved oxygen, sample depth, pH, and turbidity are being measured and logged at 15 minute intervals. Often, meteorological data, such as temperature, rainfall, wind velocity, atmospheric pressure, humidity, shortwave and longwave radiation also are measured by logging-capable of

equipment and stored as a time series. One effective way to graph time series data is to use the Scattegram option in Excel. I recommend against using the Line graph option because the x-axis with the Line graph is alpha-numeric. This means that all measurement time intervals are assumed constant and are plotted at regular intervals, which is fine if your data are recorded at regular intervals. But if the intervals are not regular, see what happens in Figure 4.2. The alpha-numeric time axis cannot account for irregular time steps. Instead, use the Scattergram option in Excel. You can join the individual observations with a line and either leave the data markers visible, or drop them, as was done in Figure 2.16.

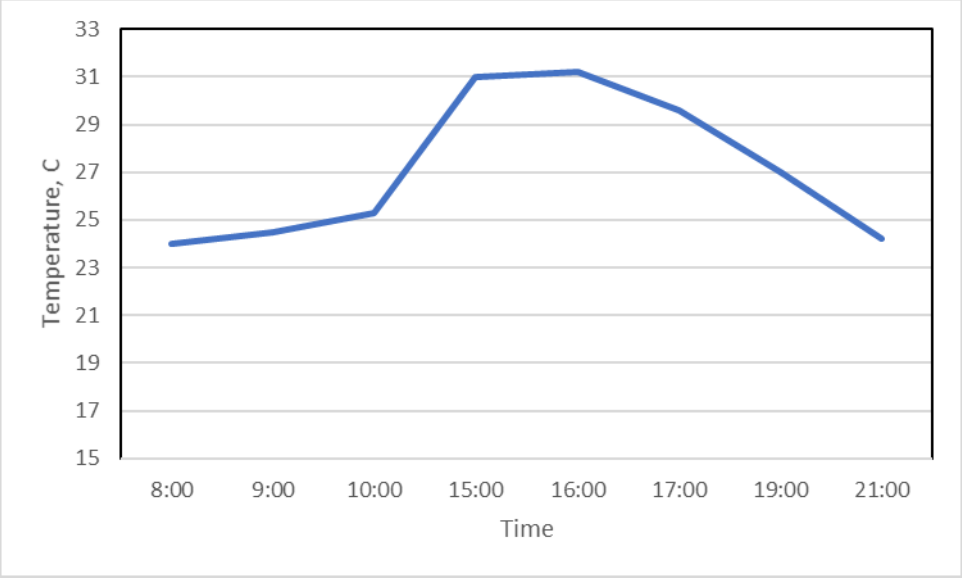


Figure 4.2 Graphing a time series with the Line graph option in Excel.

A couple of other considerations also are worth noting with the Scattergram option. First, you may want to explore the behaviour of two parameters over a period of time, as was done in Figure 2.6 for dissolved oxygen and pH. Figure 2.6 clearly illustrates the similar temporal pattern for dissolved oxygen and temperature, but it is worth noting that you may need to plot the time series on primary and secondary y-axes, depending on the absolute values of the parameters, to see the trends in both. Sometimes, you may wish to explore the relationship between two parameters irrespective of time. In this case, you still can use the Scattergram option, as was done in Figure 2.14. The trendline option, together with the $\boldsymbol{R^2}$ value, also can be used here to help explore the relationship between the two parameters. The R^2 value ranges between 0 and 1, with closer to 1 representing a stronger relationship.

Often, if you are doing a GI on a particular day with your class, you will not be able to collect water quality time series data, but instead will have samples representing a single point in time at multiple sites (e.g. different locations in a pond or stream). With this type of data collection it is not appropriate to use a Line graph (or line-connected Scattergram) since such a graph suggests in some way the data at the sample sites are continuously connected. Instead, it is appropriate to use a bar graph, as is shown in the next chapter, Figure 5.7.

A final couple of words of caution for graphing. The default graphs in Excel are terrible. It is important to edit the graphs so that they have appropriate axis labels (including the correct units), x and y axis scale (remember that bar graphs MUST have a minimum value of 0), a legend, and if the graph is to be used in a presentation where there is no figure caption, it should have an explanatory title. Please

avoid using 3-d graphs, particularly 3-d bar graphs. While they may be more visually appealing and this might be important for a powerpoint presentation, they are VERY difficult to read accurately.

4.2. Descriptive Statistics

After you have graphed your data, you may want to explore some simple descriptive (or summary) statistics. There are two broad categories of summary statistics: measures of central tendency; and measures of dispersion. Measures of central tendency seek to characterize the "typical" condition while measures of dispersion seek to describe how variable data are around the typical condition. Measures of central tendency include the mean, the median, and the mode. Measures of dispersion include the interquartile range and the standard deviation.

The type of data you collect will dictate the descriptive statistics that can be calculated, but most environmental data are ***ratio*** or ***interval*** data so you can calculate a variety of descriptive statistics. Most simply, the mode is the most frequently occurring observation (or category). The median represents the middle value (or 50th percentile) from a set of ranked observations and therefore is the value with an equal number of data units above it and below it. With an odd number of observations, the middle value is unique and defines the median. With an even number of observations, the median is defined as the midpoint of the two middle-ranked values. Assume for example, we have rainfall data for 10 locations in Singapore as in Table 4.1. In this case, we have 10 gauges, so the middle gauges are ranks 5 and 6 and the median therefore is calculated as:

$$median = \frac{320.2 + 243.2}{2} = 281.7\ mm$$

Table 4.1 Rainfall at a Sample of Singapore Rain Gauges, November, 2015

Gauge Site	Rainfall, November, 2015 (mm)	Rainfall, Ranked	Rank Number
Changi	72.6	374.6	1
Punngol	154	361.6	2
Kranji Reservoir	374.6	333	3
Lower Peirce Reservoir	324.2	324.2	4
Chao Chu Kang (central)	333	320.2	5
Tuas South	243.2	243.2	6
Clementi	320.2	216.4	7
Queenstown	216.4	154	8
Serangoon	361.6	118.4	9
Marina Parade	118.4	72.6	10

Probably all of your students can explain how to calculate a mean value. Again, using Table 4.1, they would tell you to add up the rainfall for each gauge and divide by 10. This is the arithmetic sample mean and formally is calculated as:

$$\bar{x} = \frac{\sum x_i}{n} \qquad [4.1]$$

Where $\bar{x}$ is the sample mean, x_i are the individual values of x (i.e. each rain gauge), and n is the total number of observations in the sample.

The sample standard deviation (S_x) is calculated as:

$$s_x = \sqrt{\frac{\sum\left(x_i - \bar{x}\right)^2}{n-1}} \qquad [4.2]$$

If we assume (which is not always true with environmental data, but simplifying here), that our sample data (e.g. every 15 minute measurement of pH from Figure 4.1) is normally distributed, we might think of the summary statistics as representing the condition in Figure 4.3. With a normal distribution, the mean, the median, and the mode all occur in the same position.

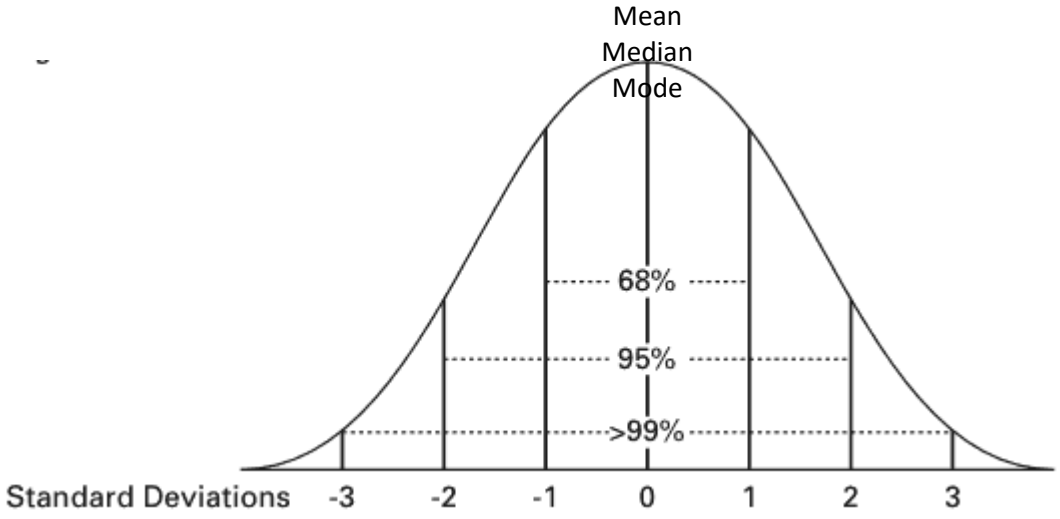


Figure 4.3 The normal probability distribution showing the percent of observations within ±1, 2, and 3 standard deviations from the mean value (here the mean value is 0).

Now, you might think that these calculations would be quite time consuming for a large data set, and you would be right. Happily, Excel automates the procedure and you can do the calculations all at once. To do this, you must make sure that your Data Analysis Add-ins are active (if you do not see Data Analysis when you are in the Data tab, use the following steps: Home>>Options>>Add-ins>>Excel Add-ins>>Go>>select Analysis ToolPak and Analysis ToolPak – VBA). In Data Analysis select Descriptive Statistics (Figure 4.4). Select the range of data you would like to analyze, what type of output you would like to see, and where the output should appear. Figure 4.5 shows the results for the weekly 15 minute pH data for a stormwater pond in Admiralty Park.

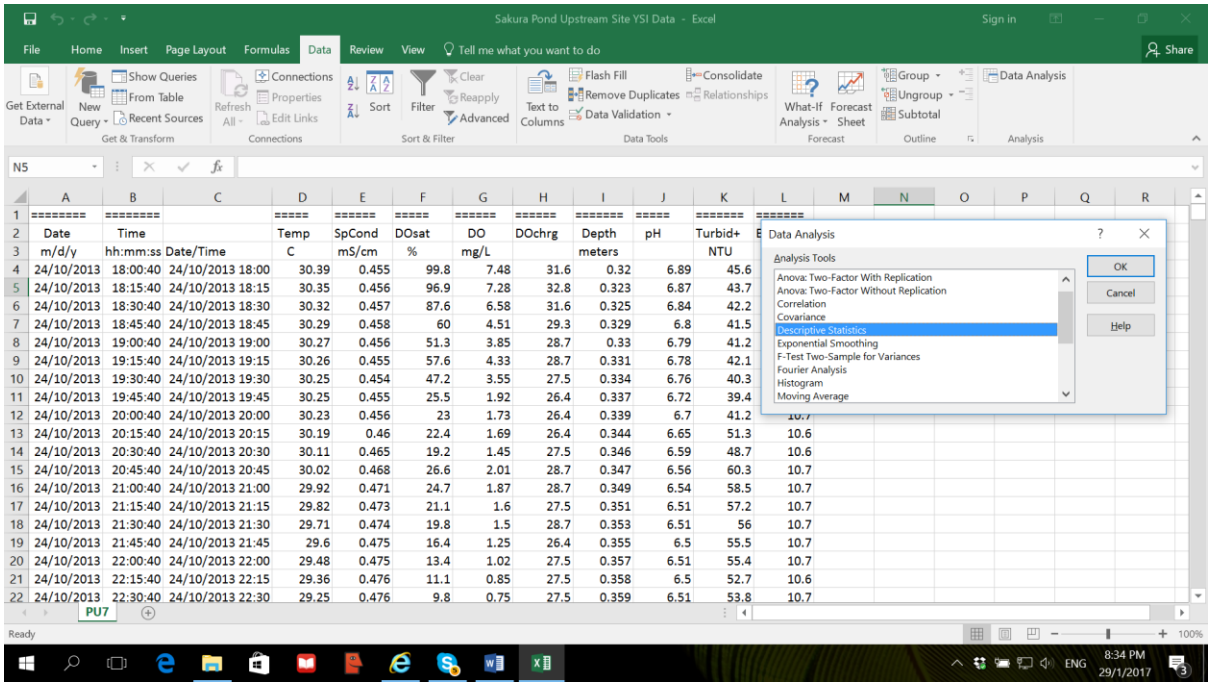


Figure 4.4 Selecting the Descriptive Statistics option in Data Analysis.

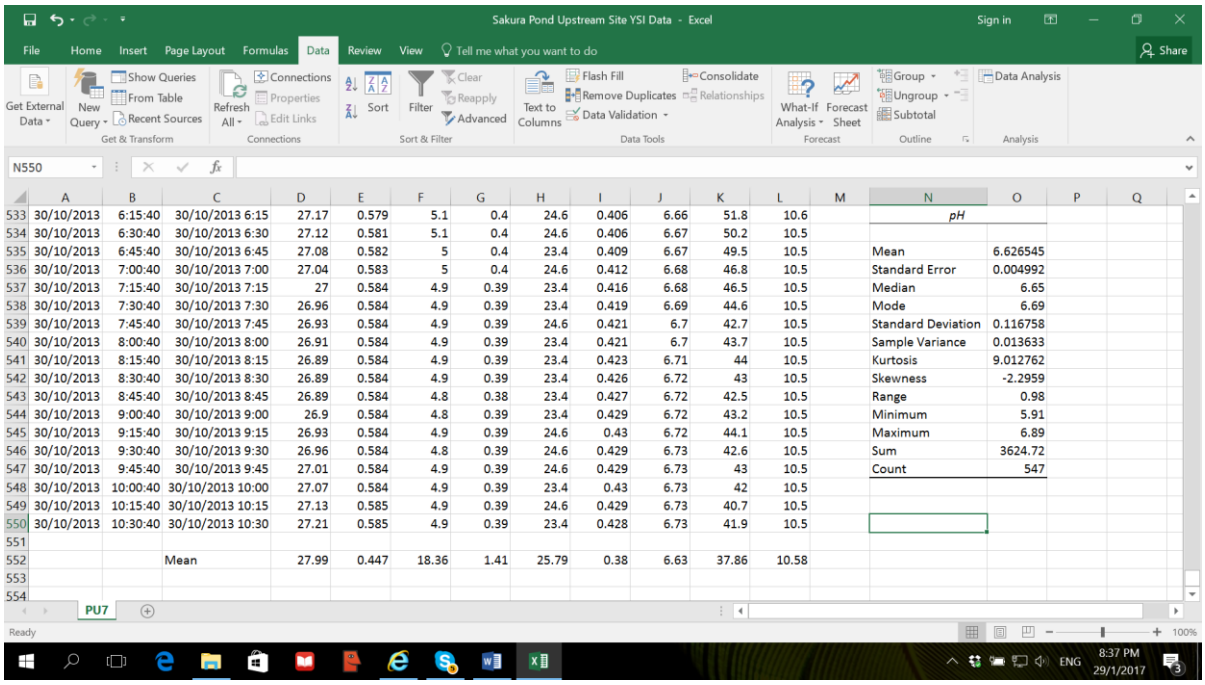


Figure 4.5 Results of Descriptive Statistics calculation for pH.

4.3. Geocoding

As geographers, we think about both temporal and spatial relationships. To effectively interpret your water quality data it is important to understand your sample site in spatial terms – for example where is the site and what is going on around the site? Ways in which maps, such as land use or locations of discharge points, can help us understand our water quality results are illustrated in Chapter 5. In this section, let me simply emphasize the importance of determining the location of your sample site. Of

course, location can be defined as the intersection between an x and y coordinate. The coordinate system may be latitude and longitude, it may be the Universal Transverse Mercator (UTM) system, or it may be some type of military grid.

You could use a handheld GPS unit to determine your sample site coordinates. Alternatively, different apps, including WaterScope and MGeo allow you and your class to identify the location of your sample site. I particularly like the Maps.me app, which is free, for mapping sample locations. It is accurate, easy to use, and can be used essentially anywhere in the world (even offline). An example of Maps.me for one area in northern Thailand that was sampled as part of the NIE Geography final year project fieldwork in 2016 is shown in Figure 4.6.

Figure 4.6 River sample sites, north of Chiang Mai, Thailand.

Chapter 5

Case Study: Application of the NSF WQI in the United States[1]

In June, 2015, 24 year 4 students from the National Institute of Education (NIE), Singapore, travelled to Buffalo, New York, U.S.A. to conduct fieldwork for their final year project. A number of the students focused on water quality assessment in the Buffalo River watershed and Simon Raj summarized all of the collected water quality data using the NSF WQI. This is the NSF WQI story for the Buffalo River Watershed.

5.1. Introduction

In 1989 the city of Buffalo began efforts to restore the chemical, physical, and biological integrity of the Buffalo River ecosystem through goals set out in its first Remedial Action Plan (RAP). A RAP aims to address these issues by formulating strategies which will eventually lead to delisting of beneficial use impairment (BUIs). These BUIs include restrictions on fish and wildlife consumption, fish tumours and other deformities, degradation of benthos, restrictions on disposal of dredged sediment and loss of fish and wildlife habitat. Since its designation as an Area of Concern (AOC), there has been a great deal of progress in remediating the different contaminant sources (e.g. inactive hazardous waste sites, historically contaminated sediment, combined sewer overflows, direct industrial discharges), but contaminant sources in the watershed upstream of the AOC are diffuse and challenging to manage (Irvine et al., 2005b).

An important component of environmental remediation is benching conditions and tracking changes over time. Although numerous studies have been done to assess the different analytes that affect water quality in the Buffalo River, two studies conducted during 1978 and 1996 specifically utilised the NSF WQI (Erie County Department of Environment and Planning, 1978; Wills and Irvine, 1996). Given that these studies were done over two decades ago, the current study aims to gain some insights as to the progress made through the RAP and the pressures of land development and its impact on water quality as defined by the WQI. In this research paper the impact that land use and storm events have on the water quality in the Buffalo AOC and the upper watershed will be investigated by analysing the spatial distribution of the NSF WQI.

5.2. Methodology

5.2.1. Study Area

The entire Buffalo River watershed occupies an area of 1,155 km^2 and the river itself drains to eastern Lake Erie (Figure 5.1). Land use in the upper watershed is a mix of forest and agriculture with a number of small towns, while in the AOC land use includes industrial and vacant (formerly industrial) areas, commercial, and residential areas.

5.2.2. Sample Sites and Data Collection

[1] This chapter is edited from the final year project done for the NIE AAG401 class in 2015 by Mr. Simon Raj. The input from other AAG401 students who collected some of the data upon which Mr. Raj's project was based also is gratefully acknowledged: Ofilia Lim, Alvin Leong, Low Pei Qi, Goh Hui Shi, Koo Ying Jia, Tan Yan Ting, and Lalithambigai D/O S Mohan.

Samples were collected at a total of 15 sites (Figure 5.1). Sampling was done by two teams; the AOC team and the upper watershed (UWS) team. The AOC team sampled 8 points in the Buffalo River AOC (Figure 5.2) and the other team sampled 7 points in the UWS (Figure 5.1). Sample site locations were selected to represent different land uses, the three major tributaries of the Buffalo River, ease of access, whether samples had been collected at the location previously, and in the case of the upper watershed, proximity to U.S. Geological Survey river gauge stations.

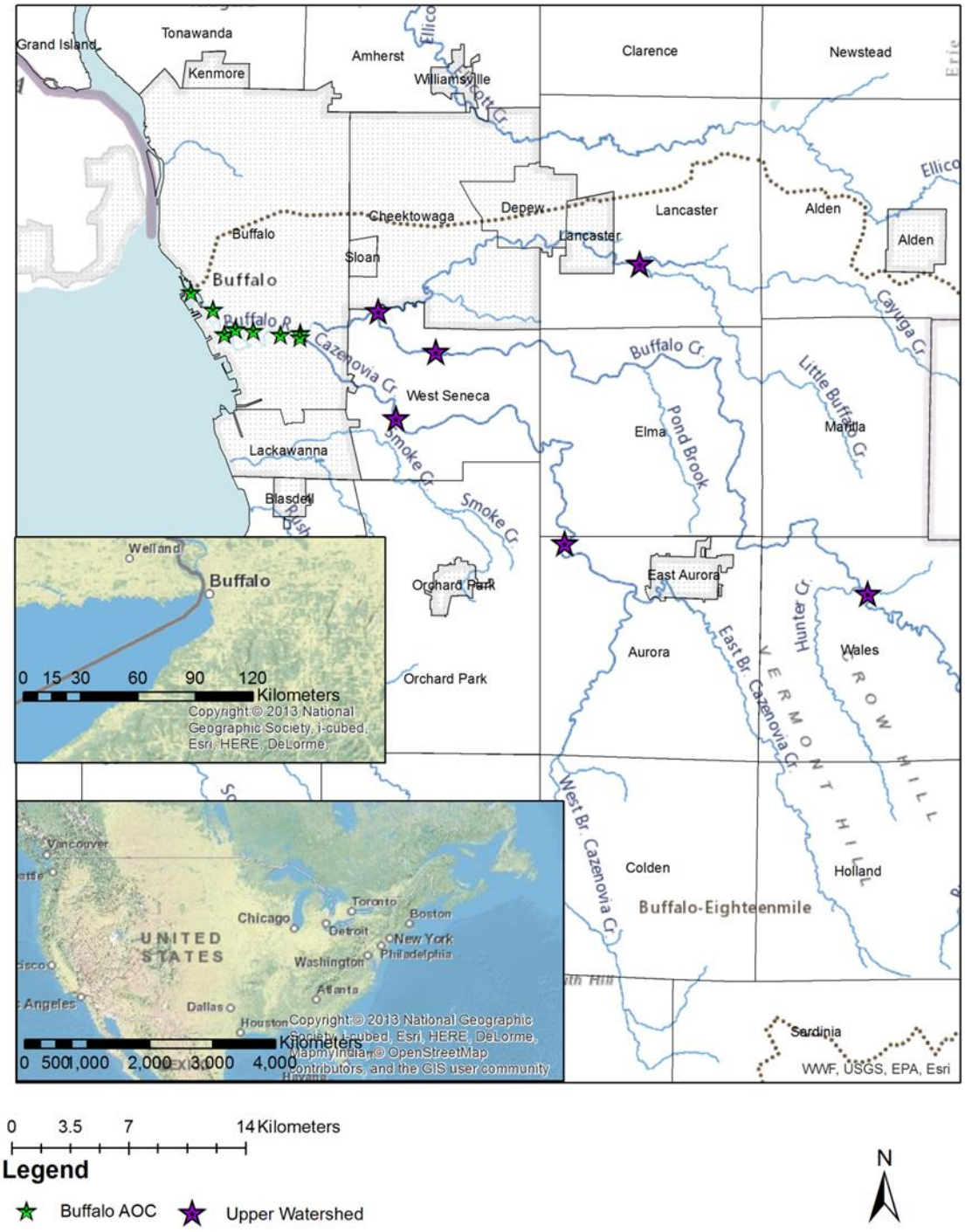


Figure 5.1 Buffalo River watershed, AOC area and sample sites.

In the AOC a Van Dorn sampler was used to sample water at 0.5m depth below the water surface as frequently the sample sites were at bridges or where the bank was too high above the water surface to allow manual grab sampling (Figure 5.3). At the UWS manual grab samples were taken at a 0.xxm depth below the water surface (Figure 5.4). These samples were brought back to the Buffalo State lab for analysis except for the analytes measure by the YSI6920 datasonde (pH, dissolved oxygen, temperature, turbidity, conductivity) which was done at the sample site (Figure 5.5 and 5.6). Duplicate samples also were taken at random sites to ensure reliability of samples. All water samples were kept on ice in a cooler box until they were analysed back in the lab at Buffalo State, State University of New York.

Sampling was done on 30/5/15, 1/6/15 and 5/6/15. The samples on 30/5/15 represented low flow, dry weather immediately before a storm event sampling of 1/6/15. The 5/6/15 sampling represented dry flow conditions.

Samples were analysed for the NSF WQI parameters per the methods outlined in Appendix A of this Handbook. However, during the course of the study Total Solids (TS) data were not measured. TS are a required variable to calculate the WQI but only the Suspended Solids (SS) measurements were available. As such, two alternative methods were evaluated for the TS parameter assessment. First, TS was simply represented by the SS values measured in this study. Second, TS was dropped from the analysis and the modified NSF WQI was calculated based on equation [3.1] in Chapter 3.

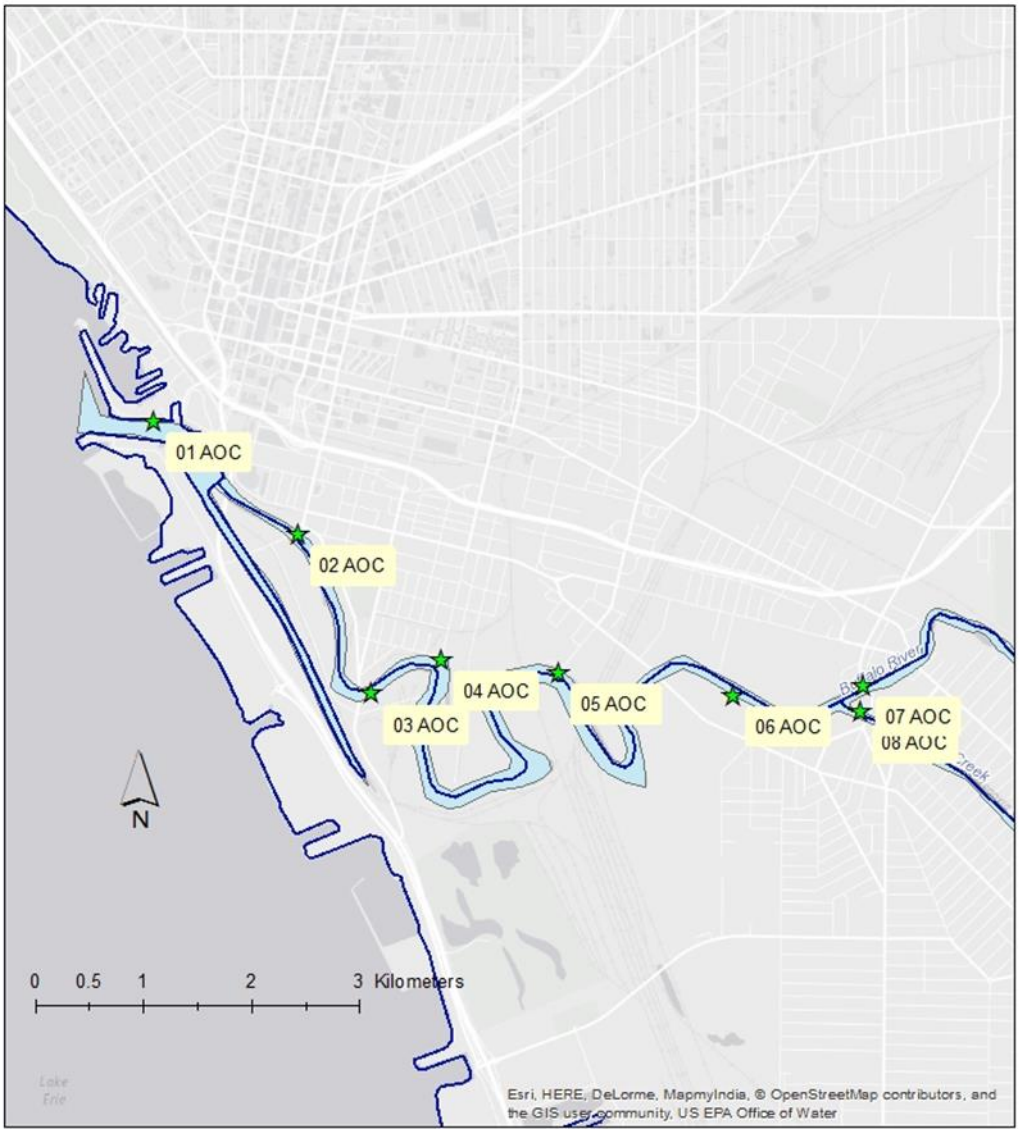


Figure 5.2. AOC sample sites.

Figure 5.3 Preparing the Van Doren sampler.

Figure 5.4 Collecting manual grab samples during a storm event. Safety must be the top priority, so the heavier, more experienced professor lends a hand in sample collection on this day. Note that it is important to stand downstream of the sample collection point to avoid contaminating the sample.

Figure 5.5 Preparing the YSI 6920 datasonde to be lowered into the Buffalo River.

Figure 5.6 Lowering the YSI 6920 into the Buffalo River AOC.

5.3. Results

The peak flows on the three major tributaries to the Buffalo River (Buffalo Creek, Cayuga Creek, and Cazenovia Creek, Figure 5.1) for each sample day are summarized in Table 5.1. The results of the NSF WQI determinations are shown in Figure 4.7. Due to the extremely poor weather conditions on 1/6/15, it was not possible to sample all sites. Therefore, results for the NSF WQI only are available for 4 AOC sites and 4 upper watershed sites.

Table 5.1 Peak flows on sample dates

BUFFALO CREEK AT GARDENVILLE NY	
Date	m^3/s
30-May	0.99
1-Jun*	25.97
5-Jun	1.84

CAYUGA CREEK NEAR LANCASTER NY	
Date	m^3/s
30-May	0.37
1-Jun*	22.09
5-Jun	0.93

CAZENOVIA CREEK AT EBENEZER NY	
Date	m^3/s
30-May	2.89
1-Jun*	34.83
5-Jun	2.07

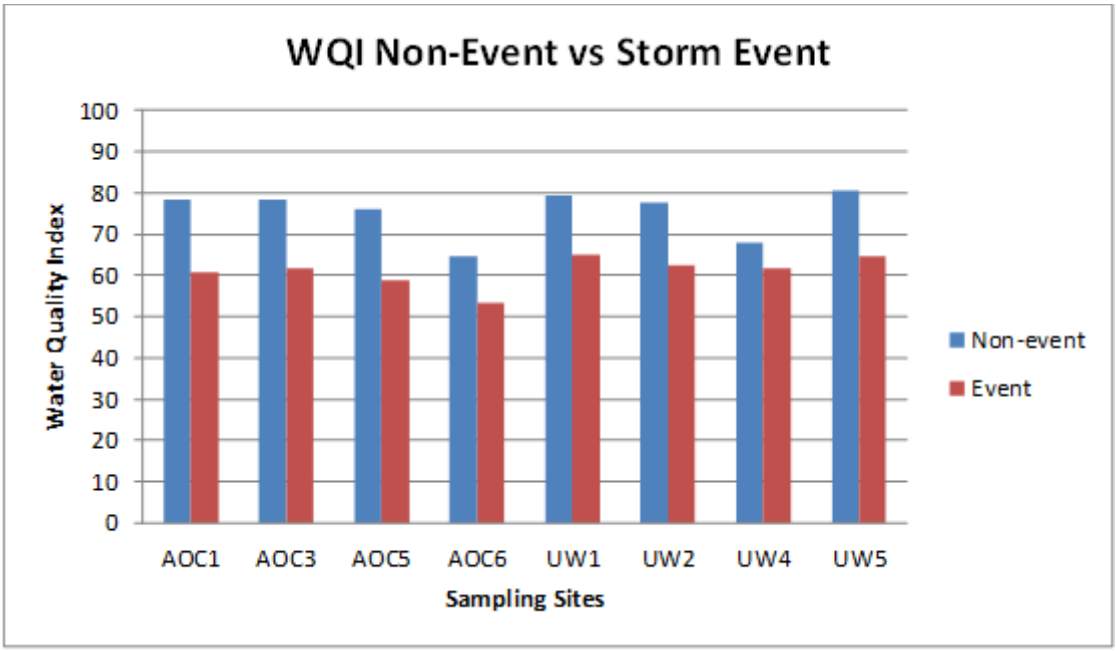


Figure 5.7 NSF WQI results. The two dry weather sample dates were averaged for this graph.

5.4. Discussion

Figure 5.7 shows that at all sites, the storm event negatively impacted water quality, as compared to dry weather flow. For the dry weather sampling dates the NSF WQI at all sites was in the "Good" category although two sites (Sites AOC 6 & 7; site 7 not shown since it was not sampled during the storm event) and one site in the upper watershed (Site UW4) was in the "Medium" category during dry weather flow. The NSF WQI dropped to the Medium category at all sites for the storm event, with AOC 6 approaching the Bad category. It was observed that suspended solids and E. coli levels increased while the dissolved oxygen level decreased for the storm event as compared to the dry weather flow.

In consideration of space in this Handbook, the full set of water quality parameter results is not shown, but can be obtained from A/P Kim Irvine.

The storm runoff appears to introduce suspended solids and E. coli to the waterways. Figure 5.8 shows the locations of combined sewer overflow points and these are likely one source of E.coli. Not plotted here are the many stormwater runoff discharge points and areas near the streams that are on a septic system that also may act as an E. coli source, particularly during storm events (e.g. Rossi et al., 2009; Irvine et al., 2011b). In addition, runoff from farms with livestock in the upper watershed may impact E. coli levels, while erosion of agricultural fields (in addition to river bed and bank erosion) may serve to increase sediment concentrations (e.g. Irvine and Pettibone, 1996). The land use change within the watershed going from the headwaters to the river mouth is quite apparent in Figure 5.9. Site AOC6 is immediately downstream of a cluster of combined sewer outfalls (Pratt et al., 1995) and this may account for the lower NSF WQI result for the sampled storm event. Nonetheless, despite the rural to urban land use gradient, during dry weather the NSF WQI is remarkably consistent across all sites.

Samples were collected at two common sites in 1978, 1996, and 2015 for which the NSF WQI can be calculated and compared (Table 5.2). All samples from 1978, 1996, and 2015 represent dry weather conditions. Water quality at Site 2 (UW1) seems to have declined between 1978 and 1996 only to recover to the near 1978 value by 2015. Unfortunately, water quality seems to have declined fairly dramatically at Site 4 (UW7) between 1978 and 1996 with a continuing (but smaller) decline in 2015. While the data are limited for Table 5.2, these results do show the potential of the NSF WQI to quickly and conveniently convey temporal trends in water quality.

Table 5.2 NSF WQI Results for Common Sites, 1978, 1996, 2015.

1978 Site No.	1996 Site No.	2015 Site No.	WQI 1978	WQI 1996	WQI 2015
2	2	UW1	80.3	71.3	79.23
4	4	UW7	83.1	72.8	71.76

As noted in Section 5.2.2., the suspended sediment concentration was used in place of total solids for the NSF WQI calculation since total solids data were not collected for this project but suspended solids concentrations were determined. The difference in the NSF WQI results between using suspended solids concentration as a surrogate for total solids and using a modified NSF WQI (equation [3.1]) with no total solids representation, is summarized in Table 5.3. It appears that there is relatively little difference in the WQI results for this study and either method could be used.

Table 5.3 Mean % Difference between Modifying the NSF WQI Formula and Estimating the TS at the AOC and Upper Watershed during Dry and Storm Event

AOC	**Upperwatershed**		
30/5/2015	1/6/2015	5/6/2016	1/6/2015
WQI	WQI	WQI	WQI
%diff	%diff	%diff	%diff
-0.71%	-3.57%	-0.45%	-1.70%

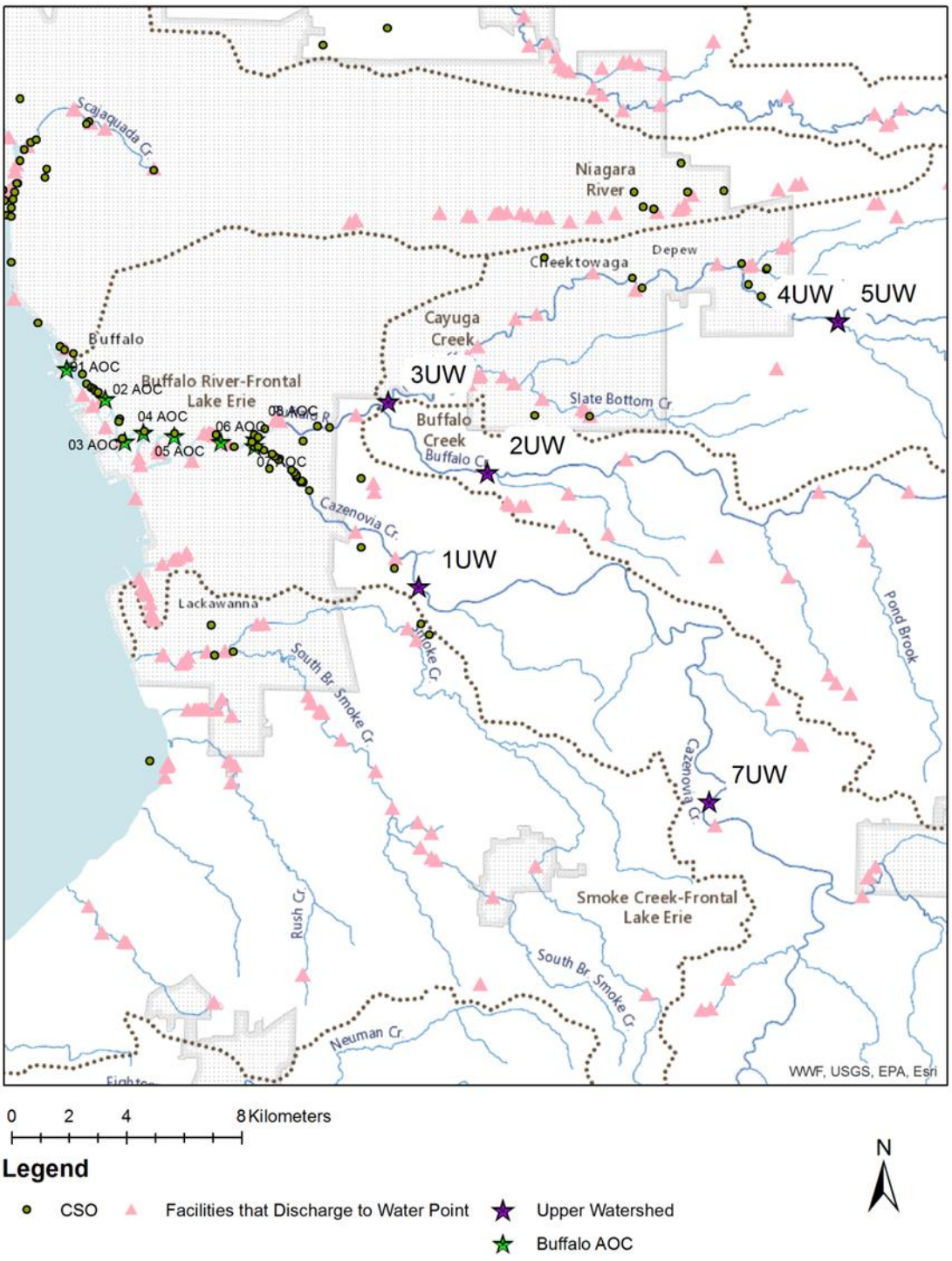


Figure 5.8 Location of CSOs and facilities that discharge to Buffalo River watershed waters.

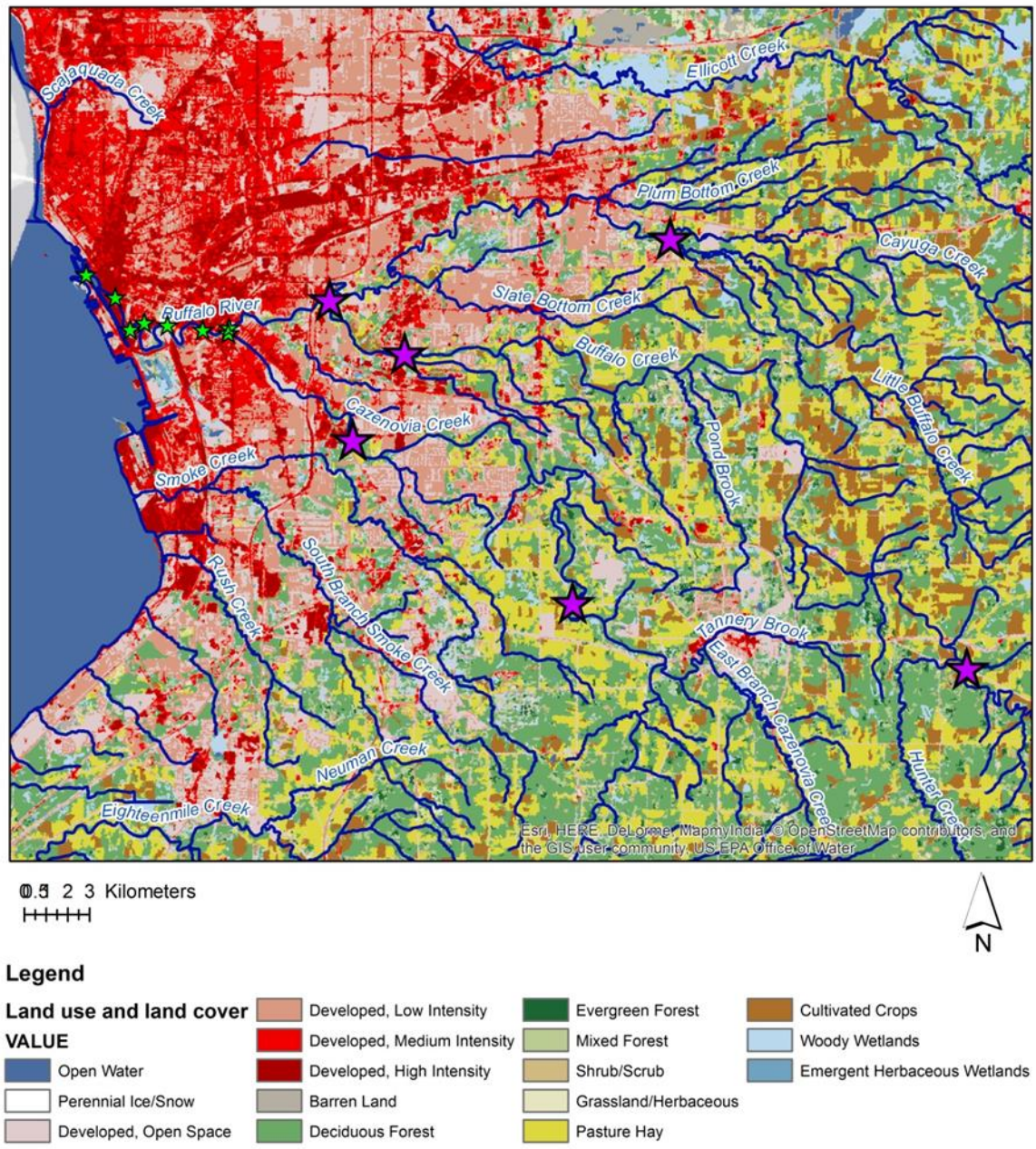


Figure 5.9 Land use in the Buffalo River watershed.

Fieldwork and Lab work as part of the “Buffalo Experience”

References

Abrahams, M. V., & Kattenfeld, M. G. (1997). The role of turbidity as a constraint on predator-prey interactions in aquatic environments. *Behavioral Ecology and Sociobiology*, *40*(3), 169-174.

Akkoyunlu, A., & Akiner, M. E. (2012). Pollution evaluation in streams using water quality indices: A case study from Turkey's Sapanca Lake Basin. *Ecological Indicators*, *18*, 501-511.

Andrews, W.A. and McEwan, S.J. (1987). *Investigating Aquatic Ecosystems,* Prentice-Hall Canada, Inc., Scarborough, Ontario.

Ansa-Asare, O. D., Marr, I. L., & Cresser, M. S. (1999). Evaluation of cycling patterns of dissolved oxygen in a tropical lake as an indicator of biodegradable organic pollution. *Science of the total environment*, *231*(2), 145-158.

Ashbolt, N. J., Grabow, W. O., & Snozzi, M. (2001). 13 Indicators of microbial water quality.

Ashbolt, N. J., Schoen, M. E., Soller, J. A., & Roser, D. J. (2010). Predicting pathogen risks to aid beach management: the real value of quantitative microbial risk assessment (QMRA). *Water research*, *44*(16), 4692-4703.

Atkinson, C. A., Jolley, D. F., & Simpson, S. L. (2007). Effect of overlying water pH, dissolved oxygen, salinity and sediment disturbances on metal release and sequestration from metal contaminated marine sediments. *Chemosphere*, *69*(9), 1428-1437.

Baxter-Potter, W. R., & Gilliland, M. W. (1988). Bacterial pollution in runoff from agricultural lands. *Journal of Environmental Quality*, *17*(1), 27-34.

Beitinger, T. L., Bennett, W. A., & McCauley, R. W. (2000). Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. *Environmental biology of fishes*, *58*(3), 237-275.

Bennett, A. (2011). Potable water: New technology enables use of alternative water sources. *Filtration+ Separation*, *48*(2), 24-27.

Berg, M., Stengel, C., Trang, P. T. K., Viet, P. H., Sampson, M. L., Leng, M., ... & Fredericks, D. (2007). Magnitude of arsenic pollution in the Mekong and Red River Deltas—Cambodia and Vietnam. *Science of the Total Environment*, *372*(2), 413-425.

Beversdorf, L. J., Bornstein-Forst, S. M., & McLellan, S. L. (2007). The potential for beach sand to serve as a reservoir for Escherichia coli and the physical influences on cell die-off. *Journal of applied microbiology*, *102*(5), 1372-1381.

Bhargava, D. S. (1983). Use of water quality index for river classification and zoning of Ganga river. *Environmental Pollution Series B, Chemical and Physical*, *6*(1), 51-67.

Boehm, A. B. (2007). Enterococci concentrations in diverse coastal environments exhibit extreme variability. *Environmental Science & Technology, 41*(24), 8227-8232.

Borchardt, M. A., Chyou, P. H., DeVries, E. O., & Belongia, E. A. (2003). Septic system density and infectious diarrhea in a defined population of children. *Environmental health perspectives*, *111*(5), 742.

River (Eastern Thailand). *Water Research*, *35*(15), 3635-3642.

Bordalo, Adriano A., Rita Teixeira, and William J. Wiebe (2006). "A water quality index applied to an international shared river basin: the case of the Douro River." *Environmental management 38*(6) 910-920.

Botkin, D.B. & Keller, E.A. (1998). *Environmental Science, Earth as a Living Planet, 2nd ed.,* Wiley & Sons, NY.

Boubel, R.W., Fox, D.L., Turner, B.D., & Stern, A. C. (1994). *Fundamentals of Air Pollution, 3rd ed.,* Academic Press, NY.

Boyacioglu, H. (2010). Utilization of the water quality index method as a classification tool. *Environmental monitoring and assessment*, *167*(1), 115-124.

Brown, R.M., McLelland, N.J., Deininger, RA. & Tozer, R.G. (1970). A Water Quality Index do we dare? *Water* & *Sewage Works,* October, 339-343.

But, K., Jindal, R., Surinkul, N., & Irvine, K. N. (2016, January). Investigations of Effluent Quality of Cha-Am Municipality Wastewater Treatment Pond System. In *International Conference on Sustainable Energy & Environmental Sciences (SEES). Proceedings* (p. 11). Global Science and Technology Forum.

Cabral, J. P. (2010). Water microbiology. Bacterial pathogens and water. *International journal of environmental research and public health*, *7*(10), 3657-3703.

Canadian Council of Ministers of the Environment, (2006). *Canadian Water Quality Guidelines for the Protection of Aquatic Life.*

Chang, CH., & Irvine, K. N. (2014). Climate change resilience and public education in response to hydrologic extremes in Singapore. *British Journal of Environment and Climate Change*, *4*(3), 328.

Chapman, P. M. (2011). Indices: attractive delusions. *Integrated Environmental Assessment and Management*, *7*(3), 313-313.

Chapman, P. M. (2016). Environmental quality benchmarks—the good, the bad, and the ugly. *Environmental Science and Pollution Research*, 1-4.

Charlet, L., & Polya, D. A. (2006). Arsenic in shallow, reducing groundwaters in southern Asia: an environmental health disaster. *Elements*, *2*(2), 91-96.

Charlton, M.N., Le Sage, R., and Milne, J.E. 1999. Lake Erie in transition: the 1990's. In *State of Lake Erie (SOLE) – Past, Present and Future,* M. Munawar, T. Edsall, and I.F. Munawar, eds., Backhuys Publishers, The Netherlands, pp. 97-123.

Chea, E., Sovann, C., & Kok, S. (2016). Assessment of population exposed to groundwater arsenic in As-affected areas of Cambodia. *Journal of Geography, Environment and Earth Science International, 5*(3), 1-14.

Cheung, W. H. S., Chang, K. C. K., Hung, R. P. S., & Kleevens, J. W. L. (1990). Health effects of beach water pollution in Hong Kong. *Epidemiology and Infection*, *105*(01), 139-162.

Chew, M. Y., Watanabe, C., & Tou, Y. (2011). The challenges in Singapore NEWater development: Co-evolutionary development for innovation and industry evolution. *Technology in society*, *33*(3), 200-211.

Cordoba, E. B., Martinez, A. C., & Ferrer, E. V. (2010). Water quality indicators: Comparison of a probabilistic index and a general quality index. The case of the Confederación Hidrográfica del Júcar (Spain). *Ecological Indicators*, *10*(5), 1049-1054.

Coutant, C. C. (1973). Effect of thermal shock on vulnerability of juvenile salmonids to predation. *Journal of the Fisheries Board of Canada*, *30*(7), 965-973.

Cowell, D. W., & Ford, D. C. (1980). Hydrochemistry of a dolomite karst: the Bruce Peninsula of Ontario. *Canadian Journal of Earth Sciences*, *17*(4), 520-526.

Cude, C. G. (2001). Oregon water quality index a tool for evaluating water quality management effectiveness. *JAWRA Journal of the American Water Resources Association*, *37*(1), 125-137.

Davies, C. M., Long, J. A., Donald, M., & Ashbolt, N. J. (1995). Survival of fecal microorganisms in marine and freshwater sediments. *Applied and Environmental Microbiology*, *61*(5), 1888-1896.

Davies-Colley, R. J., & Smith, D. G. (2001). Turbidity suspended sediment, and water clarity: a review. *JAWRA Journal of the American Water Resources Association*, *37*(5), 1085-1101.

Debels, P., Figueroa, R., Urrutia, R., Barra, R., & Niell, X. (2005). Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified water quality index. *Environmental monitoring and assessment*, *110*(1), 301-322.

Dodds, W. K., & Welch, E. B. (2000). Establishing nutrient criteria in streams. *Journal of the North American Benthological Society*, *19*(1), 186-196.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., ... & Polovina, J. (2012). Climate change impacts on marine ecosystems. *Marine Science*, 4.

Donnison, A., Ross, C., & Thorrold, B. (2004). Impact of land use on the faecal microbial quality of hill-country streams. *New Zealand Journal of Marine and Freshwater Research*, *38*(5), 845-855.

Dunnette, D. A. (1979). A geographically variable water quality index used in Oregon. *Journal (Water Pollution Control Federation)*, 53-61.

Enns, A. A., Vogel, L. J., Abdelzaher, A. M., Solo-Gabriele, H. M., Plano, L. R., Gidley, M. L., ... & Reniers, A. J. (2012). Spatial and temporal variation in indicator microbe sampling is influential in beach management decisions. *Water research*, *46*(7), 2237-2246.

Environment Canada, (2004). *Canadian Guidance Framework for the Management of Phosphorus in Freshwater Systems.* Ecosystem Health: Science-based Solutions Report No. 1-8. National Guidelines and Standards Office, Water Policy and Coordination Directorate, Environment Canada.

Erie County Department of Environment and Planning. 1978. 1977-1978 Stream Survey Project 050. Erie County Department of Environment and Planning, Buffalo, NY.

Environment Canada and U.S. EPA, (2005). *State of the Great Lakes, 2005*.

Feldman, P. R., Rosenboom, J. W., Saray, M., Samnang, C., Navuth, P., & Iddings, S. (2007). Assessment of the chemical quality of drinking water in Cambodia. *Journal of Water and Health*, *5*(1), 101-116.

Francey, D. S., Myers, D.N., & Metzker, K.D. (1993). *Escherichia coli and Fecal-coliform Bacteria as Indicators of Recreational Water Quality,* U.S. Geological Survey, Water-Resources Investigations Report 93-4083.

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination*, *309*, 197-207.

Gazzaz, N. M., Yusoff, M. K., Aris, A. Z., Juahir, H., & Ramli, M. F. (2012). Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. *Marine Pollution Bulletin*, *64*(11), 2409-2420.

Geldreich, E. E. (1972). Buffalo Lake recreational water quality: a study in bacteriological data interpretation. *Water Research*, *6*(8), 913-924.

Glass, N. R., Arnold, D. E., Galloway, J. N., Hendrey, G. R., Lee, J. J., McFee, W. W., ... & Schofield, C. L. (1982). Effects of acid precipitation. *Environmental Science & Technology, 16*(3), 162A-169A.

Goh, A. L. (2005). Towards an innovation-driven economy through industrial policy-making: An evolutionary analysis of Singapore. *The Innovation Journal: The Public Sector Innovation Journal*, *10*(3), 34.

Goyal, S. M., Gerba, C. P., & Melnick, J. L. (1977). Occurrence and distribution of bacterial indicators and pathogens in canal communities along the Texas coast. *Applied and environmental microbiology*, *34*(2), 139-149.

Granéli, E., Wallström, K., Larsson, U., Granéli, W., & Elmgren, R. (1990). Nutrient limitation of primary production in the Baltic Sea area. Ambio, 142-151.

Green R, & Chapman PM. (2011). The problem with indices. *Mar Pollut Bull,* DOI: 10.1016/j.marpolbul.2011.02.016.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. *Water research*, *43*(9), 2317-2348.

Greer, M. J., Irvine, K. N., & Tang, T. (2002). Evaluating ecosystem integrity in Great Lakes tributaries. *Clearwat*, *32*, 16-19.

Greig, S. M., Sear, D. A., & Carling, P. A. (2005). The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *Science of the total environment*, *344*(1), 241-258.

Griffin, D. W., Lipp, E. K., McLAUGHLIN, M. R., & Rose, J. B. (2001). Marine Recreation and Public Health Microbiology: Quest for the Ideal Indicator: This article addresses the historic, recent, and future directions in microbiological water quality indicator research. *Bioscience*, *51*(10), 817-826.

Gugino, H., Irvine, K., Ngern-klun, R., Sukontason, K., Sukontason, K., Prangkio, C., & Thunyapar, P. (2006). Impacts of the Urban Environment on Area Water Source: The Klong Mae Kha-Chiang Mai, Thailand. Reprinted from: Poster Presentation Proceedings, The 4th International Symposium On Southeast Asian Water Environment.

Gunn, J. M., & Keller, W. (1984). In situ manipulation of water chemistry using crushed limestone and observed effects on fish. *Fisheries, 9*(1), 19-24.

Halliday, E., & Gast, R. J. (2010). Bacteria in beach sands: an emerging challenge in protecting coastal water quality and bather health. *Environmental science & technology*, *45*(2), 370-379.

Harmel, R. D., Karthikeyan, R., Gentry, T., & Srinivasan, R. (2010). Effects of agricultural management, land use, and watershed scale on E. coli concentrations in runoff and streamflow. *Trans. ASABE*, *53*(6), 1833-1841.

Hatje, V., Payne, T. E., Hill, D. M., McOrist, G., Birch, G. F., & Szymczak, R. (2003). Kinetics of trace element uptake and release by particles in estuarine waters: effects of pH, salinity, and particle loading. Environment International, 29(5), 619-629.

Herb, W.R., Janke, B., Mohseni, O., and Stefan. H.G. 2008. Thermal pollution of streams by runoff from paved surfaces. *Hydrological Processes,* 22: 987-999.

Heugens, E. H., Hendriks, A. J., Dekker, T., Straalen, N. M. V., & Admiraal, W. (2001). A review of the effects of multiple stressors on aquatic organisms and analysis of uncertainty factors for use in risk assessment. Critical reviews in toxicology, 31(3), 247-284.

Hoegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, *328*(5985), 1523-1528.

House, M. A. (1990). Water quality indices as indicators of ecosystem change. *Environmental Monitoring and Assessment*, *15*(3), 255-263.

House, M. A., & Ellis, J. B. (1987). The development of water quality indices for operational management. *Water Science and Technology*, *19*(9), 145-154.

Hughes, L. (2000). Biological consequences of global warming: is the signal already apparent?. *Trends in ecology & evolution*, *15*(2), 56-61.

Irvine, K. N. (2013). Climate change and urban hydrology: Research needs in the developed and developing worlds. *Pragmatic Modeling of Urban Water Systems. Monograph*, *21*, 11.

Irvine, K. N., & Pettibone, G. W. (1993). Dynamics of indicator bacteria populations in sediment and river water near a combined sewer outfall. *Environmental Technology*, *14*(6), 531-542.

Irvine, K. N., & Pettibone, G. W. (1996). Planning level evaluation of densities and sources of indicator bacteria in a mixed land use watershed. *Environmental Technology*, *17*(1), 1-12.

Irvine, K. N., & Murphy, T. P. (2009). Assessment of eutrophication and phytoplankton community impairment in the Buffalo River Area of Concern. *Journal of Great Lakes Research*, *35*(1), 83-93.

Irvine, K., Vermette, S., & Mustafa, F.B. (2013). The "black waters" of Malaysia: Tracking water quality from the peat swamp forest to the sea. *Sains Malaysiana, 42*(11), 1539-1548.

Irvine, K. N., Somogye, E. L., & Pettibone, G. W. 2002. Turbidity, suspended solids, and bacteria relationships in the Buffalo River watershed. *Middle States Geographer, 35*, 42-51.

Irvine, K. N., Frothingham, K. M., Rossi, M. C., Pickard, S., Atkinson, J., & Bajak, T. (2003). Contaminated sediments in the Buffalo River area of concern—historical trends and current conditions. *Sediment Quality Assessment and Management: Insight and Progress*, 81-112.

Irvine, K. N., McCorkhill, G., & Caruso, J. (2005a). Continuous monitoring of conventional parameters to assess receiving water quality in support of combined sewer overflow abatement plans. *Water Environment Research*, *77*(5), 543-552.

Irvine, K. N., Perrelli, M. F., McCorkhill, G., & Caruso, J. (2005b). Sampling and modeling approaches to assess water quality impacts of combined sewer overflows—The importance of a watershed perspective. *Journal of Great Lakes Research*, *31*(1), 105-115.

Irvine, K. N., Caruso, J., & McCorkhill, G. (2005). Consideration of metals levels in identifying CSO abatement options. *Urban Water Journal*, *2*(3), 193-200.

Irvine, K., Rossi, M. C., Vermette, S., Bakert, J., & Kleinfelder, K. (2011a). Illicit discharge detection and elimination: Low cost options for source identification and trackdown in stormwater systems. *Urban water journal*, *8*(6), 379-395.

Irvine, K. N., Richey, J. E., Holtgrieve, G. W., Sarkkula, J., & Sampson, M. (2011b). Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River–Tonle Sap system identified using continuous monitoring. *International Journal of River Basin Management*, *9*(2), 151-168.

Irvine, K., Vermette, S., & Mustafa, F. B. (2013). The 'black waters' of Malaysia: Tracking water quality from the peat swamp forest to the sea. *Sains Malaysiana, 42*(11), 1539-1548.

Irvine, K., Chua, L., & Eikass, H. S. (2014). The Four National Taps of Singapore: A holistic approach to water resources management from drainage to drinking water. *Journal of water management modeling*, 1-11.

Irvine, K. N., Seow, T., Wai, L. K., and Cheong. S.I.D. (2015). How High's the water, mama? A reflection on water resource education in Singapore. *HSSE Online, 4*(2), 128-162.

Irvine, K.N., Chang, C.H., Das,D., Chatterjee, K., Seow, T., and Wu, B.S. (2016). Greenspace and urban sustainable living. *GeoBuzz,* (Geography Teachers Association of Singapore), 6-9.

James, W. and Verspagen, B. 1997. Thermal enrichment of stormwater by urban pavement. In W. James, ed. *Advances in Modeling the Management of Stormwater Impacts, Vol. 5,* CHI, Guelph, Ch. 8.

Järvenpää, M., & Lindström, K. (2004). Water turbidity by algal blooms causes mating system breakdown in a shallow-water fish, the sand goby Pomatoschistus minutus. *Proceedings of the Royal Society of London B: Biological Sciences*, *271*(1555), 2361-2365.

Johnson, D. B., & Hallberg, K. B. (2005). Acid mine drainage remediation options: a review. Science of the total environment, 338(1), 3-14.

Jones, G. K., Baker, J. L., Edyvane, K., & Wright, G. J. (1996). Nearshore fish community of the Port River-Barker Inlet Estuary, South Australia. I. Effect of thermal effluent on the fish community structure, and distribution and growth of economically important fish species. *Marine and freshwater Research*, *47*(6), 785-799.

Joshi, Y. K., Tortajada, C., & Biswas, A. K. (2012). Cleaning of the Singapore River and Kallang Basin in Singapore: economic, social, and environmental dimensions. *International Journal of Water Resources Development*, *28*(4), 647-658.

Kamer, J., Thomson, R., Mackenzie, T., Ooi, L. K., & Phillips, B. C. (2008). Investigating sewer rehabilitation in the Marina Reservoir Catchment in Singapore. In *Edinburgh: 11th International Conference on Urban Drainage*.

Kannel, P. R., Lee, S., Lee, Y. S., Kanel, S. R., & Khan, S. P. (2007). Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment*, *132*(1), 93-110.

Karagiannis, I. C., & Soldatos, P. G. (2008). Water desalination cost literature: review and assessment. *Desalination*, *223*(1-3), 448-456.

Kemp, P., Sear, D., Collins, A., Naden, P., & Jones, I. (2011). The impacts of fine sediment on riverine fish. *Hydrological Processes*, *25*(11), 1800-1821.

Khan, A. A., Paterson, R., & Khan, H. (2004). Modification and Application of the Canadian Council of Ministers of the Environment Water Quality Index(CCME WQI) for the Communication of Drinking Water Quality Data in Newfoundland and Labrador. *Water Quality Research Journal of Canada*, *39*(3), 285-293.

Khan, A. A., Tobin, A., Paterson, R., Khan, H., & Warren, R. (2005). Application of CCME procedures for deriving site-specific water quality guidelines for the CCME Water Quality Index. *Water Quality Research Journal of Canada*, *40*(4), 448-456.

Khoo, T. C. (2009). Singapore water: yesterday, today and tomorrow. In *Water management in 2020 and beyond* (pp. 237-250). Springer Berlin Heidelberg.

Kim, J. H., & Grant, S. B. (2004). Public mis-notification of coastal water quality: A probabilistic evaluation of posting errors at Huntington Beach, California, *Environmental Science & Technology, 38*(9), 2497-2504.

Kim, J. W., Pachepsky, Y. A., Shelton, D. R., & Coppock, C. (2010). Effect of streambed bacteria release on E. coli concentrations: Monitoring and modeling with the modified SWAT. *Ecological Modelling*, *221*(12), 1592-1604.

Kjelland, M. E., Woodley, C. M., Swannack, T. M., & Smith, D. L. (2015). A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. *Environment Systems and Decisions*, *35*(3), 334-350.

Ko, C.K. (2011) *Your First Guide to Water Quality Monitoring in Singapore.* waterqualityinsingapore.blogspot.co.

Krueger, A. M., Irvine, K. N., Prangkio, C., Chaokasad, K., Sukontason, K., Sukontason, K. L., & Ngern-klun, R. (2004). Visualizing water quality trends in Chiang Mai rice paddies: possible links between environment and health risks. *Middle States Geographer*, *37*, 1-8.

Kumar, D., & Alappat, B. J. (2009). NSF-Water Quality Index: Does It Represent the Experts' Opinion?. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, *13*(1), 75-79.

Laist, D. W., & Reynolds, J. O. H. N. (2005). Influence of power plants and other warm-water refuges on Florida manatees. *Marine Mammal Science*, *21*(4), 739-764.

Layton, A., McKay, L., Williams, D., Garrett, V., Gentry, R., & Sayler, G. (2006). Development of Bacteroides 16S rRNA gene TaqMan-based real-time PCR assays for estimation of total, human, and bovine fecal pollution in water. *Applied and environmental microbiology*, *72*(6), 4214-4224.

Lermontov, A., Yokoyama, L., Lermontov, M., & Machado, M. A. S. (2009). River quality analysis using fuzzy water quality index: Ribeira do Iguape river watershed, Brazil. *Ecological Indicators*, *9*(6), 1188-1197.

Liou, S. M., Lo, S. L., & Wang, S. H. (2004). A generalized water quality index for Taiwan. *Environmental Monitoring and Assessment*, *96*(1), 35-52.

Liss, S. N., Milligan, T. G., Droppo, I. G., & Leppard, G. G. (2004). Methods for Analyzing Floc Properties. *Flocculation in natural and engineered environmental systems*, 1-22.

Lloyd, D. S. (1987). Turbidity as a water quality standard for salmonid habitats in Alaska. *North American journal of fisheries management*, *7*(1), 34-45.

Lukšienė, D., Sandström, O., Lounasheimo, L., & Andersson, J. (2000). The effects of thermal effluent exposure on the gametogenesis of female fish. *Journal of Fish Biology*, *56*(1), 37-50.

Makarewicz, J. C., & Bertram, P. (1991). Evidence for the restoration of the Lake Erie ecosystem. *Bioscience*, *41*(4), 216-223.

Makarewicz, J.C., Boyer, G.L., Guenther, W., Arnold, M., and Lewis, T.W. (2006). The occurrence of cyanotoxins in the nearshore and coastal embayments of Lake Ontario. *Great Lakes Research Review,* 7: 25-29.

Marion, J. W., Lee, J., Lemeshow, S., & Buckley, T. J. (2010). Association of gastrointestinal illness and recreational water exposure at an inland US beach. *Water Research*, *44*(16), 4796-4804.

Marsh, W.M. (1991). *Landscape Planning Environmental Applications, 2nd ed.,* John Wiley & Sons, Inc. NY.

McBride, G.B. and Chapra, S.C. (2005). Rapid calculation of oxygen in streams: approximate delta method. *Journal of Environmental Engineering, 131*, 336-342.

Mieszkin, S., Furet, J. P., Corthier, G., & Gourmelon, M. (2009). Estimation of pig fecal contamination in a river catchment by real-time PCR using two pig-specific Bacteroidales 16S rRNA genetic markers. *Applied and environmental microbiology*, *75*(10), 3045-3054.

Milliman, J. D. (2009). River inputs. *Elements of Physical Oceanography: A derivative of the Encyclopedia of Ocean Sciences*, 457.

Minella, J. P., Merten, G. H., Reichert, J. M., & Clarke, R. T. (2008). Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. *Hydrological processes*, *22*(12), 1819-1830.

Mitchell, M. K., & Stapp, W. B. (1995). Field manual for water quality monitoring: an environmental education program for schools, 9th edn. Green Project, Thomson-Shore, Inc., *Ann Arbor, MI*.

Muirhead, R. W., Davies-Colley, R. J., Donnison, A. M., & Nagels, J. W. (2004). Faecal bacteria yields in artificial flood events: quantifying in-stream stores. *Water research*, *38*(5), 1215-1224.

New, M. B. (2002). *Farming freshwater prawns: a manual for the culture of the giant river prawn (Macrobrachium rosenbergii)* (No. 428). Food & Agriculture Org..

Ng, W. J., & Tjan, K. W. (2006). Industrial wastewater treatment (No. 628.3 N48 2006.). London: Imperial College Press.

Odum, H. T. (1956). Primary production in flowing waters. *Limnology and oceanography*, *1*(2), 102-117.

Ong, I.B.L. (2010). Singapore water management policies and practices. *International Journal of Water Resources Development, 26*(1), 65-80.

Ontario Ministry of Energy and Environment, (1999).

Palupi, K., Sumengen, S., Inswiasri, S., Agustina, L., Nunik, S. A., Sunarya, W., & Quraisyn, A. (1995). River water quality study in the vicinity of Jakarta. *Water Science and Technology*, *31*(9), 17-25.

Passerat, J., Ouattara, N. K., Mouchel, J. M., Rocher, V., & Servais, P. (2011). Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. *Water research*, *45*(2), 893-903.

Pesce, S. F., & Wunderlin, D. A. (2000). Use of water quality indices to verify the impact of Córdoba City (Argentina) on Suquía River. *Water Research*, *34*(11), 2915-2926.

Pettibone, G. W., Irvine, K. N., & Monahan, K. M. (1996). Impact of a ship passage on bacteria levels and suspended sediment characteristics in the Buffalo River, New York. *Water Research*, *30*(10), 2517-2521.

Pfannkuche, J., & Schmidt, A. (2003). Determination of suspended particulate matter concentration from turbidity measurements: particle size effects and calibration procedures. *Hydrological Processes*, *17*(10), 1951-1963.

Phan, K., Sthiannopkao, S., Kim, K. W., Wong, M. H., Sao, V., Hashim, J. H., ... & Aljunid, S. M. (2010). Health risk assessment of inorganic arsenic intake of Cambodia residents through groundwater drinking pathway. *Water Research*, *44*(19), 5777-5788.

Pitt, R., Clark, S. E., Eppakayala, V. K., & Siseshi, R. (2017). Don't throw the baby out with the bathwater – sample collection and processing issues associated with particulate solids in stormwater. *Journal of Water Management Modeling,* 25:C416, DOI:10.14796/JWMM.C416.

Pratt, E. J., Irvine, K. N., Marshall, S., Loganathan, B. G., Kumar, S., & Sikka, H. C. (1995). Planning level estimates of heavy metals (PB and Cu), total PCBs and HCB loadings to the Buffalo River, NY from combined sewer overflows. *Modern Methods for Modeling the Management of Stormwater Impacts. Computational Hydraulics International, Guelph, Ontario, Canada*, 127-149.

Price, J., Chaosakul, T., Surinkul, N., Bowles, J., Rattanakul, S., Pradhan, N., ... & Nguyen, T. V. (2011). Surface water quality and risk analysis in a peri-urban area, Thailand. In *Proceedings, 9th International Symposium on Southeast Asia Water Environment*.

PUB (2011). *ABC Waters Design Guidelines, 2nd Ed.* Singapore.

Rossi, M. C., Irvine, K. N., Hersey, T. R., & Vermette, S. J. (2009). Western New York Stormwater Coalition: Compliance through Collaboration. *Intelligent Modeling of Urban Water Systems, Monograph*, *17*.

Roy, S., Gaillardet, J., & Allegre, C. J. (1999). Geochemistry of dissolved and suspended loads of the Seine river, France: anthropogenic impact, carbonate and silicate weathering. *Geochimica et cosmochimica acta*, *63*(9), 1277-1292.

Sampson, M. L., Bostick, B., Chiew, H., Hagan, J. M., & Shantz, A. (2008). Arsenicosis in Cambodia: Case studies and policy response. *Applied Geochemistry*, *23*(11), 2977-2986.

Sánchez, E., Colmenarejo, M. F., Vicente, J., Rubio, A., García, M. G., Travieso, L., & Borja, R. (2007). Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecological Indicators*, *7*(2), 315-328.

Schindler, D. W. (1974). Eutrophication and recovery in experimental lakes: implications for lake management. *Science*, 184(4139), 897-899.

Schindler, D. W. (2012). The dilemma of controlling cultural eutrophication of lakes. *Proceedings of the Royal Society of London B: Biological Sciences,* rspb20121032.

Schindler, D. W., Hecky, R. E., Findlay, D. L., Stainton, M. P., Parker, B. R., Paterson, M. J., ... & Kasian, S. E. M. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: results of a 37-year whole-ecosystem experiment. Proceedings of the National Academy of Sciences, 105(32), 11254-11258.

Selvakumar, A., & Borst, M. (2006). Variation of microorganism concentrations in urban stormwater runoff with land use and seasons. *Journal of Water and Health*, *4*(1), 109-124.

Sharma, D., & Kansal, A. (2011). Water quality analysis of River Yamuna using water quality index in the national capital territory, India (2000–2009). *Applied Water Science*, *1*(3-4), 147-157.

Sherer, B. M., Miner, J. R., Moore, J. A., & Buckhouse, J. C. (1992). Indicator bacterial survival in stream sediments. *Journal of Environmental Quality*, *21*(4), 591-595.

Smith, D. G. (1990). A better water quality indexing system for rivers and streams. *Water Research*, *24*(10), 1237-1244.

Spigarelli, S. A. (1975). Behavioral responses of Lake Michigan fishes to a nuclear power plant discharge. *Environmental effects of cooling systems at nuclear power plants. International Atomic Energy Agency (IAEA), Vienna*, 479-498.

Staley, C., Gould, T. J., Wang, P., Phillips, J., Cotner, J. B., & Sadowsky, M. J. (2015). Species sorting and seasonal dynamics primarily shape bacterial communities in the Upper Mississippi River. *Science of the Total Environment*, *505*, 435-445.

Stephenson, G. R., & Rychert, R. C. (1982). Bottom sediment: a reservoir of Escherichia coli in rangeland streams. *Journal of Range Management*, 119-123.

Stoner, J. D. (1978). *Water-quality indices for specific water uses*. Department of the Interior, U.S. Geological Survey.

Stubblefield, A. P., Reuter, J. E., Dahlgren, R. A., & Goldman, C. R. (2007). Use of turbidometry to characterize suspended sediment and phosphorus fluxes in the Lake Tahoe basin, California, USA. *Hydrological Processes*, *21*(3), 281-291.

Sun, H., Cornish, P. S., & Daniell, T. M. (2001). Turbidity-based erosion estimation in a catchment in South Australia. *Journal of Hydrology*, *253*(1), 227-238.

Sutherland, A. B., & Meyer, J. L. (2007). Effects of increased suspended sediment on growth rate and gill condition of two southern Appalachian minnows. *Environmental Biology of Fishes*, *80*(4), 389-403.

Teixeira, T. P., Neves, L. M., & Araújo, F. G. (2009). Effects of a nuclear power plant thermal discharge on habitat complexity and fish community structure in Ilha Grande Bay, Brazil. *Marine Environmental Research*, *68*(4), 188-195.

Thompson, A.M., Kim, K., and Vandermuss, A.J. 2008. Thermal characteristics of stormwater runoff from asphalt and sod surfaces. *Journal of the American Water Resources Association,* 44(5):1325-1336.

Thurston-Enriquez, J. A., Gilley, J. E., & Eghball, B. (2005). Microbial quality of runoff following land application of cattle manure and swine slurry. *Journal of water and health*, *3*(2), 157-171.

Tomlinson, M.S. & De Carlo, E.H. (2003). The need for high resolution time series data to characterize Hawaiian streams. *Journal of the American Water Resources Association, 39*(1), 113-123.

Tortajada, C., & Pobre, K. (2011). The Singapore–Malaysia water relationship: an analysis of the media perspectives. *Hydrological Sciences Journal*, *56*(4), 597-614.

Tortajada, C., & Joshi, Y. K. (2013). Water demand management in Singapore: involving the public. *Water resources management*, *27*(8), 2729-2746.

U.S. EPA (2000) *Nutrient Criteria Technical Guidance Manual Rivers and Streams,* EPA-822-B-00-002.

U.S. EPA (2012). Recreational Water Quality Criteria, U.S. EPA Office of Water, 820-F-12-058.

Utne-Palm, A. C. (2002). Visual feeding of fish in a turbid environment: physical and behavioural aspects. *Marine and Freshwater Behaviour and Physiology*, *35*(1-2), 111-128.

Van de Meutter, F., De Meester, L., & Stoks, R. (2005). Water turbidity affects predator–prey interactions in a fish–damselfly system. *Oecologia*, *144*(2), 327-336.

Visoth, T., Yim, M., Vathna, S., Irvine, K., & Koottatep, T. (2010). Efficiency of Phnom Penh's natural wetlands in treating wastewater discharges. *Asian Journal of Water, Environment and Pollution*, *7*(3), 39-48.

Vollenweider, R.A. and Kerekes, J. (1982). Eutrophication of waters, monitoring, assessment and control. Final Report, OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Environment Directorate, OECD, Paris, 154p.

Wade, T. J., Pai, N., Eisenberg, J. N., & Colford Jr, J. M. (2003). Do US Environmental Protection Agency water quality guidelines for recreational waters prevent gastrointestinal illness? A systematic review and meta-analysis. *Environmental Health Perspectives*, *111*(8), 1102.

Wade, T. J., Calderon, R. L., Sams, E., Beach, M., Brenner, K. P., Williams, A. H., & Dufour, A. P. (2006). Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. *Environmental health perspectives*, 24-28.

Wade, T. J., Sams, E., Brenner, K. P., Haugland, R., Chern, E., Beach, M., ... & Noble, R. (2010). Rapidly measured indicators of recreational water quality and swimming-associated illness at marine beaches: a prospective cohort study. *Environmental Health*, *9*(1), 66.

Walling, D. E. (1977). Assessing the accuracy of suspended sediment rating curves for a small basin. *Water Resources Research*, *13*(3), 531-538.

Walker, J., Zipper, C., Shabman, L., & Younos, T. (2006). *A Literature Review for Use in Nutrient Criteria Development for Freshwater Streams and Rivers in Virginia*, Report for the Virginia Department of Environmental Quality, Virginia Water Resources Research Center, Blacksburg, VA.

Warren, L. A., & Haack, E. A. (2001). Biogeochemical controls on metal behaviour in freshwater environments. Earth-Science Reviews, 54(4), 261-320.

Whitman, R. L., Harwood, V. J., Edge, T. A., Nevers, M. B., Byappanahalli, M., Vijayavel, K., ... & Ferguson, D. (2014). Microbes in beach sands: integrating environment, ecology and public health. *Reviews in Environmental Science and Bio/Technology*, *13*(3), 329-368.

Wilber, D. H., & Clarke, D. G. (2001). Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. *North American Journal of Fisheries Management*, *21*(4), 855-875.

Williams, R. J., White, C., Harrow, M. L., & Neal, C. (2000). Temporal and small-scale spatial variations of dissolved oxygen in the Rivers Thames, Pang and Kennet, UK. *Science of the total environment*, *251*, 497-510.

Wills, M., & Irvine, K. N. (1996). Application of the national sanitation foundation water quality index in Cazenovia Creek, NY, pilot watershed management project. *Middle States Geographer*, *1996*, 95-104.

Wong, M., Kumar, L., Jenkins, T. M., Xagoraraki, I., Phanikumar, M. S., & Rose, J. B. (2009). Evaluation of public health risks at recreational beaches in Lake Michigan via detection of enteric viruses and a human-specific bacteriological marker. *Water research*, *43*(4), 1137-1149.

Xie, J.D.M. and James, W. 1994. Modeling solar thermal enrichment of urban stormwater. In W. James, ed. *Current Practices in Modelling the Management of Stormwater Impacts,* CRC Press, FL, pp. 205-220.

Yergeau, E., Lawrence, J. R., Sanschagrin, S., Waiser, M. J., Korber, D. R., & Greer, C. W. (2012). Next-generation sequencing of microbial communities in the Athabasca River and its tributaries in relation to oil sands mining activities. *Applied and environmental microbiology*, *78*(21), 7626-7637.

APPENDIX A

WATER QUALITY TEST PROCEDURES

Introduction

This appendix reviews possible methods to measure the parameters included in the NSF WQI. This is not an exhaustive inventory of methodologies. The methodology that you choose to implement with your class will depend on factors including your budget, availability of test equipment and kits, and the desired level of test accuracy. Over the years, we have assessed a number of different kit-based methodologies (e.g. Irvine et al., 2011b) and found the Chemetrics kits, Hach kits, and Coliscan Easygel kits to be reliable. Normally, for scientific research, we will employ meters to measure dissolved oxygen, pH, temperature, conductivity, turbidity, and chlorophyll *a* (fluorescence). A range of meters is available, from fairly inexpensive, non-recording, handheld meters that might only measure one parameter, to expensive, multi-parameter meters that will continuously log data and can be connected to the internet to remotely transmit the data.

For all laboratory analyses you should follow best laboratory safety practices, including no open toe shoes (or slippers), disposable nitrile (or similar) gloves, and safety goggles.

Dissolved Oxygen

Many will be familiar with the water quality test kits provided to the schools by PUB and dissolved oxygen is included in these test kits. As such, I do not dwell on dissolved oxygen in this methods section. It is worth noting that as shown in the companion Sustainability Learning Lab videos, however, dissolved oxygen test kits are available from Chemetrics Inc. and also can be measured using dissolved oxygen sensors, such as those available on YSI datasondes as discussed in the previous chapters. A YSI datasonde is used to measure dissolved oxygen in one of the Jurong Ecogarden stormwater ponds and the data are freely available on the Sustainability Learning Lab website, www.sll.com.

If you are using the Chemetrics kit for dissolved oxygen, it employs the indigo carmine method for analysis. In an acidic solution, oxygen oxidizes the yellow/green colored leuco form of indigo carmine to form a highly colored blue dye. The resulting blue color is proportional to the dissolved oxygen concentration in the sample. The analysis uses the following steps:

1. Fill the sample cup to the 25 mL mark with the sample to be tested.

2. Place the ampoule, tip first, into the sample cup. Snap the tip. The ampoule will fill, leaving a bubble for mixing.

3. To mix the ampoule, invert it several times, allowing the bubble to travel from end to end.

4. Dry the ampoule and wait 2 minutes for color development.

5. Obtain a test result by placing the ampoule between the color standards until the best color match is found (Figure A1). If the sample color is between standard values it is ok to estimate the sample value.

Figure A1 An M3 student from Kanaratbamrung Pathumthani school, Thailand, comparing the color standards to determine dissolved oxygen level in a sample from the Chao Phraya River.

E. Coli

The Coliscan Easygel® system from Micrology Labs (http://www.micrologylabs.com/Home), Goshen,IN, is described here to determine E. coli levels. This system is based on the principal that in order for coliforms to ferment lactose, they must produce certain enzymes which can be identified and used to verify the presence of the coliforms. General coliforms produce the enzyme galactosidase in lactose fermentation and E. coli produce the enzyme glucuronidase in addition to galactosidase. General coliforms will produce the enzyme galactosidase and the colonies that grow in the medium will be of pink color, while the E. coli, which produces both galactosidase and glucuronidase will grow as dark blue to purple colonies in the media. It is easy to distinguish and count the blue/purple colonies.

The general test procedure is as follows:

1. Collect the water sample. This should be done as ***aseptically*** as possible, but in the absence of ***autoclaved*** or sterile sample bottles, first rinse your sampler three times with the on-site water your intend to sample.

2. Using the sterile, disposable plastic pipette, extract between 1 and 5 mL of water from the sampler and disperse in the growth media. The pipette has a maximum 1 mL volume, so if you

need 5 mL, you must extract 1 mL five times. The volume you use will depend on how high you think the E. coli levels will be; if you believe the water will be fairly clean, use 5 mL.

3. Gently swirl the water and growth media. Do not shake because this will create foam which interferes with the colony counts later.

4. Pour the water and growth media mix evenly into the bottom of the petri dish, which is the smaller part of the dish. The bottom contains the special coating that helps produce a biochemical reaction to turn the E. coli colonies blue or purple. If you pour the sample into the top of the E. coli dish the test will not produce a result.

5. Let the sample sit on a level surface, away from direct sunlight, for about 20 minutes. After this time the liquid media will form a gel and you can transport the dish back to the school.

6. Make sure that each petri dish is labeled with the sample number and it is a good idea to seal the top and bottom of the dishes together with tape.

7. Let the dishes sit at room temperature for 48 hours and count the blue and purple colonies as E. coli. The pink colonies are other coliform and usually we are not interested in these (Figure A.2).

8. In doing the counting, it can be helpful to dot the colony on the outside of the petri dish with a permanent black marker. Do not remove the top of the petri dish and do not put your fingers into the media gel.

9. If you used 1 mL of water sample, multiply the number of counted colonies by 100 to get the result in M.O./100 mL. If you used 5 mL of water sample, multiply the number of counted colonies by 20 to get the result in M.O./100 mL.

10. To dispose of your samples, either give them to your Biology Department to be handled as part of their biohazard waste, or pour common bleach into the dish to kill the bacteria, let sit for a short time, and then flush the dissolved gel down a toilet.

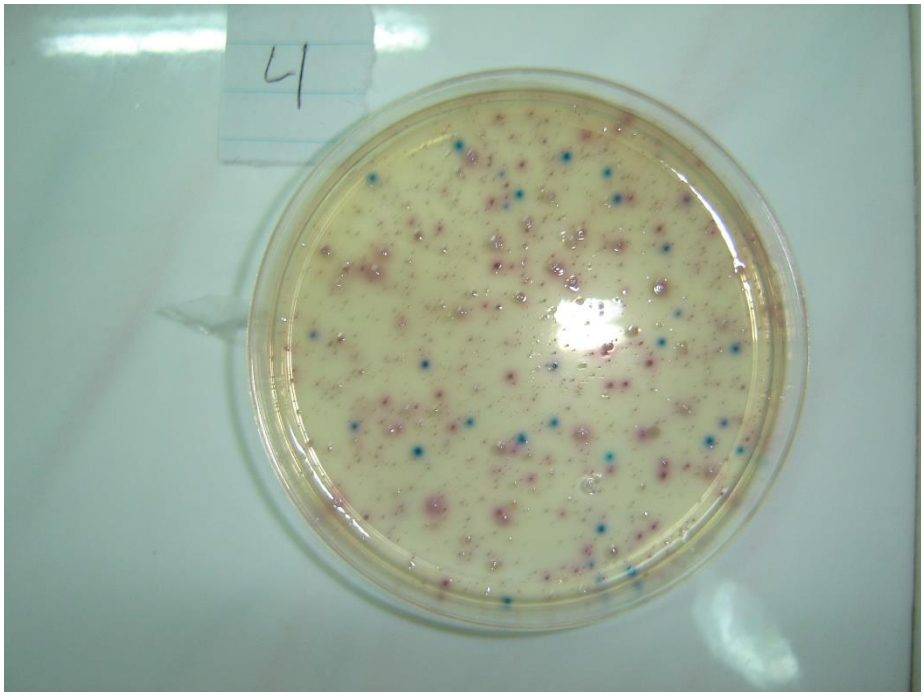


Figure A2 Coliscan results, showing the blue/purple and pink colonies. Sample from the Mekong River, near Phnom Penh, Cambodia.

pH

Many will be familiar with the water quality test kits provided to the schools by PUB and pH is included in these test kits. As such, I do not dwell on pH in this methods section. However, it is worth noting that a quick test for pH can be done using litmus test strips and these often can be obtained from fish supply stores.

BOD_5

BOD_5 can be determined using either the Chemetrics dissolved oxygen kits, the PUB dissolved oxygen kits, or a dissolved oxygen sensor. Once the dissolved oxygen level is determined at the field site, immediately place a sample of the water into an amber glass or brown polyethylene bottle. Fill the bottle full so that there is no head space (no air pocket in the top) that would affect results. The size of the bottle will depend on whether you are using the Chemetrics or PUB kit (50-100 mL bottles are sufficient) or a sensor (larger bottle needed). Allow the sample bottles to sit at room temperature (ideally, though, the temperature is standardized to 20^{oC}) and remeasure the dissolved oxygen after 5 days. The difference between the two readings will be the BOD_5. This approach will work provided you are not sampling waters with extremely high organic content (e.g. contaminated with wastewater). If the organic content is too high initially you may have to dilute the original sample.

Phosphorus

Phosphorus can be determined using a Chemetrics kit that follows the stannous chloride method (Figure A3). In an acidic solution, ortho-phosphate reacts with ammonium molybdate to form molybdophosphoric acid, which is then reduced by stannous chloride to the intensely colored molybdenum blue. The resulting blue color is directly proportional to the phosphate concentration. The analysis uses the following steps:

1. After collecting the water sample, fill the sample cup to the 25 mL mark.
2. Add 2 drops of A-8500 Activator Solution. Cap the sample cup and shake it to mix the contents well.
3. Place the phosphate ampoule, tip first, into the sample cup. Snap the tip, but make sure to keep the ampoule in the water. The ampoule will fill leaving a bubble for mixing.
4. To mix the ampoule, invert it several times, allowing the bubble to travel from end to end.
5. Dry the ampoule and wait 2 minutes for color development.
6. Obtain a test result using the appropriate comparator.
7. If the concentration is low, use the tube comparator by placing the ampoule, flat end first, into the comparator. Rotate the comparator until the best color match is found.
8. If the concentration is higher, use the regular color standards and place the ampoule between the standards until the best color match is found. If the sample color is between standard values it is ok to estimate the sample value.

Nitrate

Nitrate can be determined using a Chemetrics kit that follows the cadmium reduction method (Figure A3). Nitrate is reduced to nitrite in the presence of cadmium. In an acidic solution, the nitrite diazotizes with a primary aromatic amine and then couples with another organic molecule to produce a pink-orange colored azo dye. The resulting color is proportional to the nitrate concentration. The analysis uses the following steps:

1. Fill the reaction tube to the 15 mL mark with the sample to be tested.
2. Empty the contents of one Cadmium Foil Pack into the reaction tube. Take care in handling this pack. Cap the reaction tube and shake it vigorously for exactly 3 minutes. Allow the sample to sit for 2 minutes.
3. Pour 10 mL of the treated sample into the sample cup, being careful not to transfer any cadmium particles to the sample cup.
4. Place the nitrate ampoule in the sample cup. Snap the tip by pressing the ampoule against the side of the cup. Do not remove the ampoule until it has filled. Once the ampoule has filled, there will be a small bubble to facilitate mixing.
5. Mix the contents of the ampoule by inverting it several times, allowing the bubble to travel end to end. Dry the ampoule and wait 10 minutes for color development.
6. Place the ampoule between the color standards, moving it along the comparator until the best color match is found. If the color of the sample is between color standards, an estimate can be made.
7. Make sure you collect and dispose of all water used in the testing with the Chemistry Department at your school.

Figure A3 NIE students testing phosphate and nitrate levels in the stormwater ponds of Jurong Ecogarden.

Turbidity

As noted in Chapter 2, turbidity can be measured using a standard Secchi disk, a Secchi tube, or a turbidity sensor, depending upon the school's resources.

Total Solids

Total solids, in mg/L could be determined by placing a 50-100 mL water sample into a pre-weighed aluminum evaporation dish, allowing the water to evaporate, and re-weighing the aluminum dish once all water has evaporated (Figure A4). If 100 mL of water is used, the resultant mass of total solids would have to be multiplied by 10 to standardize in L.

Figure A4 M3 students from Kanaratbamrung Pathumthani school, Thailand, measuring total solids in an aluminum evaporation dish, using a small portable electronic balance (left) and an example sample from the Chao Phraya River (right).

It may be desirable to separately determine suspended solids concentration and dissolved solids concentration. If this is the case, suspended solids concentrations are determined by filtration. First, collect a known volume of sample. This may be between 100 and 500 mL, depending on how much sediment is in the water. Take a new glass fiber filter, (ideally place it in a desiccator for 24 hours before weighing to remove any moisture), weigh it, and then place it into the filter holder system (Figure A5). Filter the known volume of water. A hand operated vacuum pump (Figure A5) helps to create suction that draws the water through the filter. Once the water sample is fully filtered (Figure A6), place the filter in a drying oven and dry to a constant weight at 103-105^{O}C. If you have many samples, you may need to place the filters in a desiccator before weighing to keep them dry. Weigh the filter + sediment and then subtract the empty filter weight to determine the suspended sediment

concentration in mg/L. Place the filtered water that has been collected in the receiving flask into aluminum evaporation tins and determine the dissolved solids concentration following the procedure described previously for total solids.

Figure A5 Filter holder system (left) and hand operated vacuum pump that attaches to the filter holder system (right) to help draw the sample through the filter (photos courtesy of Zee Wan Teng).

Figure A6 A filtered sample (100 mL of water used in this case) from the Mekong River near Phnom Penh, Cambodia.

Appendix B

Glossary of Terms

Acid mine drainage – ore and coal mining activities that expose rocks having sulfur-bearing minerals can result in highly acidic runoff. The acidic runoff can have a direct negative effect on aquatic organisms but also can help to release (or dissolve) other metals such as copper, lead and mercury into the water, making them more bioavailable.

Adenosine triphosphate – molecule that transports chemical energy within cells for metabolism.

Aseptically – sampling method for bacteria used to ensure no contamination occurs. All sample bottles and sample equipment ideally are sterilized prior to use. Hands, gloves, etc. do not come in contact with the water sample.

Autoclaved – similar in principle to a giant pressure cooker that uses the power of steam to kill germs on equipment and in sample bottles that would survive a simple washing with boiling water and detergents. This technique sterilizes sampling equipment and sample bottles for use in collecting water for bacterial analysis.

Campylobacter – considered to be the most common bacterial cause of human gastroenteritis in the world.

Chlorophyll *a* - chlorophyll is the molecule that absorbs sunlight and uses its energy to synthesise carbohydrates from CO_2 and water; as such it is called a photoreceptor. It is found in the chloroplasts of green plants and is what makes green plants, green. Chlorophyll serves the same purpose in the cells of green algae. An interesting characteristic of chlorophyll is its ability to fluoresce when a beam of light of proper wavelength is shone into a sample. This is the basic principle behind flourometer sensors which measure the intensity of the fluorescence. A greater fluorescence indicates a higher concentration of green algae.

Combined sewer overflow – older cities throughout North America and Europe as well as many cities in Asia are serviced by a combined sewer system. This system transports sanitary waste from homes and sometimes waste from commercial establishments and industry during dry weather and hopefully the waste is treated before it is released to a waterbody. When it rains, the stormwater runoff from the streets, carparks, and buildings drains into the same sewer system and hence the sanitary waste is *combined* with the stormwater runoff. For smaller storms, the combined sewage also should be transported to a treatment facility before it is released to a waterbody. However, with larger storms, to avoid flooding and sewage backups, excess combined sewage is allowed to discharge directly to a waterbody, untreated (see Figure B1). The original thinking behind this combined system was that the clean stormwater runoff (that really is rainfall) would dilute the sanitary waste and the end results would not be so bad. This has since been proven not to be the case (e.g. Irvine et al., 2005c).

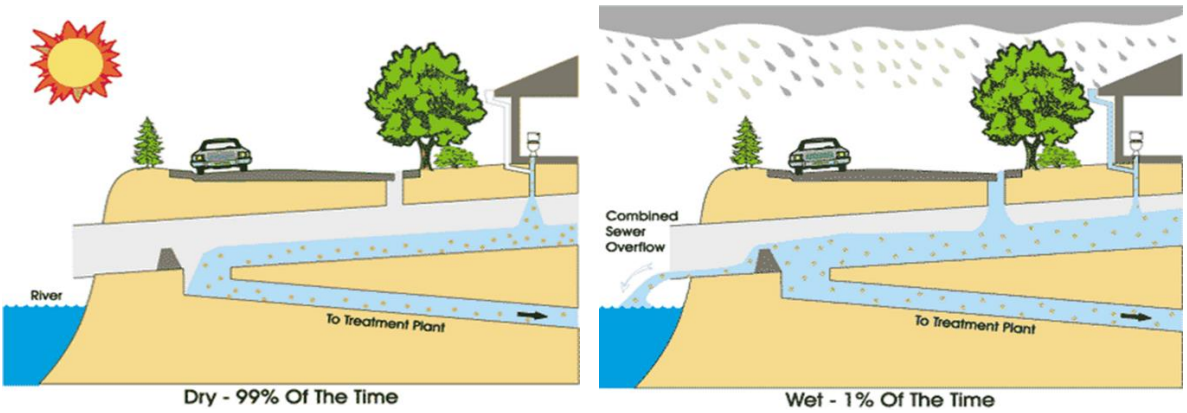


Figure B1 Combined sewer system for a typical condition in older cities of North America. Left, during dry weather sanitary flow goes to a wastewater treatment plant. Right, during larger storms, some of the combined sewage overflows to a waterbody, untreated.

Consumers – Also known as heterotrophs, these organisms must make use of food that comes from other organisms in the form of fats, carbohydrates and proteins (i.e. they feed on other organisms). There are different levels of consumers, as we go up the trophic pyramid from primary to secondary to tertiary consumers, for example (or, roughly, herbivores to carnivores to top predators).

Eutrophication – the enrichment of an aquatic ecosystem with chemical nutrients, typically compounds containing nitrogen, phosphorus, or both. It is a natural process in lakes, occurring as they age through geological time. The nutrients will lead to greater algae and green plant growth in the lakes. Sometimes, the process is accelerated due to human activities such as chemical fertilizers being spread on agricultural fields (with some of the fertilizers subsequently being transported to the lakes via stormwater runoff and soil erosion or leaching into the groundwater) or discharges of inadequately treated wastewater. This acceleration is known as cultural eutrophication and it can lead to algae blooms (i.e. an explosive growth of algae). The blooms (often seen as green mats or a green floating scum) may reduce sunlight reaching aquatic plants which results in plant death. In combination with the algae eventually dying too, the decay of this organic load can lead to a reduction of dissolved oxygen in the water which can negatively impact the ecosystem.

Gravimetric – an analysis based on mass. In this Handbook, it is the mass of suspended solids being determined via filtration.

Humic acids – produced by biodegradation of dead organic matter.

Hypolimnetic (layer) – The layer of water in a thermally stratified lake that lies below the thermocline, and also is known as the hypolimnion (Figure B2).

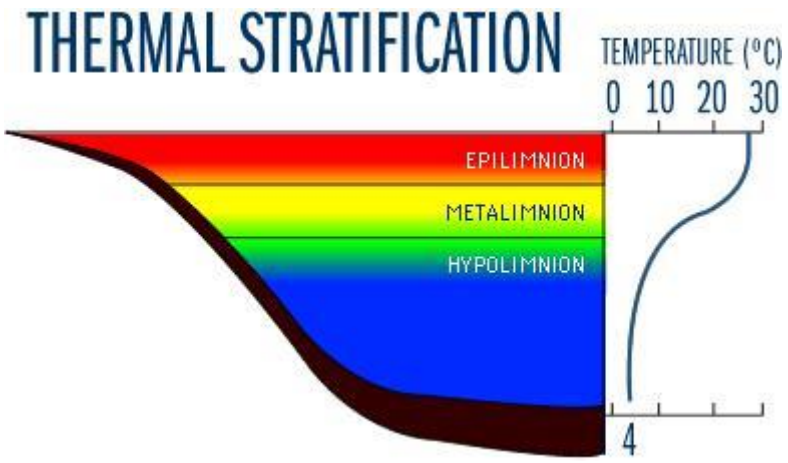


Figure B2 Thermal stratification structure in a lake. The thermocline represents the area in which there is a rapid decrease in temperature (from http://msue.anr.msu.edu/uploads/images/Nat_Res/Thermal%20stratification.jpg).

Interval data – a scale that has fixed intervals between numbers (e.g. the Celsius temperature scale), however it has an arbitrary 0 value.

Ions – a charged atom or molecule. It is charged because the number of electrons do not equal the number of protons in the atom or molecule. If the atom loses one or more electrons, it has a net positive charge and is known as a cation whereas if an atom gains electrons, it has a net negative charge and is known as an anion.

Legionella – bacterium that can result in Legionellosis, a respiratory disease that has symptoms similar to pneumonia.

Limiting Nutrient – the nutrient that is in least supply relative to need. A limiting nutrient is limiting because not only is there not enough of it but there is enough of everything else that an organism needs to allow faster or greater growth, everything except the limiting nutrient. In freshwater ecosystems, usually the limiting nutrient is phosphorus while in ocean ecosystems the limiting nutrient usually is nitrogen.

Low Impact Development – alternatively known as Water Sensitive Urban Design (WSUD) or Sustainable Urban Drainage Systems (SUDS), these technologies include raingardens, stormwater planters, green roofs, porous pavement, grassed swales, constructed wetlands, and even rain barrels. The principle is to follow natural processes to manage rainfall at the source using uniformly distributed decentralized micro-scale controls with the goal of mimicking a site's predevelopment hydrology using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source. By storing and delaying flow to storm drains, localized flooding is reduced, and as an added benefit, the filtration process of the constructed substrates helps to improve the quality of the discharge to the storm drains.

Mesotrophic – lakes with an intermediate level of nutrients and primary productivity. In North America, frequently these types of lakes are home to desirable sports fish.

Microfiltration – the first stage of the NEWater production process is known as microfiltration (MF). In this process, the treated used water is passed through membranes to filter out and retain on the membrane surface suspended solids, colloidal particles, disease-causing bacteria, some viruses and protozoan cysts. The filtered water that goes through the membrane contains only dissolved salts and organic molecules (https://www.pub.gov.sg/Documents/NEWater%20Technology.pdf).

Molecules - are made up of atoms that are held together by chemical bonds. These bonds form as a result of the sharing or exchange of electrons among atoms (Figure B3). Atoms are the basic units of matter consisting of protons, electrons, and neutrons.

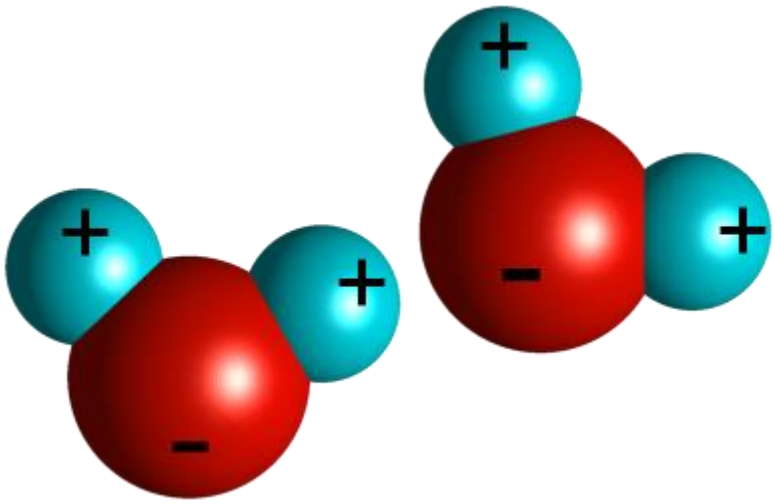


Figure B3 Two water molecules, each consisting of two hydrogen and one oxygen atom.

Nucleic acids – are molecules that allow organisms to transfer genetic information from one generation to the next. There are two types of nucleic acids: deoxyribonucleic acid (i.e. DNA) and ribonucleic acid (i.e. RNA).

Oligotrophic – water bodies that have relatively low levels of nutrients and primary productivity. These water bodies typically are quite clear (i.e. low turbidity levels).

Pathogens - bacteria, viruses, or other microorganism that can cause disease.

Perch – common name for fish belonging to the family Percidae which are widely found in the northcentral water bodies of North America and throughout Europe and northern Asia.

Phospholipids – composed of fatty acids, glycerol, and phosphate that help to provide structure to cells and are important in the construction of cell membranes.

Primary producers – Also known as autotrophs, these are organisms that are able to make energy-containing organic molecules from inorganic raw material using basic energy sources such as sunlight. Plants are the prime example of autotrophs, using photosynthesis.

Pseudomonas – bacteria that may produce skin rashes (swimmers itch) or ear infections. More serious infections also can result in those who have a weakened immune system.

Ratio data – a scale that has fixed intervals between numbers and a fixed (i.e. non-arbitary) zero indicating absence of a property (e.g. length, rainfall).

Reverse osmosis – Osmosis is a naturally occurring phenomenon where a weaker saline solution will tend to migrate to a strong saline solution through a semi-permeable membrane. Examples of osmosis are when plant roots absorb water from the soil and our kidneys absorb water from our blood. No additional energy or force is required and the process is illustrated in Figure B4a. With reverse osmosis you need to 'push' the water through the reverse osmosis membrane by applying pressure that is greater than the naturally occurring osmotic pressure in order to desalinate (or deionize or purify) the

water in the process (Figure B4b). This is the second stage of treatment in NEWater production and the technology also is used at desalination plants.

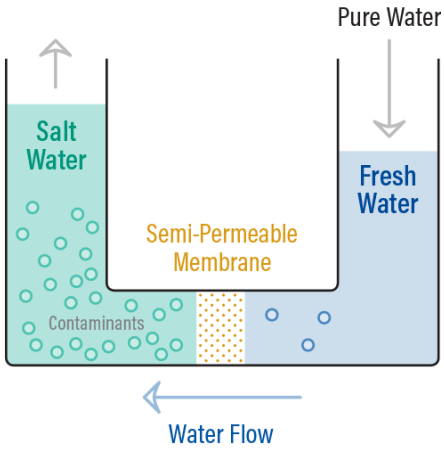


Figure B4a Process of osmosis. The semi-permeable membrane is a membrane that will allow some atoms or molecules to pass but not others (from http://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis).

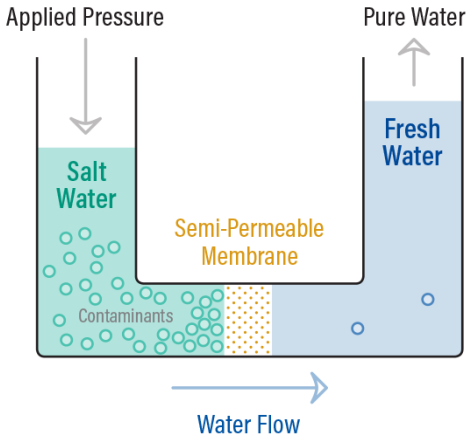


Figure B4b Process of reverse osmosis. Energy is needed to produce the applied pressure, which makes the reverse osmosis process more costly (from http://puretecwater.com/reverse-osmosis/what-is-reverse-osmosis).

R^2 – the coefficient of determination, which in a general sense can be thought of as the square of the correlation between observed y values and fitted y values (fitted with a "best fit" or trendline) and is the fraction of the variation in y that is explained by the fitted equation. The R^2 can have a value between 0 and 1 (or 0% and 100%), with values closer to 1 (or 100%) representing a stronger relationship or a greater percent variability in x that is explained by y.

Salmonella typhi – a bacterium that can produce typhoid fever.

Shigella – a bacterium that can produce dysentery.

Trout – common name for a number of species (e.g. brown trout, rainbow trout, lake trout, cutthroat trout) of freshwater fish belonging to Salmonidae family. Found in the more temperate climates of North America, Europe and northern Asia and generally is considered a desirable sport fish that requires relatively clean water to thrive.

Ultraviolet disinfection – uses short wave ultraviolet light (much like the sun's ultraviolet shortwave radiation wavelengths) to kill or inactivate microorganisms by destroying nucleic acids and disrupting their DNA.

Vibrio cholera – bacterium that can produce cholera, an acute, diarrheal illness resulting from infection of the intestine with the bacterium.