Chapter 3
Surface Water Quality and Analysis

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Contents

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Abstract The fundamental of water quality management and analysis is to adopt several monitoring actions to save water bodies and protect users. Evaluation of physiochemical and biological parameters of surface water is an important aspect for water quality model formation and adopted suitable management actions. This chapter focused on evaluation, monitoring, and analysis of surface water quality. Recently, Water Quality Indices (WQIs) was introduced as new methods for water quality management. Dissolved oxygen in surface water is necessary for aquatic life. Microbial quality of surface water should be safe and should not have adverse effect on human health. In this chapter, WQIs formation, definitions, and limitations were discussed, surface water modeling, standards and indicators of chemical and microbial quality of surface water were presented and discussed.

Keywords Water quality · Module · Physicochemical · Biological · Evaluation · Standards

Acronyms

BOD	Biochemical oxygen demand
DO	Dissolved oxygen
NH_4^+	Ammonia
NO_3^-	Nitrate
NO_2	Nitrite
EC	Electrical Conductivity
ANOVA	Analysis of variance
NSF	National Sanitation Foundation
PCA/FA	Principal component analysis/factor analysis
SO_4^{2-}	Sulfate
SWQM	Surface Water Quality Monitoring
WQIs	Water Quality Indices

Nomenclature

J	is the “diffusion flux” [(amount of substance) per unit area per unit time], for example $\frac{\mathrm{mol}}{\mathrm{m}^2.\mathrm{s}}$, J measures the amount of substance that will flow through a small area during a small time interval.
D	is the diffusion coefficient or diffusivity in dimensions of [length2 time−1], for example $\frac{\mathrm{m}^2}{\mathrm{s}}$
Φ	(for ideal mixtures) is the concentration in dimensions of [amount of substance per unit volume], for example $\frac{\mathrm{mol}}{\mathrm{m}^3}$
L	is the position [length], for example m
dM	is the change of storage mass in the system (kg)
ρ	is the density ($\mathrm{kg/m^3}$)
v	is the speed (m/s)

A	is the area (m^2)
dt	is an increment of time (s)
ţ	is time [s]
$D_{(in\ \mathrm{BOD})}$	is the saturation deficit, which can be derived from the dissolved oxygen concentration at saturation minus the actual dissolved oxygen concentration ($D = DO_{sat} - DO$). D has the dimensions $\left[\frac{\mathrm{g}}{\mathrm{m}^3}\right]$.
K_1	is the deoxygenation rate, usually in d^{-1}.
K_2	is the reaeration rate, usually in d^{-1}.
L_a	is the initial oxygen demand of organic matter in the water, also called the ultimate BOD (BOD at time t = infinity). The unit of is $\left[\frac{\mathrm{g}}{\mathrm{m}^3}\right]$.
L_t	is the oxygen demand remaining at time t.
$[O_2]$	is the observed oxygen concentration
[Osat]	is the saturated concentration of oxygen at the local temperature (and possibly altitude, barometric pressure, and salinity or conductivity).
Da	is the initial oxygen deficit $\left[\frac{\mathrm{g}}{\mathrm{m}^3}\right]$.
t	is the elapsed time, usually [d].

1 Introduction

1.1 Water Quality Monitoring and Analysis

Surface water is water collecting on the ground or in a stream, river, lake, wetland, or ocean; it is related to water collecting as groundwater or atmospheric water. Surface water is naturally replenished by precipitation and naturally lost through discharge to evaporation and sub-surface seepage into the ground.

Testing water quality data for trend over a period of time has received considerable attention recently. The interest in methods of water quality trend arises for two reasons. The first is the intrinsic interest in the question of changing water quality arising out of the environmental concern and activity. The second reason is that only recently has there been a substantial amount of data that is amenable to such an analysis. Recently, several researchers reported different methods and techniques for water quality evaluation and analysis. Naddeo et al. [1] focused on 13 rivers of southern Italy in order to evaluate and optimize the monitoring procedure of surface water. The study recommends minimizing the sampling frequencies in order to reduce the cost of samples analysis. Boyacıoğlu et al. [2] investigated the priorities in surface water quality management based on correlations and variations of different organic and inorganic parameters. Wang et al. [3] used multivariate statistical techniques, such as cluster analysis (CA) and principal component analysis/factor analysis (PCA/FA), to assess the surface water quality and identification of the source of water pollution in the Songhua River in Harbin region, China. Data on 15 parameters, including organic, inorganic, physical, chemical, heavy metals, and hazardous material through the period 2005–2009 were used. This study will provide useful information to managers to know better about how to improve water quality. Selle et al. [4] utilized spatial–temporal patterns of scores technique for surface water, springs, and deep groundwater from the wells in order to understand the processes governing water quality at catchment scales. The study demonstrated the potential analysis to identify dominant processes at catchment scales. Chung and Yoo [5] designed a wireless sensor network (WSN) with deployed field servers to detect water pollution in streams, rivers, and coastal areas. The proposed system can be efficiently performed to monitor the variation of the water quality data in streams, rivers, and coastal areas in real time. Hatvani et al. [6] used Dynamic Factor Analysis method to determine the driving background factors of a river located in an agricultural watershed to separate the role of the diffuse and point source nutrient loads. In this study, Dynamic Factor Analysis was applied to the time series (1978–2006) of 21 response parameters measured in its watershed. The study concluded that, with the aid of Dynamic Factor Analysis, the superimposed effects of the socio-economic changes which began in the mid-1980s, and the introduction of advanced wastewater treatment in the river catchment in the early 1990s, could be separated and their relative importance assessed. Chen et al. [7] prepared a comparative study of surface water quality for the major rivers and lakes in china. Data from 33,612 observations for the major rivers and lakes between 2012 and 2018 was used to evaluate the performance of ten learning models (seven traditional and three ensemble models) to explore the potential key water parameters for future model prediction. Busico et al. [8] utilized a multivariate statistical analysis to investigate a novel hybrid method for the effect of anthropogenic pollutions on groundwater in Italy. Jahin et al. [9] developed irrigation water quality index for surface water in Egypt by using multivariate analysis. Weerasinghe and Handapangoda [10] investigated the analysis of physiochemical parameters of surface water in Sri Lanka. In this study, two-way ANOVA, followed by Tukey's pairwise comparison, were used to assess the spatial and temporal variability. Carstens and Amer [11] perform spatio-temporal analysis study of urban changes and surface water quality in southeast Louisiana. The study reported that the high levels of fecal coliform were consistent with increased urbanization in water bodies. Khan et al. [12] investigated the effect of chemical and microbiological quality of sea water on reverse osmosis membrane and on fouling of RO membrane modification in RO sea water desalination plant in Saudi Arabia. Won et al. [13] evaluated the microbiological quality of tow irrigation canals and four surface reservoirs located in Ohio, USA. The study reported that the level of *Escherichia coli* in irrigation canals was higher than that in reservoirs and increased during heavy rain season. According to Texas commotion on environmental quality [14, 15], the Surface Water Quality Monitoring (SWQM) Program reported that around 1800 samples were collected from different surface water sites statewide to characterize physical, chemical, and biological parameters in order to identify emerging problems and evaluate the effectiveness and trends of water quality program. Standard values and criteria of surface water quality and monitoring has been adopted by Colorado department of public health and are presented in Tables 3.1, 3.2, and 3.3.

Table 3.1 Standard values for terrestrial surface water bodies (rivers, lakes)

Class	Standard values						
	Hydrogen ion concentration index (pH)	**Dissolved oxygen (DO) (mg/l)**	**Biological oxygen demand (BOD) (mg/l)**	**Suspended solids (SS) (mg/l)**	***E. coli* (CFU/100 ml)**	**Ammonia nitrogen (NH_3-N) (mg/l)**	**Total phosphorus (TP) (mg/l)**
A	6.5–8.5	Over 6.5	Less than 1	Less than 25	Less than 50	Less than 0.1	Less than 0.02
B	6.0–9.0	Over 5.5	Less than 2	Less than 25	Less than 5000	Less than 0.3	Less than 0.05
C	6.0–9.0	Over 4.5	Less than 4	Less than 40	Less than 10,000	Less than 0.3	–
D	6.0–9.0	Over 3	–	Less than 100	–	–	–
E	6.0–9.0	Over 2	–	No floating material and no oil	–	–	–

Marine surface water bodies

Class	Standard values			
	Hydrogen ion concentration index (pH)	**Dissolved oxygen (DO) (mg/l)**	**Biological oxygen demand (BOD) (mg/l)**	***E. coli* (CFU/100 ml)**
A	7.5–8.5	Over 5.0	Less than 2	Less than 1000
B	7.5–8.5	Over 5.0	Less than 3	–
C	7.0–8.5	Over 2.0	Less than 6	–

Notes

The following units are used for standard values in the foregoing standards:

6. pH: pH value
7. *E. coli*: colony forming units per 100 ml water sample
8. Others: milligram/liter

Table 3.2 Environmental standards for protecting human health

Water quality item		Standard value (units: mg/l)
Heavy metals	Cadmium	0.01
	Lead	0.1
	Hexavalent chromium	0.05
	Arsenic	0.05
	Mercury	0.002
	Selenium	0.05
	Copper	0.03
	Zinc	0.5
	Manganese	0.05
	Silver	0.05
Agricultural chemicals	Total organophosphates (parathion, Diazinon, Methamidophos, Monocrotophos,EPN, Chlorpyrifos) and carbamates (Fenobucarb, Carbofuran, Methomyl)	0.1
	Endrin	0.0002
	Lindane	0.004
	Toxaphene	0.005
	Endosulfan	0.003
	Heptachlor and derivatives (heptachlor, heptachlor epoxide)	0.001
	DDT and derivatives (DDT, DDD, DDE)	0.001
	Aldrin, Dieldrin	0.003
	Pentachlorophenol and salts	0.005
	Herbicides (Butachlor, Paraquat, 2,4-D)	0.1

Notes

I. The above standards provide specific values for substances posing a cumulative hazard to human health

II. These values are the maximum allowable volumes

III. These values are uniformly applicable to all public water areas

IV. The central competent authority shall add and officially announce maximum allowable volumes for other agricultural chemicals harmful to water quality

1.2 Classification of Surface Water

Calcification of water quality has been reported by Water framework directive (WFD) in 2012 [16]. WFD specified the quality elements that are used to assess the ecological and chemical status of a water body. Quality elements are generally biological (e.g. fish, invertebrates, macrophytes) or chemical (e.g., heavy metals, pesticides, nutrients). Classifications indicate where the quality of the environment is good, where it may need improvement, and what may need to be improved. They can also be used, over the years, to plan improvements, show trends, and to monitor success. Based on WFD, there are two status classifications which are commonly reported: ecological and chemical.

Table 3.3 Value standards (concentrations in μg/l unless noted) [8]

Parameter[a]	Table value standards[b, c]
Ammonia[d]	Cold water $\text{acute} = \frac{0.275}{1+10^{7.204-\text{pH}}} + \frac{39.0}{1+10^{\text{pH}-7.204}}$ $\text{chronic} = \left(\frac{0.0577}{1+10^{7.688-\text{pH}}} + \frac{2.487}{1+10^{\text{pH}-7.688}}\right) * \text{MIN}\left(2.85, 1.45 * 10^{0.028(25-T)}\right)$ Warm water $\text{acute} = \frac{0.411}{1+10^{7.204-\text{pH}}} + \frac{58.4}{1+10^{\text{pH}-7.204}}$ $\text{chronic (Apr1} - \text{Aug31)} = \left(\frac{0.0577}{1+10^{7.688-\text{pH}}} + \frac{2.487}{1+10^{\text{pH}-7.688}}\right) * \text{MIN}\left(2.85, 1.45 * 10^{0.028(25-T)}\right)$ $\text{chronic (Sep1} - \text{Mar31)} = \left(\frac{0.0577}{1+10^{7.688-\text{pH}}} + \frac{2.487}{1+10^{\text{pH}-7.688}}\right) * 1.45 * 10^{0.028*(25-\text{MAX}(T,7))}$
NH3 = old TVS	Cold water acute = 0.43/FT/FPH/2[e] in mg/l (N) Warm water acute = 0.62/FT/FPH/2[e] in mg/(N)
Cadmium	Acute = (1.136672–[ln(hardness) × (0.041838)]) × $e^{0.9151[\ln(\text{hardness})]-3.1485}$ Acute(trout) = (1.136672–[ln(hardness) × (0.041838)]) × $e^{0.9151[\ln(\text{hardness})]-3.6236}$ Chronic = (1.101672–[ln(hardness) × (0.041838)] × $e^{0.7998[\ln(\text{hardness})]-4.4451}$
Chromium III[f]	Acute = $e^{(0.819[\ln(\text{hardness})] + 2.5736)}$ Chronic = $e^{(0.819[\ln(\text{hardness})] + 0.5340)}$
Chromium VI[f]	Acute = 16 Chronic = 11
Copper	Acute = $e^{(0.9422[\ln(\text{hardness})]-1.7408)}$ Chronic = $e^{(0.8545[\ln(\text{hardness})]-1.7428)}$
Lead	Acute = (1.46203-[ln(hardness)*(0.145712)]) * $e^{(1.273[\ln(\text{hardness})]-1.46)}$ Chronic = (1.46203-[ln(hardness)*(0.145712)]) * $e^{(1.273[\ln(\text{hardness})]-4.705)}$
Manganese	Acute = $e^{(0.3331[\ln(\text{hardness})] + 6.4676)}$ Chronic = $e^{(0.3331\ [\ln(\text{hardness})] + 5.8743)}$
Nickel	Acute = $e^{(0.846[\ln(\text{hardness})] + 2.253)}$ Chronic = $e^{(0.846[\ln(\text{hardness})] + 0.0554)}$

(continued)

Table 3.3 (continued)

Parameter[a]	Table value standards[b, c]
Selenium[g]	Acute $= 18.4$ Chronic $= 4.6$
Silver	Acute $= ½e^{(1.72[\ln(\text{hardness})] - 6.52)}$ Chronic $= e^{(1.72[\ln(\text{hardness})]-9.06)}$ Chronic(trout) $= e^{(1.72[\ln(\text{hardness})]-10.51)}$
Uranium	Acute $= e^{(1.1021[\ln(\text{hardness})] + 2.7088)}$ Chronic $= e^{(1.1021[\ln(\text{hardness})] + 2.2382)}$
Zinc	Acute $= 0.978\ e^{(0.8525[\ln(\text{hardness})] + 1.0617)}$ Chronic $= 0.986\ e^{(0.8525[\ln(\text{hardness})] + 0.9109)}$

[a] Metals are stated as dissolved unless otherwise specified

[b] Hardness values to be used in equations are in mg/l as calcium carbonate and shall be no greater than 400 mg/L. The hardness values used in calculating the appropriate metal standard should be based on the lower 95% confidence limit of the mean hardness value at the periodic low flow criteria as determined from a regression analysis of site-specific data. Where insufficient site-specific data exists to define the mean hardness value at the periodic low flow criteria, representative regional data shall be used to perform the regression analysis. Where a regression analysis is not appropriate, a site-specific method should be used. In calculating a hardness value, regression analyses should not be extrapolated past the point that data exist

[c] Both acute and chronic numbers adopted as stream standards are levels not to be exceeded more than once every three years on an average

[d] $FT = 100.03(20–TCAP)$
Where TCAP is $\leq T \leq 30$
$FT = 100.03(20\text{-}T)$
Where 0 is $\leq T \leq$ TCAP
TCAP $= 20$ °C cold water aquatic life species present
TCAP $= 25$ °C cold water aquatic life species absent
FPH $= 1$; Where $8 < \text{pH} \leq 9\ 6$
FPH $= 1 + 10(7.4\text{-pH})$
1.3 Where $6.5 \leq \text{pH} \leq 8$
FPH means the acute pH adjustment factor, defined by the above formulas
FT means the acute temperature adjustment factor, defined by the above formulas
T means temperature measured in degrees
TCAP means temperature CAP; the maximum temperature which affects the toxicity of ammonia to salmonid and non-salmonid fish groups
NOTE: If the calculated acute value is less than the calculated chronic value, then the calculated chronic value shall be used as the acute standard

[e] For acute conditions the default assumption is that salmonids could be present in cold water segments and should be protected, and that salmonids do not need to be protected in warm water segments. For chronic conditions, the default assumptions are that early life stages could be present all year in cold water segments and should be protected. In warm water segments, the default assumption is that early life stages are present and should be protected only from April 1 through August 31. These assumptions can be modified by the commission on a site-specific basis where appropriate evidence is submitted

[f] Unless the stability of the chromium valence state in receiving waters can be clearly demonstrated, the standard for chromium should be in terms of chromium VI. In no case can the sum of the instream levels of Hexavalent and Trivalent Chromium exceed the water supply standard of 50 ug/l total chromium in those waters classified for domestic water use

[g] Selenium is a bioaccumulative metal and subject to a range of toxicity values depending upon numerous site-specific variables

Chemical status is assessed from compliance with environmental standards for chemicals that are priority substances and/or priority hazardous substances. Table 3.4 presents the list of priority substances for chemical status adapted from Environmental Quality Standards Directive (2008/105/EC). Chemical status is recorded as ‘good’ or ‘fail’. Chemical status for a water body is determined by the worst scoring chemical (one-out-all-out approach). The priority substances were monitored only in water bodies where there are known discharges of these pollutants. Water bodies without discharges of priority substances are reported as being at good chemical status.

Ecological status classification consists of four different types of assessments:

1. An assessment of status indicated by a biological quality element, such as fish, invertebrates, or algae
2. An assessment of compliance with environmental standards for supporting physico-chemical conditions, such as dissolved oxygen, phosphorus, and ammonia
3. An assessment of compliance with environmental standards for concentrations of specific pollutants, such as zinc, cypermethrin, or arsenic and in determining high status only
4. A series of tests to make sure that hydromorphology is largely undisturbed and Tables 3.5 and 3.6 illustrate the biological and chemical quality elements, respectively.

Based on WFD, ecological status is recorded as high, good, moderate, poor, or bad. ‘High’ represents “largely undisturbed conditions”. Figure 3.1 shows a diagram for the summary of classification.

1.3 Water Quality Indices (WQIs)

Water quality assessment can be defined as the evaluation of the physical, chemical, and biological nature of water in relation to natural quality, human effects, and intended uses. Water quality indices (WQIs) can be defined as the translation of numerical values of several water quality characteristics of a sample into a single value used in the monitoring, comparison, and control of water quality [16]. WQIs reduce a great amount of parameters to a simpler expression to enable easier interpretation of the monitoring data.

The concept of WQIs has been reported in Germany in 1848 (the presence or absence of certain organisms in water was used as the indicator) [17]. A wide range of WQIs has been developed and applied to classify the quality of water in different regions. Traditionally, most of these WQIs were introduced to deal with data from different manual and automated sampling networks and monitoring programs.

WQIs can be classified into three categories: hysic-chemical, biological, and hydro-morphological WQIs, as shown in Table 3.2. A large number of WQIs has

Table 3.4 EQS Directive priority substances

CAS number[a]	EU number[b]	Name of priority substance[c]	Identified as priority hazardous substance
15,972-60-8	240-110-8	Alachlor	
120-12-7	204-371-1	Anthracene	X
1912-24-9	217-617-8	Atrazine	
71-43-2	200-753-7	Benzene	
Not applicable	Not applicable	Brominated diphenylether[d]	X
32,534-81-9	Not applicable	Pentabromodiphenylether (congener numbers 28, 47, 99, 100, 153 and 154)e	
7440-43-9	231-152-8	Cadmium and its compounds	X
85,535-84-8	287-476-5	Chloroalkanes, C10-13[d]	X
470-90-6	207-432-0	Chlorfenvinphos	
2921-88-2	220-864-4	Chlorpyrifos	
(Chlorpyrifos-ethyl)			
107-06-2	203-458-1	1,2-Dichloroethane	
75-09-2	200-838-9	Dichloromethane	
117-81-7	204-211-0	Di(2-ethylhexyl)phthalate (DEHP)	
330-54-1	206-354-4	Diuron	
115-29-7	204-079-4	Endosulfan	X
206-44-0	205-912-4	Fluoranthene[f]	
118-74-1	204-273-9	Hexachlorobenzene	X
87-68-3	201-765-5	Hexachlorobutadiene	X
608-73-1	210-158-9	Hexachlorocyclohexane	X
34,123-59-6	251-835-4	Isoproturon	
7439-92-1	231-100-4	Lead and its compounds	
7439-97-6	231-106-7	Mercury and its compounds	X
91-20-3	202-049-5	Naphthalene	
7440-02-0	231-111-4	Nickel and its compounds	
25,154-52-3	246-672-0	Nonylphenols	X
104-40-5	203-199-4	(4-nonylphenol)	X
1806-26-4	217-302-5	Octylphenols	
140-66-9	Not applicable	(4-(1,1′,3,3′-tetramethylbutyl)-phenol)	
608-93-5	210-172-5	Pentachlorobenzene	X
87-86-5	201-778-6	Pentachlorophenol	
Not applicable	Not applicable	Polyaromatic hydrocarbons	X
50-32-8	200-028-5	(Benzo(a)pyrene)	X
205-99-2	205-911-9	(Benzo(b)fluoranthene)	X
191-24-2	205-883-8	(Benzo(g,h,i)perylene)	X
207-08-9	205-916-6	(Benzo(k)fluoranthene)	X
193-39-5	205-893-2	(Indeno(1,2,3-cd)pyrene)	X
122-34-9	204-535-2	Simazine	

(continued)

Table 3.4 (continued)

CAS number[a]	EU number[b]	Name of priority substance[c]	Identified as priority hazardous substance
Not applicable	Not applicable	Tributyltin compounds	X
36,643-28-4	Not applicable	(Tributyltin-cation)	X
12,002-48-1	234-413-4	Trichlorobenzenes	
67-66-3	200-663-8	Trichloromethane (chloroform)	
1582-09-8	216-428-8	Trifluralin	

[a] CAS: Chemical Abstracts Service

[b] EU number: European Inventory of Existing Commercial Substances (EINECS) or European List of Notified Chemical Substances (ELINCS)

[c] Where groups of substances have been selected, typical individual representatives are listed as indicative parameters (in brackets and without number). For these groups of substances, the indicative parameter must be defined through the analytical method

[d] These groups of substances normally include a considerable number of individual compounds. At present, appropriate indicative parameters cannot be given

[e] Only Pentabromobiphenylether (CAS number 32534 81 9)

[f] Fluoranthene is on the list as an indicator of other, more dangerous polyaromatic hydrocarbons

Table 3.5 Biological quality elements monitored for each water category [9]

Category	Quality element	Description
Rivers	Macrophytes and phytobenthos – diatoms	Microscopic diatoms (algae) found on rocks and plants
	Macrophytes and phytobenthos – macrophytes	Water plants visible to the naked eye, growing in the river
	Macroinvertebrates	Insects, worms, molluscs, crustacea, etc., living on the river bed
	Fish	Including eel
Lakes	Phytoplankton	Free-floating microscopic plants
	Macrophytes and phytobenthos – diatoms	Microscopic diatoms (algae) found on rocks and plants
	Macrophytes and phytobenthos – macrophytes	Water plants visible to the naked eye, growing in the lake
	Macroinvertebrates	Insect larvae, worms, molluscs, crustacean, etc., living on the lake bed.
TraC	Phytoplankton	Free-floating microscopic plants
	Macroalgae	Seaweeds visible to the naked eye
	Angiosperms	Sea grasses and saltmarsh plants
	Benthic invertebrates	Worms, molluscs, and crustacean, etc., living in or on the bed of the estuary or sea
	Fish (transitional only)	Fish which spend all or part of their life in transitional waters

Table 3.6 Physico-chemical quality elements monitored for each water category [9]

Quality element	Rivers	Lakes	TraC
pH	✓	✓	
Ammonia (total as N)	✓	✓	
Phosphate	✓	✓	
Dissolved inorganic nitrogen			✓
Dissolved oxygen	✓	✓	✓
Specific pollutants (annex VIII)	✓	✓	✓
Acid neutralizing capacity		✓	
Temperature	✓		

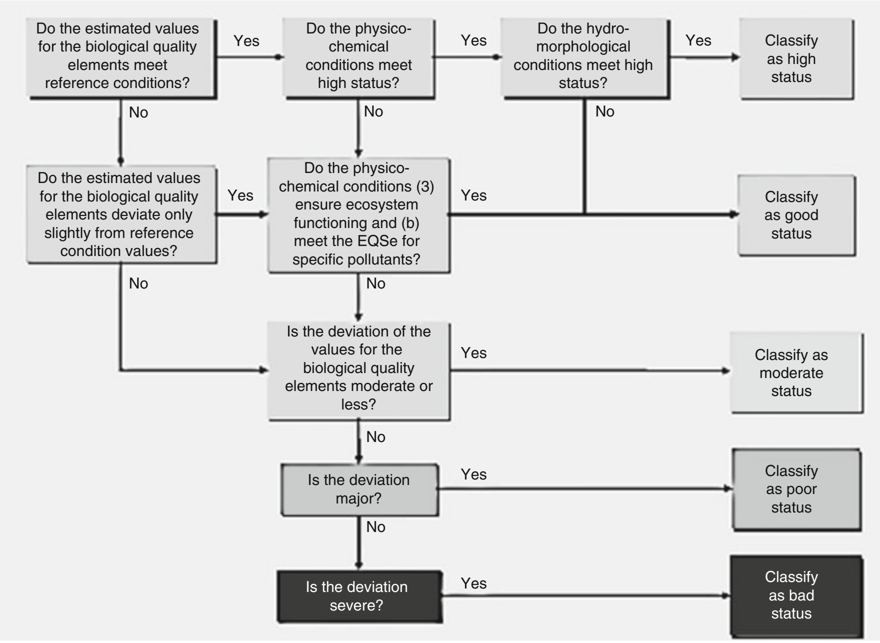


Fig. 3.1 Decision-tree illustrating the criteria determining the different ecological status classes

been designed for hysic-chemical parameters. The development of a WQI is normally through different steps [18–20] and are as follows:

1. Selection of the optimum set of parameters that together reflect the overall quality of the water body with respect to a given end use
2. Transformation of the required parameters of different units and dimensions into a common scale based on their impact on the health and ecosystem
3. Determination of weights of selected parameters
4. Calculation of the index score is obtained by aggregating the respective sub-indices into a common function

Suitable WQIs should have clear objectives, good synthetic capacities, and be able to achieve a reasonable balance between the simplification of reality and the complexity of the environment. They should include variables that are normally and continuously monitored and that have a clear effect on water quality (e.g., potentially affecting aquatic life, bathing, public supply, irrigation, and recreational uses). WQI is most useful for comparative purposes and for general questions. Site-specific questions that should be addressed by an analysis of the original data. It is limited in that while a certain site may receive a good score, it may still be impaired or degraded based on a parameter not included in the index calculation. Also, aggregation of data may either mask or over-emphasize short-term (acute) water quality problems. Table 3.4 summarizes developments and practical WQIs' applications. The WQIs summarized below are a version of a WQI that was adapted from work conducted by the National Sanitation Foundation (NSF) in the 1970s. Concentrations of nine parameters (dissolved oxygen, fecal coliform, pH, biochemical oxygen demand (BOD), total nitrates and phosphates, total solids, temperature, and turbidity) were each assigned an individual rating based on existing standards or best professional judgment on a scale of 0–100. Each rating was then multiplied and the root of the product computed to obtain the final rating (Eq. 3.1)

$$\mathrm{WQI} = (\mathrm{Pi} * \mathrm{Pi2} * \mathrm{Pi3} * \ldots * \mathrm{Pi} + n)^{1/n} \qquad (3.1)$$

Where the final index value is assigned as follows: 0–20 poor, 20–40 below average, 40–60 average, 60–80 above average and from 80–100 good (Table 3.7).

Three steps were described to calculate the WQI as follow:

1. Converted each result to an index score ranging from 1 to 100 using the quadratic equation (Eq. 2) derived from regression curve data. The specific formula used at each station varied by stream class or ecoregion for that station.
2. Aggregating WQIs by month and calculating a simple average and applying penalty factors if necessary to reduce the likelihood of one low-scoring parameter being masked by the averaging process. The overall WQI per station is the average of the three lowest-scoring months. A similar procedure was followed to determine a WQI for each parameter.
3. Moderation of low scores that could be attributed to natural variance.

$$\mathrm{WQI} = a + b_1(\mathrm{Parameter}) + b_2(\mathrm{Parameter})^2 \qquad (3.2)$$

Table 3.8 summarized indicators of water quality and the reasons for including in the WQI.

Table 3.7 Description of water quality indices

References	Purpose of WQI	Parameters	WQI Development
[15]	Simplify WQ reporting to the public.	DO as percent saturation, fecal coliform, pH, BOD_5, total nitrates, total phosphates, TS, temperature, and turbidity	Standardize parameter concentration to sub-index score. Final WQI computed using an unweighted product equation of sub-indices.
[16]	Used as a tool to summarize and report routine stream monitoring data to the public. Indicates whether WQ is less than expected to support designated uses.	DO as concentration, fecal coliform, pH, total nitrogen, total phosphorus, TSS, and turbidity.	Quadratic equation to convert results to sub-index score. Apply weightings and other rules to account for strongly correlated parameters and to avoid double weighting. Final WQI is average of three lowest sub-index scores.
[17]	Evaluate WQ data in a way that is scientifically valid and easily understood by professionals and the public.	Variable. Based on recorded biological response of indicator organism (e.g., fish or benthos) by ecoregion. As an example, they used field measurements of DO, pH, temperature, and conductance.	Standardization of parameter concentration to biological response and narrative category. Assign numerical rank to narrative category. Final WQI is average of all worse case ranks over monitoring period.
[18]	Same as above, but they wanted to develop a new WQI with fewer parameters that is simpler than most other WQIs.	DO, fecal coliform, turbidity, total phosphorus, and specific conductance.	No standardization of variables to sub-index score. Rank and weight parameters based on significance. Conversion to logarithmic scale to keep final WQI a small number.
[19]	Used as an aid to describe WQ variables related to a watershed study exploring relationships between urban non-point pollution, land use (imperviousness), habitat and benthos across an urban-forest gradient in New Haven, Connecticut.	TSS, TDS, fecal coliform, nitrate, phosphate, the chloride to sulfate ratio, and the nitrate to total nitrogen ratio.	No standardization of variables to a sub-index score. Tuned a common WQI to quantify non-point source pollution levels in urbanized watersheds. Equation was described as a normalized average of seven parameters.
[20]	Intended to develop a WQI that would not hide or “eclipse” vital information.	Varied base on designated use. DO, pH, TSS, turbidity, actual temperature, temperature above natural, BOD_5, ammonia, and fecal coliform.	Panel of experts selected parameters and produced graphs to standardize results to sub-index scale and aggregated sub-index scores for final WQI using the lowest sub-index score or “minimum operator” function.

Table 3.8 List of parameters or indicators and reasons for including them in the WQI

Parameters/indicators of water quality	Include as part of WQI?	Reasoning
Specific conductance (μS/cm)	Yes	Compared to reference conditions, it indicates dissolved pollutants and potential upstream watershed disturbances.
Dissolved oxygen (%)	Yes	A standard water quality parameter. It indicates oxygen demand as well as supersaturation (evidence of excessive alga and nutrient enrichment).
pH (s.u.)	Yes	A standard water quality parameter. Values outside of desired range may indicate a water quality problem.
Water temperature (°C)	Maybe	If monitoring is conducted in summer then yes; otherwise, no. project dependent (Mtns vs. coast)
Nitrite-nitrate nitrogen (mg/L)	Yes	Compared to reference conditions, it provides evidence of nutrient enrichment, disturbance, and pollution sources.
Total Kjeldahl nitrogen (mg/L)	Yes	Same as above.
Ammonia nitrogen (mg/L)	Yes	Same as above.
Total phosphorus (mg/L)	Yes	Same as above.
Total suspended residue (mg/L)	No	Turbidity and bank stability metrics below will capture potential sediment pollution. During baseflow, this parameter may not adequately reflect the potential for sediment pollution.
Turbidity (NTU)	Depends	Indicates potential sediment or particulate pollution. If stream bank stability metric below is included, turbidity may not need to be included. However, it could provide evidence of sources if turbidity is present during baseflow.
Sodium (mg/L)	No	Specific conductance will capture problem levels.
Chloride (mg/L)	No	Same as above.
Metals (Cu, Zn, Pb, etc.)	No	Typically levels are very low. Uncertainty remains in interpreting total recoverable vs. dissolved data. Turbidity and other sediment indicators will capture potential problem.
Fecal coliform (cols/100 mL)	Yes	Indicates potential sewer line leaks, failing septic systems and upstream livestock operations.
Organics	No	Too expensive. Other parameters could be a surrogate for organic pollutants.
Livestock access	Yes	We know that livestock represent a stressor to both water quality and the riparian environment.
Light penetration (shading)	No	Riparian vegetation would capture this parameter.
Bank stability	Yes	This metric captures a source of sediment pollution during storm flow and may be the sole metric to represent potential sediment pollution during storm flow. Others are listed below.

(continued)

Table 3.8 (continued)

Parameters/indicators of water quality	Include as part of WQI?	Reasoning
Bank height ratio (BHR)	Maybe	This estimate may a more robust measure of potential sediment pollution during storm flow than simply bank stability. However, this metric and estimates of bank stability (a sort of pseudo BEHI) would be a powerful parameter combination indicating sediment pollution.
Riparian zone width/ vegetation	Yes	We know that riparian conditions (width and type of vegetation) affect water quality functions. Conventional chemistry parameters alone do not adequately address this metric.
Bottom substrate	Maybe	This would address sediment pollution in terms of bed load and may not be needed if one of the other sediment related metrics are included.

1.3.1 WQIs for Data Generated from Automated Networks

Automated sampling networks generate a limited range of physico-chemical parameters that are measured continuously in specific locations at high temporal frequency. This process creates a significant volume of data that is eventually stored in data tables, which are not translated into intelligible information describing the status of the water body. As not all the existing indices are suitable to deal with data of this nature, we need to select an index. Terrado et al. [17] proposed different suitable WQIs to deal with data generated from automated sampling networks, and Table 3.4 summarizes the main characteristics of proposed indices (Tables 3.9 and 3.10).

Figure 3.2 shows the proposed criteria that can be used to compare the different WQIs [18]. Five proposed indices were selected depending on whether they fulfill these particular criteria in a good, a fair, or a bad way. Significant parameters, such as pH, conductivity, turbidity, dissolved oxygen, water temperature, ammonia, nitrates, chlorides, and phosphates, were considered for proposed WQIs. Different objectives and a flexible index that allowed use of different parameters were established depending on various water uses. A higher value on simplicity in programming, tolerance to missing and erroneous data, and the possibility of the index working with non-synchronized data were performed. Accordingly, Canadian Council of Ministers of the Environment (CCME) was selected as the most suitable tool for categorizing water bodies using data generated by automated sampling stations. Figures 3.3 and 3.4 illustrate chart for developing WQIs.

For example, British Columbia Ministry of Environment [21] developed formula for CCME WQI. The index number ranges between 0 (poor water quality) and 100 (excellent water quality), divided into five descriptive categories: Poor: (0–44), Marginal: (44.1–64), Fair: (64.1–79), Good: (79.1–94) and Excellent: (CCME 94.1–100). Table 3.11, summarizes descriptive index criteria and Table 3.7 illustrates the advantages and disadvantages of CCME WQI index.

There are three elements that can be used for calculation and modification of the range of index; F_1 (scope), F_2 (frequency) and F_3 (amplitude). F_1 represents the

Table 3.9 Classification of water quality indices [11]

	Indices for general	Horton Index
Physico-chemical indices	Water quality	National Sanitation Foundation Water Quality Index
		Prati's Implicit Index of Pollution
		McDuffie and Haney's River Pollution Index
		Diniu's Water Quality Index
		British Columbia Water Quality Index
		Oregon Water Quality Index
		Florida Stream Water Quality Index
		Overall Index of Pollution
		Pesce and Wunderlin's Water Quality Index
		Water Quality Index of Central Pollution Control Board
		River Pollution Index
		Universal Water Quality Index
		Canadian Water Quality Index
		Simplified Water Quality Index
		Said et al.'s Water Quality Index
	Indices for specific water uses	O'Connor Indices: Fish and Wildlife Index and Public Water
		Supply Index
		Deininger and Landwehr Index for Public Water Supply
		Walski and Parker's Index for Recreation
		Stoner's Index for Dual Uses (PWS and Irrigation)
		Nemerow and Sumitomo's Pollution Index for Three Uses
		Smith's Index for Four Water Uses: 1) General, 2) Regular
		Public Bathing, 3) Water Supply, and 4) Fish Spawning
		Viet and Bhargava's Index
		Gekov et al.'s Index
		Haire et al.'s Nutrient Loading Index and Eutrophication Index
		Li's Regional Water Resource Quality Assessment Index
	Indices for planning	Truett et al.'s Prevalence Duration Intensity Index
		Truett et al.'s National Planning Priorities Index
		Truett et al.'s Priority Action Index
		Dee et al.'s Environmental Evaluation System
		Inhaber's Canadian National Index
		Zoeteman's Pollution Potential Index
		Johansson and Johnson Pollution Index

(continued)

Table 3.9 (continued)

	Statistical approaches	Shoji et al.'s Composite Pollution Index
		Joung et al.'s Index of Partial Nutrients (Factor Analysis)
		Joung et al.'s Index of Total Nutrients (Factor Analysis)
		Coughlin et al.'s Principal Component Index (Principal
		Component Analysis)
		Shin and Lam (Principal Component Analysis)
		Parinet et al.'s (Principal Component Analysis)
		Harkins's Index (Kendall Ranking Approach, 1975) (Non-
		Parametric Classification)
		Schaeffer and Janardan's Beta Function Index
		Kung et al.'_s Fuzzy Clustering
Biological indices	Macroinvertebrates	Biomonitoring Working Party
		Biological Families Index
	Fish	Index of Biological Integrity
		Extended Biological Index (Adapted from Woodiwis (1978)
		Biological Index)
	Diatoms	Index of Sensitivity to Pollution (CEMAGREF, 1982)
		Biological Index of Diatoms
	Macrophytes	Macrophytes Index
		Index of Macroscopic Aquatic Vegetation
Hydro-morphological indices	Connectivity Habitat	Fluvial Connectivity Index
		Fluvial Habitat Index
		Qualitative Habitat Evaluation Index
	Vegetation	Fluvial Vegetation Index
		Bank Vegetation Quality Index

percentage of variables that do not meet their objectives at least once during the time period under consideration (failed variables) in relation to the total number of variables measured; F_2 represents the percentage of individual tests that do not meet objectives (failed tests) and; F_3 represents the amount by which failed test values do not meet their objectives.

$$F_1 = \left(\frac{\text{Number of failed variable}}{\text{Total nomber of variables}}\right) \times 100 \tag{3.3}$$

Table 3.10 Parameters, sub-index and aggregation functions, weights, and quality classification procedure of the different proposed physico-chemical indices for the evaluation of water quality

Index	Parameter	Application limits	Sub-index function	Weight	Aggregation function	Water-quality classification
ISQA	Temperature (_C)	≤20	IT = 1 -	ISQA = $I_T(I_{TOC} + I_{SS} + I_{DO} + I_{COND})$		0 (minimum quality) – 100 (maximum quality)
		>20	IT = 1–(T–20)*0.0125			
	Total organic carbon	≤5	ITOC = 30–TOC			
	(mg/L)	12 ≥ TOC > 5	ITOC = 21–(0.35*TOC)			
		>12	ITOC = 0			
	Suspended solids	≤100	ISS = 25–(0.15*SS)			
	(mg/L)	250 > SS > 100	ISS = 17–(0.07*SS)			
		>250	ISS = 0			
	Dissolved oxygen	<10	IDO = 2.5*DO			
	(mg/L)	≥10	IDO = 25			
	Conductivity (lS/cm)	≤4000	ICOND = (3.6-log COND)*15.4			
		>4000	ICOND = 0			
Pesce and Wunderlin	Dissolved oxygen (mg/L)	≤1 2 ≥ DO>1	IDO = 0 –IDO = 10	$\mathrm{WQI}_{\min}\frac{1}{3}\cdot\sum_{i=1}^{3}I_i$		0 (minimum quality) – 100 (maximum quality)
		3 ≥ DO>2	IDO = 20			
		3.5 ≥ DO>3	IDO = 30			
		4 ≥ DO>3.5	IDO = 40			
		5 ≥ DO>4	IDO = 50			
		6 ≥ DO>5	IDO = 60			
		6.5 ≥ DO>6	IDO = 70			
		7 ≥ DO>6.5	IDO = 80			

		7.5 > DO>7	IDO = 90		
		≥7.5	IDO = 100		
	Conductivity (lS/cm)	>12,000	ICOND = 0		
		12,000 ≥ COND ≥ 8000	ICOND = 10		
		8000 > COND ≥ 5000	ICOND = 20		
		5000 > COND ≥ 3000	ICOND = 30		
		3000 > COND ≥ 2500	ICOND = 40		
		2500 > COND ≥ 2000	ICOND = 50		
		2000 > COND ≥ 1500	ICOND = 60		
		1500 > COND ≥ 1250	ICOND = 70		
		1250 > COND ≥ 1000	ICOND = 80		
		1000 > COND ≥ 750	ICOND = 90		
		<750	ICOND = 100		
	Turbidity (NTU)	>100	ITURB = 0		
		100 ≥ TURB ≥ 80	ITURB = 10		
		80 > TURB ≥ 60	ITURB = 20		
		60 > TURB ≥ 40	ITURB = 30		
		40 > TURB ≥ 30	ITURB = 40		
		30 > TURB ≥ 25	ITURB = 50		
		25 > TURB ≥ 20	ITURB = 60		
		20 > TURB ≥ 15	ITURB = 70		
		15 > TURB ≥ 10	ITURB = 80		
		10 > TURB ≥ 5	ITURB = 90		
		<5	ITURB = 100		

(continued)

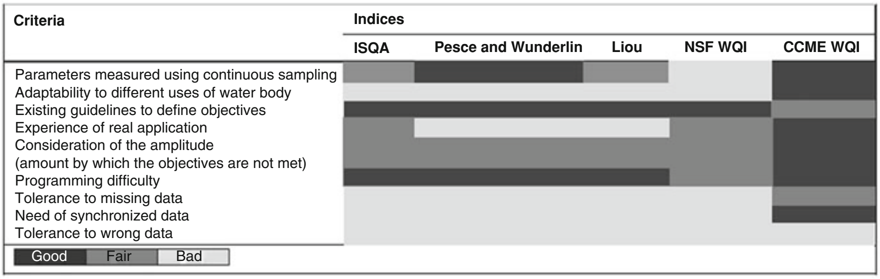
Table 3.10 (continued)

Index	Parameter	Application limits	Sub-index function	Weight	Aggregation function	Water-quality classification
Liou	Dissolved oxygen (mg/L)	>6.5 IDO = 1 4.6–6.5 IDO = 3	–	$\text{IWQI} = \frac{1}{4} \cdot \sum_{i=1}^{4} I_i$		<2 = good 2–3 = slightly polluted 3.1–6 = moderately polluted >6 = very polluted
		2–4.5 IDO = 6				
		<2 IDO = 10				
	BOD5 (mg/L)	<3 IBOD = 1				
		3–4.9 IBOD = 3				
		5–15 IBOD = 6				
		>15 IBOD = 10				
	Suspended solids	<20 ISS = 1				
	(mg/L)	20–49 ISS = 3				
		50–100 ISS = 6				
		>100 ISS = 10				
	Ammonia nitrogen	<0.5 INH3-N = 1				
	(mg/L)	0.5–0.99 INH3-N = 3				
		1–3 INH3-N = 6				
		>3 INH3-N = 10				

NSF WQI	Dissolved oxygen (% saturation)	Values extracted from the quality graphic elaborated for each parameter[a]	0.17	NSWFQI$^{(3)}$ $= \frac{\sum_{i=1}^{n} W_i I_i}{\sum W_i}$	0–25 = very bad 26–50 = bad 51–70 = regular 71–90 = good 91–100 = excellent
	Fecal coliforms[b]		0.16		
	(1b/100 ml)				
	pH		0.11		
	BOD5 (mg/L)		0.11		
	Nitrates (mg/L)		0.10		
	Phosphates (mg/L)		0.10		
	Temperature (_C)		0.10		
	Turbidity (NTU)		0.08		
	Total solids (mg/L)		0.07		
CCME WQI	No specific parameters defined.	F1: Scope (% of variables that do not meet their objectives at least once)	–	CCME WQI = 100- $\left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$	0–44 = poor 45–64 = marinal 65–79 = regular 80–94 = good 95–100 = excellent
	It is a flexible index used with several different parameters.	F2: Frequency (% of individual tests that do not meet their objectives)			
	For each parameter, a maximum and a minimum water quality objective need to be	F3: amplitude (amount by which failed tests do not meet their objectives)			
		** sub-indices F1, F2 and F3			

[a] Graphics for each of the parameters are available on the http://www.water-research.net/watrqualindex/waterqualityindex.htm web page.

[b] Fecal coliforms is not a parameter usually obtained from the automated sampling networks. However, this is not a problem, since some of the variables can be omitted in calculating the NSF WQI.



Criteria	Indices				
	ISQA	Pesce and Wunderlin	Liou	NSF WQI	CCME WQI
Parameters measured using continuous sampling	Fair	Good	Fair	Bad	Good
Adaptability to different uses of water body	Bad	Bad	Bad	Bad	Good
Existing guidelines to define objectives	Good	Good	Good	Good	Fair
Experience of real application	Fair	Bad	Bad	Fair	Good
Consideration of the amplitude (amount by which the objectives are not met)	Fair	Fair	Fair	Fair	Good
Programming difficulty	Good	Good	Good	Fair	Good
Tolerance to missing data	Bad	Bad	Bad	Bad	Fair
Need of synchronized data	Bad	Bad	Bad	Bad	Good
Tolerance to wrong data	Bad	Bad	Bad	Bad	Bad

Fig. 3.2 Comparison of WQI with different criteria [11]

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right) \times 100 \tag{3.4}$$

F_3 can be calculated as follows: the number of times by which an individual concentration is greater than (or less than, when the objective is minimum). The objective is termed “excursion”, then; when the test value not exceed the objective, excursion can be influenced by Eq. (3.5), while when test value not fall below the objective, Eq. (3.6) can be performed:

$$\text{excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_i}\right) - 1 \tag{3.5}$$

$$\text{excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed test value}_i}\right) - 1 \tag{3.6}$$

The collective amount by which individual tests are out of compliance can be calculated by summing the excursions of individual tests from their objectives and dividing the total number of tests (both those meeting objectives and those not meeting objectives). This variable, referred to as the normalized sum of excursions, or nse, can be calculated as:

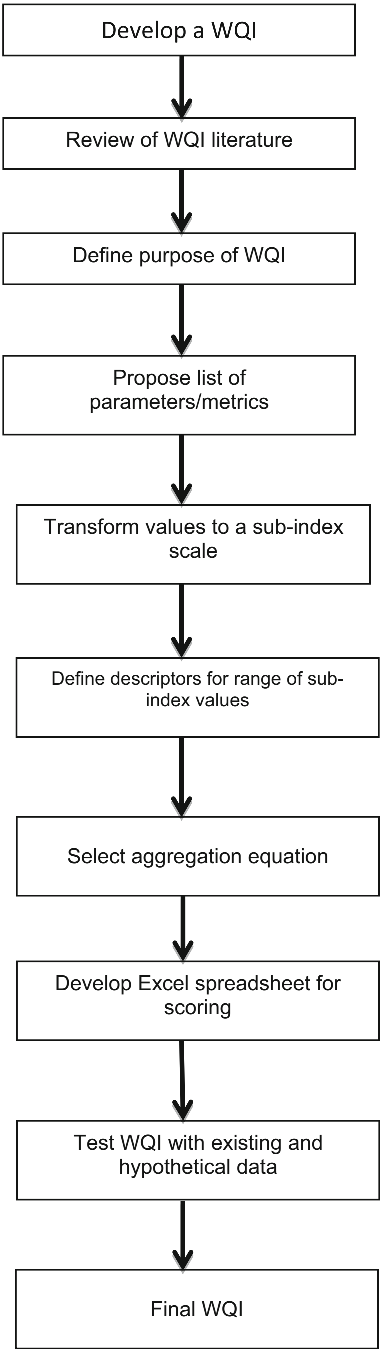
$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{total number of tests}} \tag{3.7}$$

F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from

objectives (nse) to yield a range between 0 and 100.

$$F_3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01}\right) \tag{3.8}$$

Fig. 3.3 Flowchart of progressive tasks to be completed for development of a WQI for surface water



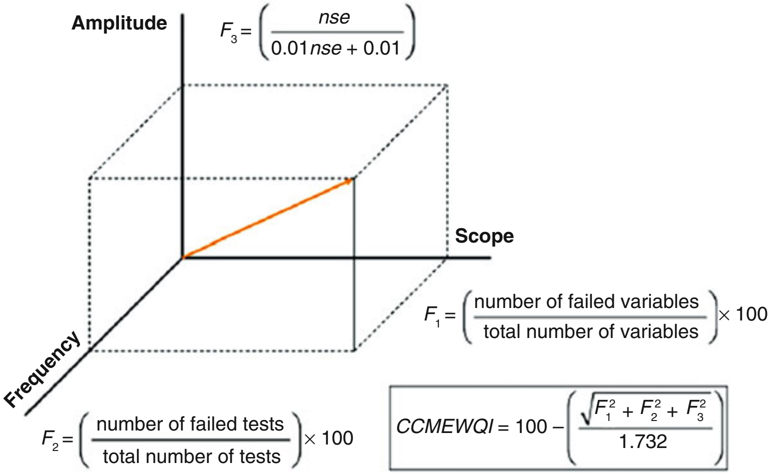
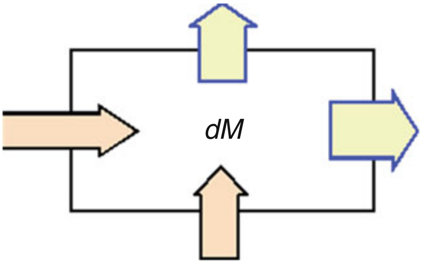


Fig. 3.4 Graphical representation of water quality indices (WQI) calculated in a three dimensional space by summing three factors (F_1, F_2, and F_3) as vectors

Table 3.11 Description of CCME WQI index criteria [11, 20]

Poor	CCME WQI value 0–44: water quality is almost always threatened or impaired conditions usually depart from natural or desirable levels
Marginal	CCME WQI value 44.1–64: Water quality is frequently threatened or impaired conditions often depart from natural or desirable levels
Fair	CCME WQI value 64.1–79: Water quality is usually protected but occasionally threatened or impaired conditions sometimes depart from natural or desirable levels
Good	CCME WQI value 79.1–94: Water quality is protected with only a minor degree of threat or impairment conditions rarely depart from natural or desirable levels
Excellent	CCME WQI value 94.1–100: Water quality is protected with a virtual absence of threat or impairment – Conditions very close to natural or pristine levels.

Fig. 3.5 Mass balance conservation

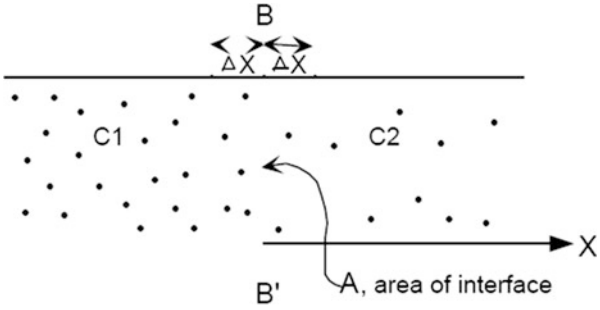


Then the index, as a three-dimensional space, can be calculated (Eq. 3.7) by summing the three factors as shown in Fig. 3.2. The sum of the squares of each factor is therefore equal to the square of the index. This approach treats (Fig. 3.5, Table 3.12)

Table 3.12 Advantages and disadvantages of CCME WQI [11]

Advantages		Disadvantages	
1.	Flexibility in the selection of input parameters and objectives	1.	Missing guidelines about the variables to be used for the index calculation
2.	Adaptability to different legal requirements and different water uses	2.	Missing guidelines about the objectives specific to each location and particular water use
3.	Statistical simplification of complex multivariate data		
4.	Clear and intelligible diagnostic for managers and the general public	3.	Easy to manipulate (biased)
		4.	The same importance is given to all variables
5.	Suitable tool for water quality evaluation in a specific location	5.	No combination with other indicators or biological data
6.	Easy to calculate	6.	Only partial diagnostic of the water quality
7.	Tolerance to missing data	7.	F1 not working appropriately when too few variables are considered or when too much covariance exists among them. The n factor has too much weight in calculating the index
8.	Suitable for analysis of data coming from automated sampling		
9.	Experience in implementation		
10.	Considers amplitude (of difference from the objective)		

Fig. 3.6 Conceptual model for diffusion



$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{3.9}$$

2 Water Quality Module Formation

A general water quality module with diffusion transportation can be readily derived based on the mass conservation and *Fick's* diffusion principle (Eq. 3.10).

$$J = -D\frac{\partial \Phi}{\partial x} \tag{3.10}$$

where

J is the "diffusion flux" [(amount of substance) per unit area per unit time], for example $\frac{\text{mol}}{\text{m}^2.\text{s}}$, J measures the amount of substance that will flow through a small area during a small time interval.

D is the diffusion coefficient or diffusivity in dimensions of [length2 time−1], example $\frac{\text{m}^2}{\text{s}}$

Φ (for ideal mixtures) is the concentration in dimensions of [amount of substance per unit volume], example $\frac{\text{mol}}{\text{m}^3}$

x is the position [length], example m

The Law of Conservation of Mass states that mass can neither be created nor destroyed. The inflows, outflows, and change in storage of mass in a system must be in balance. The mass flow in and out of a control volume (through a physical or virtual boundary) can, for a limited increment of time, be expressed as (Fig. 3.6):

$$dM = \rho i\ vi\ Ai\ dt - \rho o\ vo\ Ao\ dt \tag{3.11}$$

where

dM = change of storage mass in the system (kg)
ρ = density (kg/m^3)
v = speed (m/s)
A = area (m^2)
dt = an increment of time (s)

If the outflow is higher than the inflow, the change of mass dM is negative and the mass of the system decreases, while the mass in a system increases if the inflow is higher than the outflow. The Law of Mass Conservation is a fundament in fluid mechanics and a basis for the Equation of Continuity and the Bernoulli Equation.

Diffusion is defined as the net transport due to random motion. *Fick's second law* (Eq. 3.12) predicts how diffusion causes the concentration to change with time.

$$\frac{\partial \Phi}{\partial t} = D\frac{\partial^2 \Phi}{\partial x^2} \tag{3.12}$$

Where

Φ is the concentration in dimensions of [(amount of substance) length^{-3}], example $\frac{\text{mol}}{\text{m}^3}$

t is time [s]

D is the diffusion coefficient in dimensions of [length2 time^{-1}], example $\frac{\text{m}^2}{\text{s}}$

x is the position [length], example m.

The use of a particular model depends on the systems to be modeled and on the legislation in place in that country. Water Quality Models are usually classified into subdivision categories based on:

1. Identifying the environment modeled
2. Purpose of the model
3. Consideration of the number of ‘dimensions’
4. Description of the main process
5. The data used are discrete observed measurements or statistical distributions, and
6. Consideration of temporal variability.

A model for diffusive flux can be constructed from the following example. Consider a one-dimensional system with motion in the X direction only (Fig. 3.7). An interface B-B′ separates two regions of different concentration, C1 and C2 = particles/volume on the left and right side of the interface, respectively. The motion of each particle is a one-dimensional random walk. In each time interval, Δt, each particle will move a distance $\pm\ \Delta X$, moving right ($+\ \Delta X$) or left ($-\ \Delta X$) with equal probability.

Within each time step, any particle within a distance ΔX of the interface B-B′ has a 50% probability of crossing over that interface. The number of particles with the potential to cross B-B′ from left to right (positive mass flux) is (C1 $\Delta X\,A$), where A is the area of interface B-B′. On average, half of these take a positive step and cross the interface in time Δt such that the flux left to right is (0.5 C1 $\Delta X\,A$). Similarly, the number of particles crossing right to left in Δt (negative mass flux) will be (0.5 C2 $\Delta X\,A$). The resulting mass flux, q_X, is

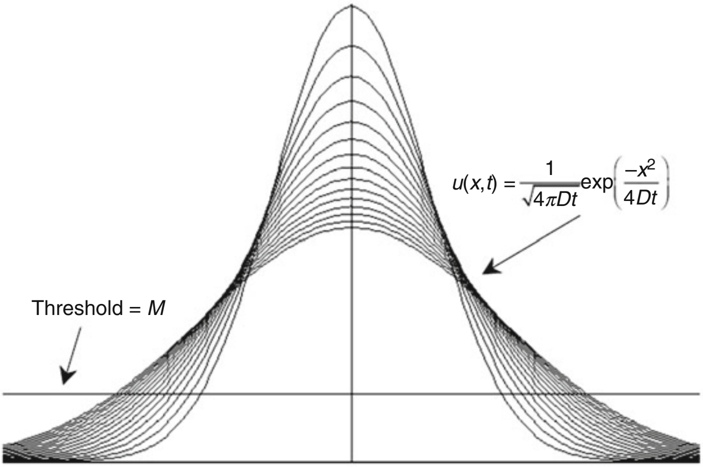


Fig. 3.7 The formula for distance within which the pheromone is sensed is given by $\sqrt{-2\,D\,t.\mathrm{Ln}\left(4M^2\pi\,D.t\right)}$

$$q_x = \frac{0.5\ \Delta X\, A\ (\mathrm{C1} - \mathrm{C2})}{\Delta t} \tag{3.13}$$

If $C(x)$ is continuous, then C2 ≈ C1 + $\Delta X\ \partial C/\partial x$, and Eq. 3.12 becomes

$$q_x = -\left\lfloor \frac{\Delta X^2}{2\Delta t} \right\rfloor A\ \frac{\partial C}{\partial x} = -D\,A\frac{\partial C}{\partial x}\left[\frac{\text{mass}}{\text{time}}\right] \tag{3.14}$$

Which is the mathematical expression of Fick's equation.

The coefficient of diffusion, D~(1/2)ΔX2/Δt, has units of [length^2 time^{-1}]. The diffusivity of a chemical molecule in a given fluid depends on the ease with which the molecule can move, specifically, how far, ΔX, the molecule can move in a given time interval. The ease of molecular motion, and thus the diffusivity of a particular chemical, will depend on the molecule size and polarity, the type of fluid, and the temperature.

Diffusion from a point source

If there is a unit mass at $x = 0$ and $t = 0$, then the concentration of the diffusing material is given by the following formula.

$$U(x,t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left(\frac{-x^2}{4Dt}\right) \tag{3.15}$$

The graph below shows how the concentration changes with time. Diffusion from a point source can be used to model diffusion of an insect pheromone. In this case, there would be a threshold below which the pheromone would not be detected. The horizontal line in the graph indicates this threshold level. Wherever the concentration is above the line, it would be sensed, and wherever below the line, it would not be sensed (Fig. 3.8).

The duration of the effect of the pheromone will be $t_{\max} = \frac{1}{4M^2\pi.D}$. The greatest distance at which it can be detected during its duration will be at time $t_0 = \frac{1}{4M^2\pi.D.e}$ and the distance will be $X_{\max} = \sqrt{\frac{\log(e)}{2\ M^2\pi.e}}$

2.1 *Module Subdivision and Classification*

The subdivisions based on purpose can be rather subjective, but they do provide useful information with regard to the limitations of a particular model. A mixing-zone model will only represent that proportion of the system that is immediately downstream of, or adjacent to, a discharge into the main water body, and a time-of-travel model provides the user with the time of arrival of pollutants downstream of an 'incident' and so is only used to simulate simple pollution incidents. Time-of-travel models do not generally include anything other than a conservative description of solute movements, but are essentially simple instream water quality models. The

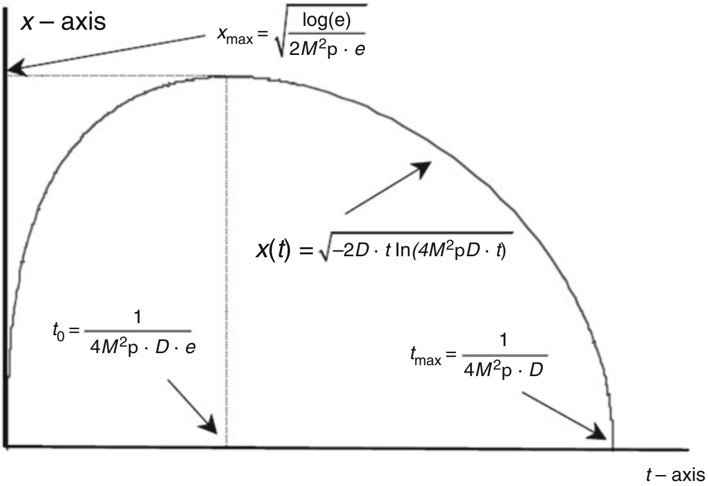


Fig. 3.8 Plot of range of pheromone

division is used here because instream models are not used routinely in pollution incident assessments unless they have been calibrated specifically for that purpose. The dimensions simulated by a particular model will provide information on both the complexity of a model and also on its suitability to specific applications. A zero-dimensional (0D) model does not represent the processes of dispersion of contaminants in any direction, but simply represents the volumes and concentrations assuming that the water body is completely and instantaneously mixed. A one-dimensional (1D) model represents the water flow and the advection and dispersion of solutes in just one direction (i.e., downstream in a river model) and so the stream is assumed to be completely (and instantaneously) mixed across its width and depth. Following from this, a two dimensional (2D) model will either simulate dispersion across the width or the depth of the stream, but not both. A width-averaged model is often used in simulating thermal stratification of deepwater bodies or when there may be layers of salt and freshwater at different depths in estuaries. Depth-averaged models are useful when the river is broad and shallow such that stratification is limited, but dispersion across the width of the river is slow. Three-dimensional (3D) models account for the water flows and solute transport in all directions. These models are highly sophisticated, and 3D water quality models are usually reserved for large (i.e., deep and wide) estuaries where the mixing patterns are complex (Fig. 3.9).

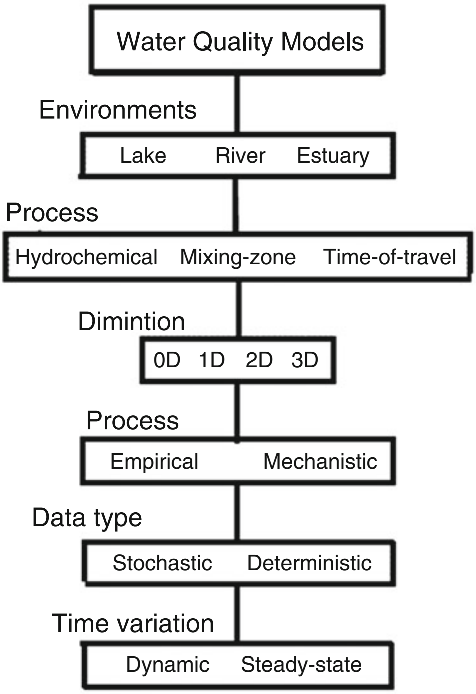


Fig. 3.9 Subdivisions of water quality models in common use

3 Oxygen Consumption and Replenishment in Receiving Water

Dissolved oxygen analysis measures the amount of gaseous oxygen (O_2) dissolved in an aqueous solution. Dissolved oxygen is one of the most important parameters in aquatic systems. This gas is an absolute requirement for the metabolism of aerobic organisms and also influences inorganic chemical reactions. Therefore, knowledge of the solubility and dynamics of oxygen distribution is essential to interpreting both biological and chemical processes within water bodies. Oxygen gets into water by diffusion from the surrounding air, by aeration (rapid movement) and as a waste product of photosynthesis. Adequate dissolved oxygen is necessary for good water quality. Oxygen is a necessary element to all forms of life. Natural stream purification processes require adequate oxygen levels in order to provide for aerobic life forms. Moreover, oxygen affects a vast number of other water indicators, not only biochemical but esthetic ones, like odor, clarity, and taste. Consequently, oxygen is perhaps the most well-established indicator of water quality. Some pollutants, such as acid mine drainage, produce direct chemical demands on oxygen in the water. Dissolved oxygen is consumed in the oxidation-reduction reactions of introduced chemical compounds, such as nitrate (NO_3^-) and ammonia (NH_4^+), sulfate (SO_4^{2-}) and iron ions. In this section, these factors are discussed.

3.1 Effect of Physical Characteristics of Water on Dissolved Oxygen

Oxygen is typically a limiting factor in aquatic ecosystems. Dissolved oxygen (DO) concentrations are expressed as milligrams of oxygen per liter of water (mg/L). DO also regulates the availability of certain nutrients in the water. Many physical factors affect the amount of dissolved oxygen in a stream. The physical factors that influence DO are temperature, altitude, salinity, and stream structure. Temperature inversely controls the solubility of oxygen in water; as temperature increases, oxygen is less soluble. In contrast, there is a direct relationship between atmospheric pressure and DO; as the pressure increases due to weather or elevation changes, oxygen solubility increases. Salinity also reduces the solubility of oxygen in water. Table 3.13 presents the relationship between amounts of dissolved oxygen in the water and temperature and salinity of water. Cold water can hold more dissolved oxygen than warm water and fresh water can hold more dissolved oxygen than salt water. So the warmer and saltier the water, the less dissolved oxygen there can be. The maximum amount of dissolved oxygen that the water can hold is called

Table 3.13 Maximum dissolved oxygen concentrates vary with temperature [14]

Temperature (°C)	DO (mg/l)	Temperature (°C)	DO (mg/l)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.16
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.41
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

the saturation value. Dissolved oxygen measurements are given as a percent of saturation (%) or in units of milligrams per liter (mg/l) [22]

The oxygen content of natural waters can vary widely depending on the physical, chemical, and biological processes in the water body as already indicated. Running waters generally have higher oxygen content than stagnant waters. As explained, the major source of oxygen in natural waters is the atmospheric air. Oxygen enters water by the process of diffusion and higher the mixing of air and water due to surface-water agitation, such as by wave action and turbulence in running water or due to artificial process of aeration by compressed air diffusers and use of agitators, in aquaria and ponds, the higher the oxygen saturation. Apart from diffusion from the air, water bodies gain oxygen through photosynthesis of chlorophyll-bearing aquatic organisms, i.e., higher plants, phytoplankton, and photosynthetic bacteria. Oxygen is lost from the water body by the respiration of animals and plants and also by decomposition of organic matter. Excess oxygen will also be released from water to air by diffusion.

The four commonly recognized profiles described are indicated in Fig. 3.10. Stratification of lakes with reference to temperature and physico-chemical conditions, though mainly recognized in temperate conditions, are also seen in tropical water bodies in a modified form; these are of special importance for aquaculturists working to stock open waters, which is also part of the present course.

3.2 *Biochemical Decay of Organic Waste Materials*

Natural organic detritus and organic waste from waste water treatment plants, failing septic systems, and agricultural and urban runoff, act as food sources for water-borne bacteria. Bacteria decompose these organic materials using dissolved oxygen. Biochemical oxygen demand (BOD) is a measure of the amount of oxygen that bacteria will consume while decomposing organic matter under aerobic conditions. The main focus of wastewater treatment plants is to reduce the BOD in the effluent discharged to natural waters. Wastewater treatment plants are designed to function as bacteria farms, where bacteria are fed oxygen and organic waste [23].

The BOD test can be used to investigate the controls on consumption of dissolved oxygen in the water column and to derive decay rates for water quality models.

$$\mathrm{BOD}_t = \mathrm{BOD}_u \left(1 - e^{-kt}\right) \tag{3.16}$$

Where, BOD_t is the exerted biochemical oxygen demand (mg/L of O_2) at time t, BOD_u is the ultimate BOD (mg/L of O_2), k is the first-order decay rate (1/day), and t is the time (days).

The Streeter-Phelps equation is used in water pollution as a water quality modeling tool. The model describes how dissolved oxygen (DO) decreases in a river or stream along a certain distance by degradation of biochemical oxygen demand

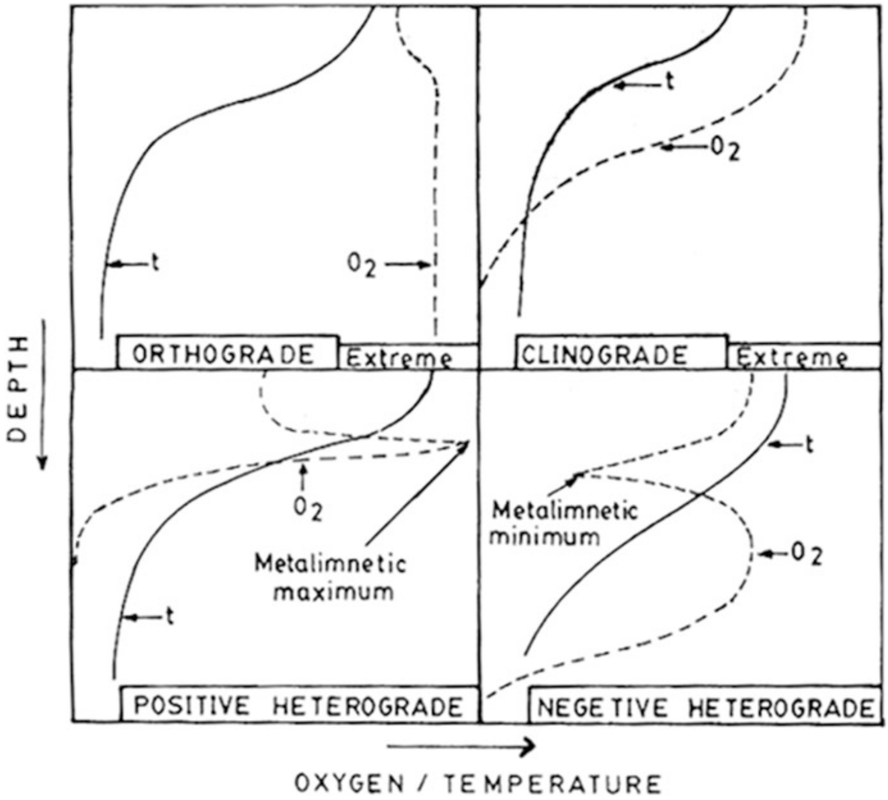


Fig. 3.10 Types of vertical-oxygen profiles in lakes typically of a stratified condition [15]

(BOD). The equation was derived by Streeter and Phelps in 1925, based on field data from the Ohio River. The equation is also known as the DO sag equation. It determines the relation between the dissolved oxygen concentration and the biological oxygen demand over time and is a solution to the linear first order differential equation [24]. This differential equation states that the total change in oxygen deficit (D) is equal to the difference between the two rates of deoxygenating and reaeration at any time (Fig. 3.11).

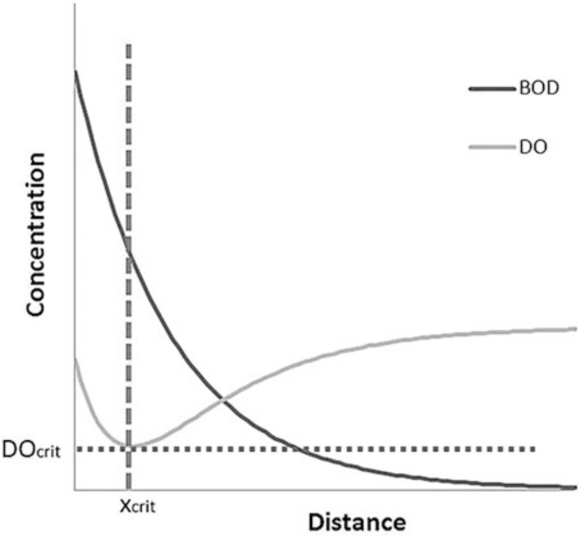
$$D = \frac{K_1 L_1}{K_2 - L_2} \left(e^{-k1t} - e^{-k2t}\right) + D_a e^{-k2t} \tag{3.17}$$

Where

D is the saturation deficit, which can be derived from the dissolved oxygen concentration at saturation minus the actual dissolved oxygen concentration ($D = DO_{\text{sat}} - DO$). D has the dimensions $\left[\frac{\text{g}}{\text{m}^3}\right]$.

K_1 is the deoxygenation rate, usually in d^{-1} .

Fig. 3.11 Streeter-Phelps DO sag curve and BOD development



K_2 is the reaeration rate, usually in d^{-1}.

L_a is the initial oxygen demand of organic matter in the water, also called the ultimate BOD (BOD at time t = infinity). The unit of is $\left[\frac{\mathrm{g}}{\mathrm{m}^3}\right]$.

L_t is the oxygen demand remaining at time t.

D_a is the initial oxygen deficit $\left[\frac{\mathrm{g}}{\mathrm{m}^3}\right]$.

t is the elapsed time, usually [d].

The relationship for the change in oxygen concentration due to oxidation of organics should be developed first. The rate that oxygen is used will be proportional to the rate that substrate (or biochemical oxygen demand) is oxidized. The rate of substrate utilization by bacteria is given by the Monod relationship

$$\frac{dL}{dt} = \frac{-kLX}{K_s + L} \tag{3.18}$$

where L is substrate concentration expressed as oxygen demand or BODL [mg/L], k is the maximum specific substrate utilization rate, K_s is the half velocity constant, and X is the concentration of bacteria. However, the concentration of bacteria is a function of the substrate concentration and thus application of the Monod equation to a polluted river is not trivial. Often the bacterial concentration remains relatively constant. If the half velocity concentration is large relative to the concentration of substrate we obtain

$$\frac{dL}{dt} = \frac{-kXL}{K_s + L} \cong \left[\frac{-kX}{K_s}\right] L \cong -k_{\text{ox}} L \tag{3.19}$$

where k_{ox} is a first-order oxidation rate constant that includes both the approximation that the bacteria concentration is roughly constant and that the substrate concentration is smaller than the half velocity constant.

Separate variables and integrate

$$\int_{L_o}^{L} \frac{dL}{L} = \int_{0}^{t} (-k_{\text{ox}}) dt \tag{3.20}$$

$$L = L_o e^{-k_{\text{ox}} t} \tag{3.21}$$

The rate of oxygen utilization is equal to the rate of substrate utilization (when measured as oxygen demand) and thus we have

$$\frac{\partial C_{\text{oxidation}}}{\partial t} = \frac{dL}{dt} = -k_{\text{ox}} L \tag{3.22}$$

where C is the dissolved oxygen concentration [mg/L]. Now we can substitute for L in Eq. 3.22 using Eq. 3.21 to obtain.

3.3 Reaeration Portion of the DO Mass Balance

The driving force for reaeration is the dissolved oxygen deficit, D (mgO_2/L), a representation of how ‘hungry’ the water is for oxygen. The deficit is defined as the departure from saturation or the difference between the maximum amount of oxygen that the water can hold and the actual oxygen concentration,

$$D = DO_{\text{sat}} - DO_{\text{act}} \tag{3.23}$$

The maximum amount of oxygen that the water can hold is termed the saturation concentration and varies with temperature according to Henry’s Law,

$$DO_{\text{sat}} = K_{\text{H}} \cdot P_{\text{O}_2} \tag{3.24}$$

The value for Henry’s Law constant for oxygen (K_{H}) decreases as temperature increases and thus the value of DO_{sat} is lower at higher temperatures.

3.4 Oxygen Percent Saturation and Temperature

Oxygen saturation levels indicate how much biological processes have affected the water recently. Community respiration, mainly by bacteria, reduces oxygen concentrations. The high water temperature and decomposable organic matter and other bacterial substrates in the water are the main factors for dissolved oxygen consumption and reduction. Phytoplankton photosynthesis, plus some contribution from photosynthesis of submersed plants and benthic algae around the shallow edges of a lake or pond, can increase oxygen concentrations above saturated levels, but only during the day when photosynthesis is occurring. Oxygen percent saturation compares an observed oxygen concentration to the absolute solubility of oxygen at a particular water temperature. This index often takes into account barometric pressure and salinity effects at the measurement site, but usually ignores effects of water pressure at depths below a lake or stream surface. Solubility of gases increases by an amount equal to the surface saturation concentration for about every 10 m increase in depth.

$$\% = ([\mathrm{O_2}]/[\mathrm{Osat}]) \times 100 \tag{3.25}$$

where

$\%$ = percent saturation
$[\mathrm{O_2}]$ = observed oxygen concentration, and
$[\mathrm{Osat}]$ = saturated concentration of oxygen at the local temperature (and possibly altitude, barometric pressure, and salinity or conductivity).

Reaeration is a first-order reaction based on the reaeration rate coefficient, K_a (d^{-1}), and a driving force as represented by the dissolved oxygen deficit,

$$\frac{dO_2}{dt} = k_\mathrm{a} \cdot D \tag{3.26}$$

The magnitude of the reaeration rate coefficient varies with temperature (increases with increasing temperature) and the turbulence of the stream (increases with increasing turbulence). Consider the effects of temperature and turbulence on the DO sag curve.

3.5 Quantifying the DO Mass Balance

All of the inputs to the DO mass balance can be quantified following:

$$\frac{dO_2}{dt} = k_a \cdot D - k_L \cdot L \tag{3.27}$$

In practice, the mass balance is written in terms of D because it is really D not DO that drives the reaeration term,

$$\frac{dD}{dt} = k_L \cdot L - k_a \cdot D \tag{3.28}$$

In order to apply this equation in modeling the oxygen resources of a river, the equation must be integrated,

$$D_t = \frac{k_1 \cdot L_0}{(k_2 - k_1)} \cdot \left(e^{-k_1 \cdot t} - e^{-k_2 \cdot t}\right) + D_0 \cdot e^{-k_2 \cdot t} \tag{3.29}$$

3.6 Nitrification

Nitrification is a microbial process that involves the transformation of ammonia to nitrate in the presence of organic nitrogen and ammonia in surface water. Nitrification is a critical step in the biochemical nitrogen (N) cycle. This process is very significant for water quality of fluvial ecosystems (mainly polluted ones) and the organisms occupying them, because it is an integral part of the biological mechanism of river self-purification and takes part in the nitrogen cycle [25]. Nitrification can have adverse impacts of increasing nitrite and nitrate levels, reducing alkalinity, pH, dissolved oxygen, and chloramine residuals, and promoting bacterial regrowth [26]. Summary of water quality problems associated with nitrification were presented in Table 3.14. When unbalanced by anthropogenic activities, rapid nitrification overwhelms denitrification in the N cycle, leading to the accumulation of nitrate and resulting in the contamination of ground waters and eutrophication of lakes. The oxidation of ammonia into nitrite is performed by two groups of organisms, ammonia-oxidizing bacteria, *Nitrosomonas*, which convert ammonia to nitrite (NO_2), and *Nitrobacter*, which convert nitrite to nitrate (NO_3^-) [27–30].

$$2\ NH_3 + 3\ O_2 \rightarrow 2\ NO_2^- + 2\ H_2O + 2\ H^+\ \text{(Nitrosomonas)} \tag{3.30}$$

$$2\ NO_2^- + 1\ O_2 \rightarrow 2\ NO_3^-\ \text{(Nitrobacter, Nitrospina)} \tag{3.31}$$

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^- \tag{3.32}$$

$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^- \tag{3.33}$$

Nitrifying bacteria are very sensitive to pH (Fig. 3.12). *Nitrosomonas* has an optimal pH between approximately 7.0 and 8.0, and the optimum pH range for

Table 3.14 Summary of water quality problems associated with nitrification

Chemical issues	Biological issues
Disinfectant depletion	HPC increase
Nitrite/nitrate formation	Ammonia oxidizing bacteria (AOB) increase
Dissolved oxygen depletion	Nitrite oxidizing bacteria (NOB) increase
Reduction in pH and alkalinity	
DBP formation due to mitigation techniques	

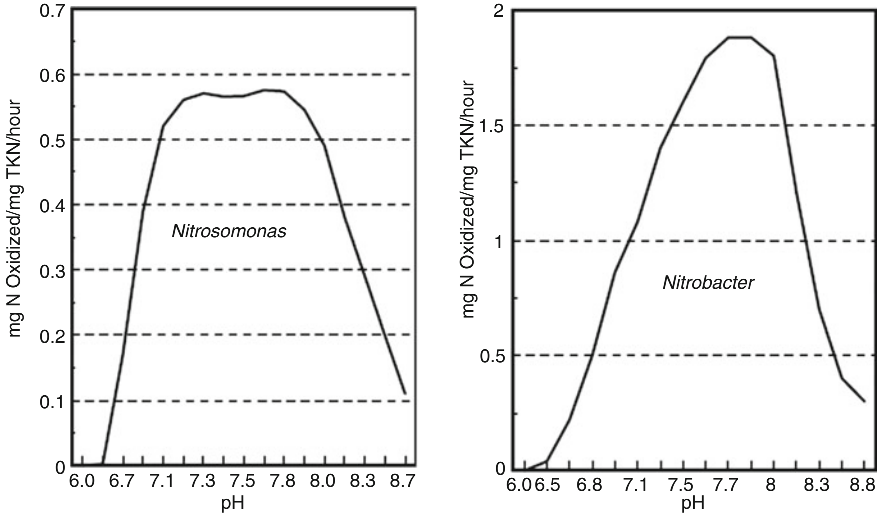


Fig. 3.12 Effects of pH on *Nitrosomonas* and *Nitrobacter* enrichment cultures [33]

Nitrobacter is approximately 7.5 to 8.0. Some utilities have reported that an increase in pH (to greater than 9)—prepared by American Water Works Association (AWWA) with assistance from Economic and Engineering Services, Inc.—10 can be used to reduce the occurrence of nitrification [31]. However, many other factors contribute to the viability of nitrifying bacteria and, as a result, nitrification episodes have been observed at pH levels ranging from 6.6 to 9.7 [32].

4 Microbiological Water Quality

Microbial water quality is regularly monitored and used to identify changes in a watershed that are useful for regulatory compliance and future watershed planning. Monitoring can also identify locations where there are problems related to land use practices. Surface water quality affects human and animal health and microbial water quality is especially important. The evaluation of microbial water quality for a

Table 3.15 Categories of water quality based on the River Bacterial Index formula [35]

96–100	Excellent – guidelines almost always met; best quality
81–95	Good – guidelines occasionally exceeded, but usually by small amounts; threat to quality is minimal
66–80	Fair – guidelines sometimes exceeded by moderate amounts; quality occasionally departs from desirable levels
46–65	Marginal – guidelines often exceeded, sometimes by large amounts; quality is threatened, often departing from desirable levels
0–45	Poor – guidelines almost always exceeded by large amounts; quality is impaired and well below desirable levels; worst quality

specific water body is typically based on the major uses for that source. Regions of extensive agriculture and sewage outfalls have the potential to introduce pathogens into surface waters which must be removed by water treatment before direct consumption. Bacterial water quality is an indication of the potential presence of various organisms such as *Escherichia coli, Giardia*, and *Cryptosporidium*. Fecal contamination by *E. coli* is widely used as an indicator of related pathogenic organisms such as *Salmonella, Shigella*, *Campylobacter, and Yersinia* [34]. *E. coli* occurs naturally in human and animal bodies, but some strains contain toxic cell wall components, some of which can be fatal as shown by the Walkerton tragedy. The guidelines for water quality stipulated by Alberta Environment indicate acceptable levels of indicator organisms that can be present to minimize the possibility of waterborne disease [35]. Livestock can be important sources of these microorganisms, especially during periods of high runoff. Agricultural inputs are generally considered to be non-point sources because of their wide geographic distribution and are difficult to control. Point sources, such as sewage outfalls, are much easier to regulate and treat. Based on Alberta formula for surface water quality guidelines [35], the river index bacteria formula was used, it includes the number of times bacterial density in these samples exceeds a guideline (frequency) and the extent to which the guideline is exceeded (amplitude). The result is a number between 0 and 100, where 100 represents the excellent guality of the river water and zero represents the poor quality. Table 3.15 presents the five categories of water quality based on the River Bacterial Index formula.

4.1 Indicator of Microbiological Water Quality

Indicator bacteria are types of bacteria used to detect and estimate the level of fecal contamination of water.

Indicator bacteria are not themselves dangerous to health but are used to indicate the presence of a health risk. These bacteria may include species of pathogenic bacteria, such as *Salmonella* or *Campylobacter*, associated with gastroenteritis. In addition, feces may contain pathogenic viruses, protozoa, and parasites. Fecal

Table 3.16 Definitions for indicator and index micro-organisms of public health concern [36]

Group	Definition
Process indicator	A group of organisms that demonstrates the efficacy of a process, such as total heterotrophic bacteria or total coliforms for chlorine disinfection.
Fecal indicator	A group of organisms that indicates the presence of fecal contamination, such as the bacterial group's thermotolerant coliforms or *E. coli*. Hence, they only infer that pathogens may be present.
Index and model organisms	A group/or species indicative of pathogen presence and behavior, respectively, such as *E. coli* as an index for *Salmonella* and F-RNA coliphages as models of human enteric viruses.

material can enter the environment from many sources including waste water treatment plants, livestock or poultry manure, sanitary landfills, septic systems, sewage sludge, pets, and wildlife. If sufficient quantities are ingested, fecal pathogens can cause disease. Table 3.16 provides definitions of indicators of microorganisms [36]. The variety and often low concentrations of pathogens in environmental waters makes them difficult to test for individually. Public agencies therefore use the presence of other more abundant and more easily detected fecal bacteria as indicators of the presence of fecal contamination. Table 3.17 presents Summary of Water Quality Criteria for Microbiological Indicators [37].

4.2 Monitoring of Microbiological Water Quality

Fecal pollution of surface water can lead to health problems because of the presence of infectious microorganisms. These may be derived from human sewage or animal sources (Tables 3.18 and 3.19).

Sanitary inspection and assessment of microbiological water quality are very important aspects in the monitoring of surface water bodies. Kostyla et al. [38] reviewed 22 studies in developing countries that used fecal contamination as an indicator for surface water quality. Figure 3.13 shows classification criteria for microbiological water quality. This classification is very important to grade the recreational areas and provide on-site safety guidance and identification and promotion of effective management interventions.

Microbial contamination of surface water quality may be strongly influenced by factors such as rainfall leading to relatively short periods of elevated fecal pollution. Classification of recreational water quality based on sanitary inspection and microbial quality assessment with prevention of exposure can be designed as shown in Fig. 3.14. Users can be shown to be effectively discouraged from entering the water following occasional and predictable water quality deteriorations (linked to, for example, rainfall), the area may be upgraded to reflect the water quality that users are exposed to, but only with the accompanying explanatory material.

Table 3.17 Summary of water quality criteria for microbiological indicators [37]

Water use	*Escherichia coli*	Enterococci	*Pseudomonas aeruginosa*	Fecal coliforms
Raw drinking water No treatment	0/100 mL	0/100 mL	0/100 mL	0/100 mL
Raw drinking water Disinfection only	Less than or equal to 10/100 mL 90th percentile	Less than or equal to 3/100 mL 90th percentile	None applicable	Less than or equal to 10/100 mL 90th percentile
Raw drinking water Partial treatment	Less than or equal to 100/100 mL 90th percentile	Less than or equal to 25/100 mL 90th percentile	None applicable	Less than or equal to 100/100 mL 90th percentile
Raw drinking water Complete treatment	None applicable	None applicable	None applicable	None applicable
Aquatic life Shellfish harvesting	Less than or equal to 43/100 mL 90th percentile	Less than or equal to 11/100 mL 90th percentile	None applicable	Less than or equal to 43/100 mL 90th percentile
Aquatic life Shellfish harvesting	Less than or equal to 14/100 mL median	Less than or equal to 4/100 mL median	None applicable	Less than or equal to 14/100 mL median
Wildlife	None applicable	None applicable	None applicable	None applicable
Livestock Free range animals	None applicable	None applicable	None applicable	None applicable
Livestock General livestock use	200/100 mL maximum	50/100 mL maximum	None applicable	200/100 mL maximum
Livestock Closely confined (no treatment)	0/100 mL maximum	0/100 mL maximum	None applicable	0/100 mL maximum
Livestock Closely confined (disinfection only)	Less than or equal to 10/100 mL 90th percentile	Less than or equal to 3/100 mL 90th percentile	None applicable	Less than or equal to 10/100 mL 90th percentile
Livestock Closely confined (partial treatment)	Less than or equal to 100/100 mL 90th percentile	Less than or equal to 25/100 mL 90th percentile	None applicable	Less than or equal to 100/100 mL 90th percentile
Livestock Closely confined (complete treatment)	None applicable	None applicable	None applicable	None applicable

(continued)

Table 3.17 (continued)

Water use	*Escherichia coli*	Enterococci	*Pseudomonas aeruginosa*	Fecal coliforms
Irrigation Crops eaten raw	Less than or equal to 77/100 mL geometric mean	Less than or equal to 20/100 mL geometric mean	None applicable	Less than or equal to 200/100 mL geometric mean
Irrigation Public access Livestock access	Less than or equal to 385/100 mL geometric mean	Less than or equal to 100/100 mL geometric mean	Less than or equal to 10/100 mL 75th percentile	None applicable
Irrigation General irrigation	Less than or equal to 1000/100 mL geometric mean	Less than or equal to 250/100 mL geometric mean	None applicable	Less than or equal to 1000/100 mL geometric mean
Recreation Aesthetics Non-contact	None applicable	None applicable	None applicable	None applicable
Recreation Secondary contact Crustacean harvesting	Less than or equal to 385/100 mL geometric mean	Less than or equal to 100/100 mL geometric mean	Less than or equal to 10/100 mL 75th percentile	None applicable
Recreation Primary contact	Less than or equal to 77/100 mL geometric mean	Less than or equal to 20/100 mL geometric mean	Less than or equal to 2/100 mL 75th percentile	Less than or equal to 200/100 mL geometric mean
Industrial water (dairy, food processing) No treatment	0/100 mL	0/100 mL	None applicable	0/100 mL
Industrial water (dairy, food processing) Disinfection only	Less than or equal to 10/100 mL 90th percentile	Less than or equal to 3/100 mL 90th percentile	None applicable	Less than or equal to 10/100 mL 90th percentile
Industrial water (dairy, food processing) Partial treatment	Less than or equal to 100/100 mL 90th percentile	Less than or equal to 25/100 mL 90th percentile	None applicable	Less than or equal to 100/100 mL 90th percentile
Industrial water (dairy, food processing) Complete treatment	None applicable	None applicable	None applicable	None applicable
Industrial water Other industries	Less than or equal to 385/100 mL geometric mean	Less than or equal to 100/100 mL geometric mean	Less than or equal to 10/100 mL 75th percentile	None applicable

Table 3.18 Examples of Pathogens and index organism concentrations in raw sewage [38]

Pathogen/index organism	Disease/role	Numbers per 100 ml
Bacteria		
Campylobacter spp.	Gastroenteritis	10^4–10^5
Clostridium perfringens spores	Index organism	6 ×10^4–8 × 10^4
Escherichia coli	Index organism (except specific strains)	106–107
Fecal streptococci/intestinal enterococci	Index organism	4.7 × 10^3–4 × 10^5
Salmonella spp.	Gastroenteritis	0.2–8000
Shigella spp.	Bacillary dysentery	0.1–1000
Viruses		
Polioviruses	Index organism (vaccine strains),	180–500,000
	Poliomyelitis	
Rotaviruses	Diarrhea, vomiting	400–85,000
Adenoviruses	Respiratory disease, gastroenteritis	Not enumerated
Norwalk viruses	Diarrhea, vomiting	Not enumerated
Hepatitis A	Hepatitis	Not enumerated
Parasitic protozoa		
Cryptosporidium parvum oocysts	Diarrhea	0.1–39
Entamoeba histolytica	Amoebic dysentery	0.4
Giardia lamblia cysts	Diarrhea	12.5–20,000
Helminths (ova)		
Ascaris spp.	Ascariasis	0.5–11
Ancylostoma spp. and Necator sp.	Anemia	0.6–19
Trichuris spp.	Diarrhea	1–4

4.3 Fecal Coliform Bacterial Die-Off in Urban Watershed

Fecal coliform bacteria are microscopic organisms that live in the intestines of warm-blooded animals. They also live in the waste material or feces excreted from the intestinal tract. When fecal coliform bacteria are present in high numbers in a water sample, it means that the water may have received fecal matter from one source or another. Unlike the other conventional water quality parameters, fecal coliform bacteria are living organisms. They multiply quickly when conditions are favorable for growth and die in large numbers when they are not. Because bacterial concentrations are dependent upon specific conditions for growth and these conditions change quickly, fecal coliform bacteria counts are not easy to predict. For example, although winter rains may wash more fecal matter from urban areas into a lake, cool water temperatures may cause many of the organisms to die. Direct exposure to sunlight is also lethal to bacteria, so die-off may be high even in the warmer water of summer time. Based on bacterial die-off modeled (Fig. 3.15), about 90% of bacteria will disappear from fresh water within two to five days [39], while the die-off rate is

Table 3.19 Microbial indicators (average numbers per gram wet weight) excreted in the feces of warm-blooded animals [37]

Group	Thermotolerant coliforms	Fecal streptococci	*Clostridium perfringens*	F-RNA coliphage	Excretion (g/day)
Farm animals					
Chicken	1,300,000	3,400,000	250	1867	182 (71.6)
Cow	230,000	1,300,000	200	84	23,600 (83.3)
Duck	33,000,000	54,000,000	–	13.1	336 (61.0)
Horse	12,600	6,300,000	<1	950	20,000
Pig	3,300,000	84,000,000	3980	4136	2700 (66.7)
Sheep	16,000,000	38,000,000	199,000	1.5	1130 (74.4)
Turkey	290,000	2,800,000	–	–	448 (62.0)
Domestic pets					
Cat	7,900,000	27,000,000	25,100,000		
Dog	23,000,000	980,000,000	251,000,000	2.1	413
Human	13,000,000	3,000,000	1580a	<1.0–6.25	150 (77.0)
Ratios in raw	50	5	0.3	1	–
Sewage					

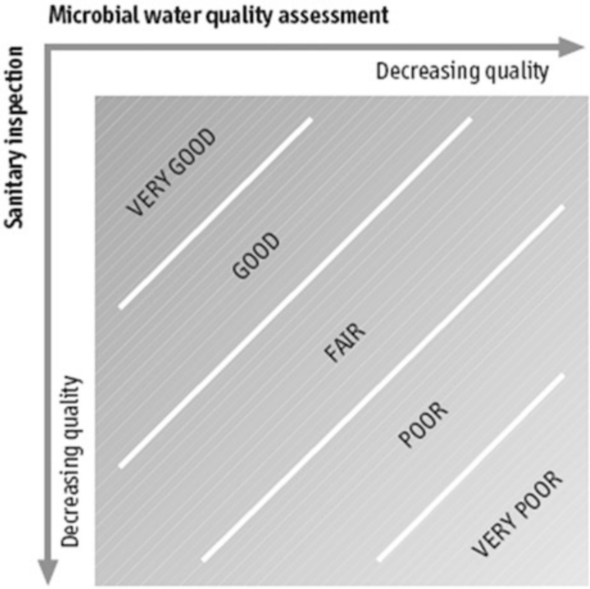


Fig. 3.13 Sampled classification matrix of microbial water quality [38]

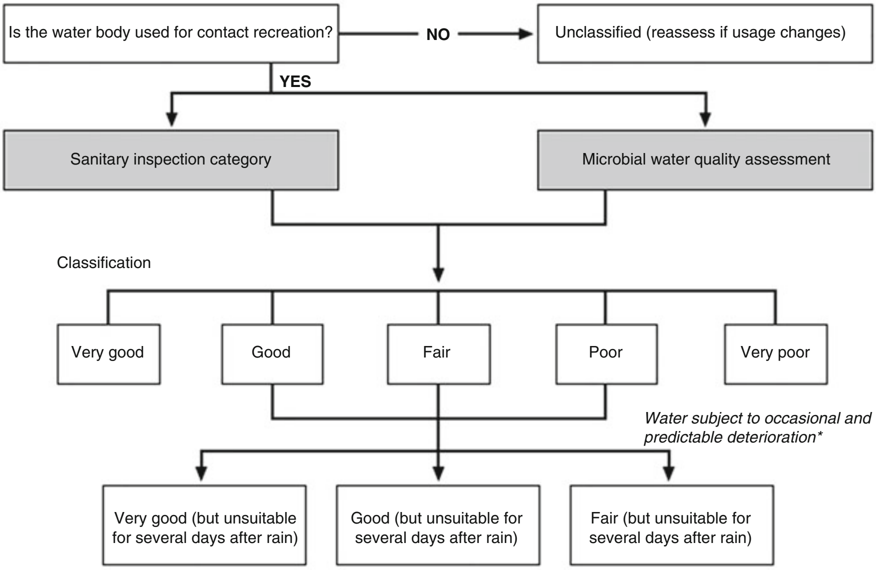


Fig. 3.14 Simplified framework for assessing surface (recreational) water environments

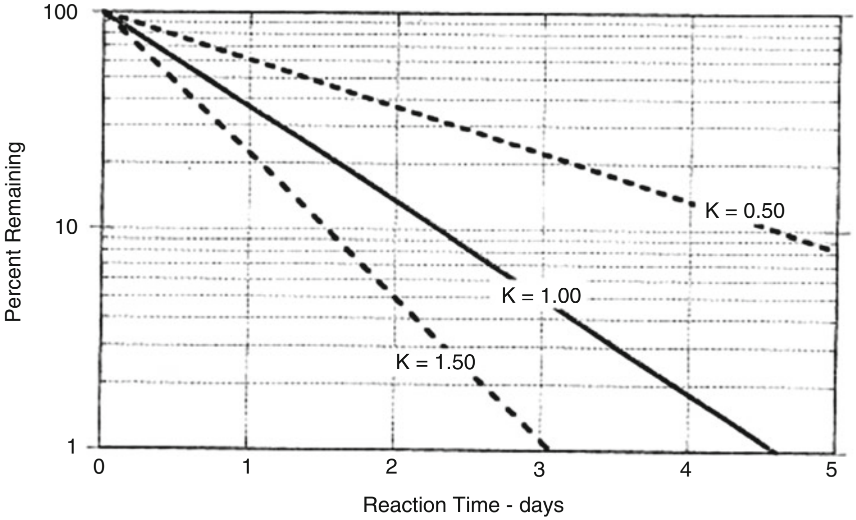


Fig. 3.15 Effect of different die-off rates (k) on bacteria mortality [39]

generally much faster in marine and estuarine waters than freshwater [40, 41]. Exposure of bacteria to sunlight is one of the most important factors causing bacteria die-off, while different treatment processes of surface water can significantly affect die-off of bacteria. Table 3.20 summarizes comparison of die-off rates and treatment effectiveness for different microbes.

Table 3.20 Comparison of die-off rates and treatment effectiveness for different microbes

Microbial indicator	Light?	Settling?	Surface filtration?	Die-off rates (k)	Ability to multiply	Survival in sediments?
Total coliforms	Yes	Yes	Yes	1/day	Yes	Moderate
Fecal coliforms	Yes	Yes	Yes	0.7–1.0/day	Yes	Days
Fecal streptococci	Yes	Yes	Yes	1/day	Low	Weeks
Escherichia coli	Yes	Yes	Yes	1/day	Low	Months
Salmonella spp.	Yes	Yes	Yes	1.5/day	Yes	Weeks to months
Psuedonomas aeruginosa	Yes	Partial	Yes	?	Yes	Months
Crytospoidium spp.	No	Partial	Partial	1.5/day	No	Months
Giardia spp.	No	Partial	Partial	1.5/day	No	Months

Glossary

American Water Works Association (AWWA)	An international non-profit, scientific, and educational association founded to improve water quality and supply
Canadian Council of Ministers of the Environment (CCME)	Is the primary minister-led intergovernmental forum for collective action on environmental issues of national and international concern
DO_{sat}	Dissolved oxygen in water at saturation concentration
K_H	The value for the Henry's Law constant for oxygen decreases as temperature increases
Normalized Sum of Excursions (*nse*)	Is the collective amount by which individual tests are out of compliance. This is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests
Principal component analysis/factor analysis (PCA/FA)	are multivariate statistical methods that analyze several variables to reduce a large dimension of data to a relatively smaller number of dimensions.
Surface Water Quality Monitoring (SWQM)	Program that monitors and evaluates physical, chemical, and biological characteristics of aquatic systems as a basis for effective policy.
Water framework directive (WFD)	EU directive which commits European Union member states to achieve good qualitative and quantitative status of all water bodies
Water quality	The condition of the water, including chemical, physical, and biological characteristics, usually with respect to its suitability for a particular purpose, such as drinking or swimming.
Water Quality Indices (WQIs)	A tool that aggregates results of several types of physical, chemical, and biological measurements into a single indicator of water quality conditions for streams and lakes.
Exerted biochemical oxygen demand (mg/L of O_2) at time t (BOD_t)	Is the increases of the amount of dissolved oxygen needed (i.e., demanded) by aerobic biological organisms to break down organic material present in a given water sample by a time

Ultimate BOD (mg/L of O_2) (BOD_u)	The total amount of oxygen consumed when the biochemical reaction is allowed to proceed to completion. First-order decay rate (1/day) (K): An equation relating the rate constant k to the initial concentration [A]0 and the concentration [A]t present after any given time t.

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