

Water Quality

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1 Introduction

This guide is written to familiarize water engineers and water managers working in agriculture in Middle Eastern and Northern African (MENA) countries with water quality aspects. In arid and semi-arid areas, like the MENA countries, water quantity is usually the first concern of water managers in agriculture. Water quality is more often associated with drinking water standards. However, water quality is increasingly important in agriculture as well, not only for production, but also to assess the impact that agricultural water management has on the environment and other parts of the water section. The continually decreasing volumes of good quality water (pollution) and increasing demands in- and outside the agricultural sector make an integrated approach to water quality and water quantity mandatory.

Water sources are varied in the MENA countries. Some countries depend mainly on surface waters (e.g. Egypt and Algeria), while others depend mainly on groundwater (Libya). Countries like Oman and Qatar are heavily dependent on desalinization of sea water for their source. Water quality in all these waters can refer to the natural composition of water (e.g. fossil groundwater containing certain amounts of salts), or man-made pollution (e.g. waste water return flow to natural streams). The objective of this guide is therefore to familiarize agricultural water managers with the concept of water quality. This guide will also provide tools, when possible, to estimate the quality of water without immediately resorting to complicated laboratory tests.

The selection of indicators for any water quality assessment depends on the objectives of the water quality assessment and monitoring program. Appropriate selection of indicators will help these objectives to be met efficiently and in the most cost effective way. This guide discusses indicators with respect to its origin, source, behavior and transformation in the aquatic system. It will also discuss the range of indicator values that have been measured in natural and polluted freshwaters, the role of the indicator in water quality assessment programs, methods for sampling of the water and special handling or treatment of samples that is required.

The guide is divided into four major sections, each describing a different category of water quality indicators. In the first section, the chemical water quality parameters are discussed. The second section describes the major physical properties of water. The third section describes different biological indicators, while in the fourth section hydrological aspects are discussed in relation to water quality. The four sections are followed by a chapter suggesting combinations of indicators that can be used for water quality monitoring programs.

The methods employed to measure the selected indicators depend on access to equipment and reagents, availability of technical staff and their degree of expertise, and the level of accuracy required by the objectives of the monitoring program. Detailed descriptions of sampling and analytical methods are available in a number of standard reference guides published by various international organizations and programs or national agencies like the World Health Organization (WHO, 1978) or the American Public Health Association (APHA, 1989). In addition a worldwide federation of national standards bodies and international organizations, the International Standards Organization (ISO), publishes a series of "International Standards" which includes methods for determining water quality.

This guide is not intended to be complete. However, more extensive literature exists and is recommended for further detail on water quality parameters. Especially publications by the United States Geological Survey (Hem, 1989) and Environment Canada (WQB, 1983) are recommended for further reading.

2 Chemical Water-Quality Parameters

Water has unique chemical properties. One water molecule exists of 1 oxygen atom and 2 hydrogen atoms (Figure 1). The hydrogen atoms are positioned in such a way around the oxygen atom that the water molecule is a dipole: the molecule is slightly charged with a positive and a negative side. The result of this charge is that many materials can be dissolved in water; Water is also known as the universal solvent.

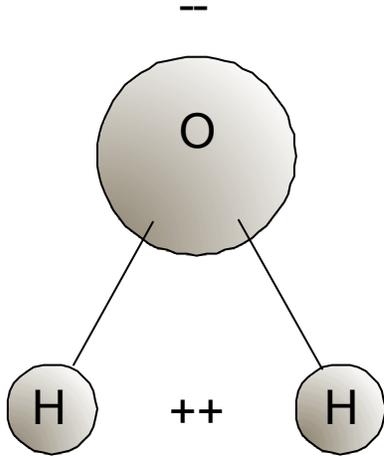


Figure 1: Composition of water molecule, resulting in unique water properties

The effect of the solvent capabilities of water is that it can contain many different compounds, especially salts. Salts are composed of positively and negatively charged ions, being cations and anions respectively. If salts dissolve in water, the cations associate with the negative side of the water molecules, while the anions associate with the positive side of the water molecules. Common cations in natural waters are sodium, potassium, calcium and magnesium, while common anions are chloride, bicarbonate and sulfate. Many ions are necessary compounds for most forms of life. For some laboratory or industrial purposes, no impurities should be in water. Water is then treated to remove all dissolved compounds, and distilled water, or d.i. water, is the result.

The ultimate use determines limitations on impurities that can be allowed in water. For agriculture and environment, the most important indicators of water quality and limiting factors, are discussed in this chapter.

2.1 INORGANIC CHEMICAL WATER-QUALITY PARAMETERS

2.1.1 SALINITY

Salinity is a measure of the total amount of ions dissolved in water. Total salinity is fairly easy to measure. Water quality standards for human consumption and cattle have been developed for total salinity. Although the specific composition of ions in water is important, salinity measurements do not provide information on the type of ions present in the water solution.

Salinity of water is commonly expressed as Total Dissolved Solids (TDS). The total dissolved solids can fairly accurately be derived from the Electrical Conductivity (EC), which is much easier to determine. Total dissolved solids are expressed as the mass of salt per unit mass of water. As the mass of 1 litre of

water is approximately 1kg, TDS is generally expressed in milligram per liter (mg/L), which is the same as parts per million (ppm). Table 1. Presents the major units that are used to express concentrations. Table 1. Main concentration units

g per litre water (g/l)	= ‰ (parts per mil or per thousand)
mg per litre water (mg/l)	= parts per million (' ppm ') = 0.001 g. per 1000 g. water
µg per litre water (µg/l)	= parts per billion (' ppb ') = 10 ⁻⁶ g. per 1000 g. water
mol per litre water (mol/l)	
milli-mol per litre water (mmol/l)	
eq. (equivalent) per litre water (eq/l)	
meq. (milli-equivalent) per litre water (meq/l) etc.	

Electrical conductivity is a different measure of salinity. It does not measure the mass of salts in water, but the conductivity of ions dissolved in water. Conductivity of water is directly dependent on the amount of free ions. The charge of these ions allows the conductance of electrons. Electrical conductivity is measured between two electrically charged plates at a certain distance from each other. The conductivity of the water between the two plates is measured in mS/cm.

Other common units to express the electrical conductivity are µS/cm (micro-Siemens per centimetre) and dS/m (deci-Siemens per m). In old handbooks sometimes 'mho' is used for Siemens (1 mho = 1/Ω = 1 Siemens).

Distilled water, with a minimal amount of ions, has a low conductivity. "Clean" water has therefore a low electrical conductivity. However, water with for instance organic components that do not dissociate in water conducts current poorly. A low electrical conductivity reading does therefore not necessarily mean that the water is "clean". Freshly made distilled water will have lower conductivity measurements than distilled water out of storage. Over time, - the dissolution of atmospheric carbondioxyde, and to a lesser extent ammonia, will add free ions to the water.

The relation between TDS measurements and EC measurements is not constant. It depends on the composition of the ions in solution, since the conductivity depends on the charge of the ion, ion mobility and the temperature of the solution (usually reported at 25°C). Different ions have different charges (sodium has one positive charge, noted in chemistry as Na⁺, while calcium has two positive charges, noted in chemistry as Ca²⁺, or sometimes Ca⁺⁺). USDA-Handbook 60 (Richards, 1954) shows that the relation between TDS and EC for irrigation water can be written as

$$EC \text{ (dS/m)} = 640 * TDS \text{ (mg/L)}$$

This is valid for water less than 8 dS/m total salinity. For water with a high salinity, this conversion factor will be more than 640:

$$1 \text{ dS/m} \cong 640 \text{ mg/l}$$

$$10 \text{ dS/m} \cong 7000 \text{ mg/l}$$

Box 1: Units of Electrical Conductivity (EC)

$$1 \text{ dS/m} = 1 \text{ mS/cm} (= 1 \text{ mmho/cm}) = 1000 \text{ µS/cm}$$

$$1 \text{ dS/m} = 640 \text{ ppm} \text{ (EC} < 8 \text{ dS/m)}$$

To obtain concentrations in ppm : Multiply EC in dS/cm with 640

or multiply EC in µS/cm with 2/3

Drinking water standards have upper limits between 500 and 1000 mg/L (EC 0.80 -1.60 dS/m). Drinking water in Egypt ranges typically between 0.3 and 0.9 dS/m. The River Nile water salinity is less than 0.5 dS/m. Groundwater could reach values higher than 30 dS/m. The Pacific Ocean has salinity levels around 50 dS/m, while salinity values in the Dead Sea of 500 dS/m have been measured.

2.1.1.1 Measurements

Electrical conductivity can be measured in a laboratory setting. However, for field measurements, simple handheld devices are available. These devices are submerged in the sample, and will give a reading of the electrical conductivity. As the electrical conductivity depends on the temperature, all measurements should be corrected to obtain the electrical conductivity at the (standard) temperature of 25 °C. Most equipment will conduct this correction automatically.

Tasting the water can be a quick field method to determine the level of salinity. Care should be taken that the taste of NaCl, the main salt used in cooking, has a different taste than for example CaCO₃ (chalk). However, Na⁺ and Cl⁻ are frequently the predominant salts in agriculture related salinity problems.

A direct measurement of total dissolved solids can be made by completely evaporating a sample of water which has been filtered to remove the suspended solids. The remaining residue is weighted and represents the TDS in the water. A distinction can be made between the organic and inorganic fraction of TDS. To measure the inorganic fraction of TDS, the residue is burned at 600°C, which will remove the organic fraction.

2.1.2 *SPECIFIC IONS*

Sometimes, the composition of water is more important than the overall salinity. The distribution between monovalent cations (sodium and potassium) and bivalent cations (calcium and magnesium) in irrigation water could be important on the effect of irrigation on soil structure. Or, arsenic in water could make it unsuitable for drinking water.

Major elements are chemical compounds that are abundant in natural waters. They are, generally, expressed in mg/l. **Minor elements** or **trace elements** are chemical compounds that are present in smaller quantities. They are, generally, expressed in µg/l.

The major elements are listed in Table 21.

Table 1. Major elements in natural waters

Major cations (positively charged)		Major anions (negatively charged)	
Compound:	Representation:	Compound:	Representation:
Sodium	Na ⁺	Chloride	Cl ⁻
Potassium	K ⁺	Bicarbonate (hydrogencarbonate)	HCO ₃ ⁻
Calcium	Ca ²⁺	Carbonate	CO ₃ ²⁻
Magnesium	Mg ²⁺	Sulphate	SO ₄ ²⁻
Ammonium	NH ₄ ⁺	Nitrate	NO ₃ ⁻

Table 21: Some trace elements in natural water.

	Trace elements
	Iron Strontium Potassium
	Nitrate Fluoride Boron Silica

For effluent water, drainage water as well as wastewater, phosphates and nitrates could be of major importance, mainly because of the potential environmental and health impacts.

2.1.2.1 Measurements

Measurements of specific ion concentrations in water are done in a laboratory and reported in mg/L, µg/L or meq/L. There are no fast field methods to determine ion composition. However, some laboratory instruments are now designed to bring to the field, and some components can now be determined immediately after the water sample is taken.

The total charge of a specific ion in a water sample is expressed in meq/L (milli-equivalent per liter). The conversion from meq to mg is explained in Box 2. The electrical charges of the ions in water are directly related to the electrical conductivity. The overall charge (**not** conductivity) of a water sample is always zero (electro-neutrality). This means that the sum of cation equivalent (positive charges) should equal the sum of the anion equivalent (negative charges). This information is important to check the laboratory results for your samples. Box 3 shows an example for a water sample taken from drainage water.

Box 2: Relation between milli-equivalent, milli-mole and milli-gram for chemical elements.

The periodic table is a table that contains all known chemical elements on earth. Each element is shown in the table with its properties (for an example of the periodic table, see <http://chemlab.pc.maricopa.edu/periodic/periodic.html>).

Necessary information for the conversion from meq to mg is the molecular weight of an element. The molecular weight is the weight that 1 mole of the element weighs. One mole is a standard unit that contains a standard amount of molecules (namely 6.0220×10^{23} molecules/mole, also called Avogadro's constant).

For example, 1 mole of sodium (symbol Na, element number 11 in the periodic table) weighs 22.98977 grams. Thus, 1 mmole weighs 22.98977 mg.

Sodium has an ion-charge of 1+ (thus, the notation Na^+). This means that 1 mmole equals 1 meq, thus 1 meq weighs 22.98977 mg.

One mole of calcium (symbol Ca, element number 20) weighs 40.08 gram. Calcium has a positive charge of 2+ (Ca^{2+}), thus 2 meq. Since 1 mmole equals 2 meq, and 1 mmole equals 40.08 mg, 1 meq of Ca weighs 20.04 mg.

Box 3: Calculating Ion Balance

WaterSource	Date	pH	EC (dS/m)	Boron (mg/L)	Chloride (meq/L)	No3-N (mg/L)	S (mg/L)	K (mg/L)	Mo (µg/L)
Subsurface Drainage	1/22/1999	8.21	11.43	12.2	49.1	103.8	1185.546	58.851	0
Subsurface Drainage	5/5/2000	7.46	9.07	9.4	34.5	78.9	1184.2	5.2	0
Subsurface Drainage	6/30/2000	8.12	8.52	8.2	30.4	68.7	1055.6	5.7	0
Subsurface Drainage	6/5/2001	7.91	9.7	10.2	34.8	80.4	1097.7	6.9	0.1
Subsurface Drainage	7/19/2001	7.91	10	10.9	38.6	83.3	1189.2	6	0

WaterSource	Date	continued	Mg (mg/L)	Ca (mg/L)	Na (mg/L)	PO4-P (mg/L)	Se (µg/L)	Carbonate (meq/L)	BiCarbonate (meq/L)
Subsurface Drainage	1/22/1999		237.863	558.274	1939.024	0	820.8	0.2	4.5
Subsurface Drainage	5/5/2000		258.8	527.3	1687.6	-	392	0	4.3
Subsurface Drainage	6/30/2000		217.5	506.9	1593.2	0	378.9	0	4.5
Subsurface Drainage	6/5/2001		224.8	468.2	1715.2	-	404.8	0	4.5
Subsurface Drainage	7/19/2001		221	527.5	1887.1	-	601.6	0	4.8

Calculating ion balance of sample “drainage water 1/22/1999”.

- Step 1: Convert all weights into meq
- Step 2: Add anions and cations separately
- Step 3: Calculate balance error (cations - anions) / (cations + anions)

Note that in the example (an actual printout from the laboratory analysis) the sulfate is measured as sulfur only, and nitrate is measured as nitrogen only.

CATIONS	conc mg/L	Mol weight gr/mole	Charge	Equivalent conc meq/L
Ca	558.3	40.1	2	27.8
Mg	237.9	24.3	2	19.6
Na	1939	23	1	84.3
K	58.9	39.1	1	1.5
B	12.2	10.8	1	1.1
SUM				134.4 meq/L

ANIONS	conc mg/L	Mol weight gr/mole	Charge	Equivalent conc meq/L
Cl			1	49.1
SO4 (as S)	1185.5	32.1	2	73.9
HCO3 -		61	1	4.5
NO3- (as N)	103.8	14	1	7.4
SUM				134.9 meq/L

$$\text{Balance Error} = \frac{134.4 - 134.9}{134.4 + 134.9} * 100\% = -0.37\%$$

In general, a mass balance of less than 5% is acceptable.

Another rule of thumb is that the EC_w multiplied by 10 is an indication of total cations. In this example, the EC_w on 1/22/1999 was measured as 11.43 dS/m, while total cations was 134.4 meq/L.

An alternative method to show the ion balance is through a bar diagram:

Ca	Mg	Na		
Cl		SO ₄		

Note: for more detailed analysis of chemical composition of water several software programs are available. A program recommended for use is the freely downloadable “PHREEQC”, written by staff from the USGS. See also http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/

2.1.3 ALKALINITY

Alkalinity is defined as the quantity of ions in water that will react to neutralize hydrogen ions. Alkalinity is thus a measure of the ability of water to neutralize acids. Alkalinity is known as a ‘buffer’.

2.1.3.1 Sources

Constituents of alkalinity in natural water systems include CO_3^{2-} , HCO_3^- , OH^- , HSO_3^- , HPO_4^{2-} , HS^- . These compounds result from the dissolution of mineral substances in the soil and atmosphere. Phosphates may also originate from detergents in wastewater discharge and from fertilizers and insecticides from agricultural land. Hydrogen sulfide and ammonia may be products of microbial decomposition of organic material.

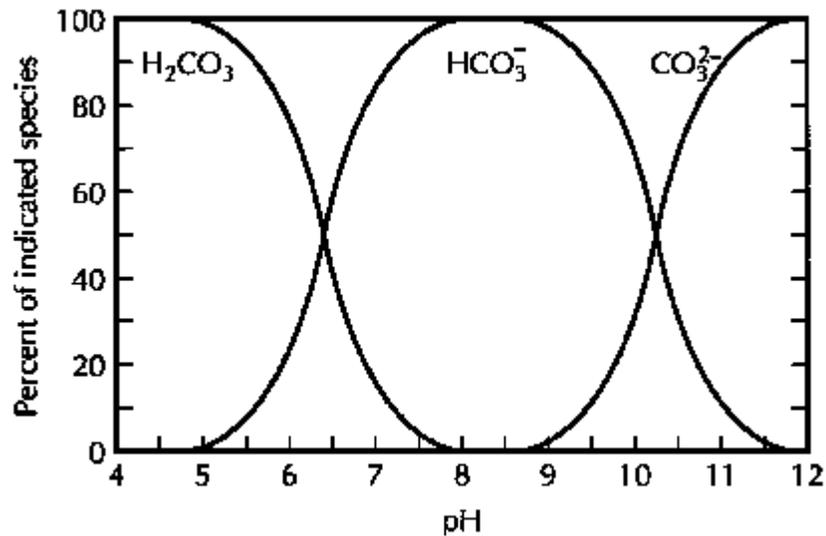
The bicarbonate (HCO_3^-) ion is the principal alkaline constituent in almost all water supplies. Alkalinity in drinking water supplies seldom exceeds 300 mg/L. Bicarbonate alkalinity is introduced into the water by CO_2 dissolving carbonate-containing minerals.

In addition to their mineral origin, these substances can originate from carbon dioxide, a constituent of the atmosphere and product of microbial decomposition of organic material. These reactions are as follows:

- 1) $\text{CO}_2 + \text{H}_2\text{O} \Leftrightarrow \text{H}_2\text{CO}_3$ (dissolved CO_2 and carbonic acid)
- 2) $\text{H}_2\text{CO}_3 \Leftrightarrow \text{H}^+ + \text{HCO}_3^-$ (carbonic acid and bicarbonate)
- 3) $\text{HCO}_3^- \Leftrightarrow \text{H}^+ + \text{CO}_3^{2-}$ (bicarbonate and carbonate)
- 4) $\text{CO}_3^{2-} + \text{H}_2\text{O} \Leftrightarrow \text{HCO}_3^- + \text{OH}^-$

The last reaction is a weak reaction chemically. However, utilization of the bicarbonate ion as a carbon source by algae can drive the reaction to the right and result in substantial accumulation of OH^- . Water with heavy algae growth often has pH values as high as 9 to 10. Because the reactions represented by the above equations involve hydrogen or hydroxide ions, the relative quantities of the alkalinity species with changing pH are shown graphically in Figure 2.

Figure 2: Variation with pH for carbonate buffer system



Below a pH of 6.3, H_2CO_3 becomes the dominant species, above a pH of 10.3, CO_3^{2-} becomes the dominant species. At a pH of 8.3, there is almost entirely HCO_3^- .

2.1.3.2 Impacts

In large quantities, alkalinity imparts a bitter taste to water. The principal objection to alkaline water, however, is the reactions that can occur between alkalinity and certain cations in the water. The resultant precipitate can foul pipes and other water-systems accessories. Alkalinity control is important in boiler feed water, cooling tower water, and in the beverage industry. Alkalinity neutralizes the acidity in fruit flavors; and in the textile industry, it interferes with acid dyeing.

On the other hand, alkalinity is essential for the formation of flocs in coagulation with aluminum and iron salts. Carbonate alkalinity is essential for removal of calcium hardness in softening and hydroxide alkalinity is required for the removal of magnesium hardness.

2.1.3.3 Measurement and use

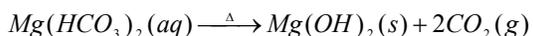
Alkalinity measurements are made by titration with an acid and determining the hydrogen equivalent. Alkalinity is then expressed as milligrams per liter. No easy field methods for measurements are available, although it is possible to do a titration in the field. Alkalinity measurements are often included in the analysis of natural waters to determine their buffering capacity. It is also used frequently as a process control variable in water and wastewater treatment. Maximum levels of 60 mg/L alkalinity have been set by EPA for drinking water.

2.1.4 *HARDNESS*

Hardness is defined as the concentration of multivalent metallic actions in solution. The hardness in natural water depends mainly on the presence of dissolved calcium and magnesium salts. The total content of these salts is known as general hardness, which can be further divided into carbonate hardness, non-carbonate

hardness and total hardness.

Carbonate hardness (temporary hardness) which is determined by concentrations of calcium and magnesium hydrocarbonate, eg. CaCO_3 , MgCO_3 , CaHCO_3 and MgHCO_3 . Hydro carbonates are transformed during the boiling of water into carbonate, which usually precipitate. The hardness remaining in the water after boiling is called constant hardness.



Non-carbonate hardness (permanent hardness) is determined by calcium and magnesium salts of strong acids, eg: CaCl_2 , CaSO_4 , $\text{Ca}(\text{NO}_3)_2$, MgCl_2 , MgSO_4 and $\text{Mg}(\text{NO}_3)_2$.

Total hardness is usually related to total alkalinity because the cations of hardness (Ca^{2+} and Mg^{2+}) and the anions of alkalinity (HCO_3^{2-} , CO_3^{2-}) are normally derived from the solution of carbonate minerals. Thus meq/L of Ca^{2+} & Mg^{2+} are similar in magnitude to meq/L of HCO_3^- and CO_3^{2-} .

Different countries have different hardness units, following different techniques that have been developed. Hardness is very important for the aquarium market, and several “home” kits are available to measure hardness. Units and their conversion factors are shown in Table 2.

Table 2: Conversion factors for various national grades of water hardness

		mmol/L	Germany °dH	Uk °Clark, °e	France °f	USA ppm, mg/L
		100 mg CaCO_3 per 1 L water	10 mg CaO per 1 L water	14.3 mg CaCO_3 per 1 L water	10 mg CaCO_3 per 1 L water	1 mg CaCO_3 per 1 L water
Germany	mmol l ⁻¹	1	5.6	7.00	10	100
	°dH	0.179	1	1.25	1.79	17.86
Uk	°Clark	0.143	0.80	1	1.43	14.29
France	°f	0.100	0.56	0.70	1	10
USA	ppm or mg/L	0.010	0.056	0.07	0.1	1

Source: ISO, 1984

2.1.4.1 Sources

The multivalent metallic ions most abundant in natural water are calcium and magnesium. Others may include iron and manganese in their reduced states (Fe^{2+} , Mn^{2+}), strontium (Sr^{2+}), and aluminum (Al^{3+}). The latter are usually found in much smaller quantities than calcium and magnesium. However, the principle natural sources of hardness are sedimentary rocks, seepage and run-off from soil.

Hard water normally originates in areas with thick top soil and limestone formation. Groundwater rich in carbonic acid usually possesses a high leaching potential towards soils or rocks that contain appreciable amount of the minerals. (e.g. calcite, gypsum and dolomite). Consequently, hardness levels of up to several thousands mg/L can result.

2.1.4.2 Impacts

Soft water

It is known that soft water has a greater tendency to cause pipe corrosion and consequently heavy metals such as copper, zinc and cadmium may be released. The degree to which this corrosion and increased solubility of metals occur is also a function of pH, alkalinity and dissolved oxygen. In some communities corrosion is so severe that special precautions must be taken with the supply, such as blending it with hard water or addition of lime. Very soft waters are said to boost coronary diseases, possibly by leaching metal like lead and cadmium from the pipes.

Hard water

Very hard water boosts the building of renal stones and boiler scale. The result of the carbonate hardness precipitate may cause considerable economic loss through fouling of water heaters and hot-water pipes. Magnesium hardness, particularly associated with the sulfate ion, has a laxative effect on persons unaccustomed to it. Magnesium concentrations of less than 50 mg/L are desirable in potable waters, although many public water supplies exceed this amount. Calcium hardness presents no public health problem. In fact, hard water is apparently beneficial to the human cardiovascular system.

2.1.4.3 Use

Analysis for hardness is commonly made on natural waters and on waters intended for certain industrial uses. Hardness may range from practically zero to several hundred, or even several thousand mg/L. Acceptability levels vary according to a consumer's acclimation to hardness. A generally accepted classification is shown in Table 3.

Table 3: Hardness categories

Hardness category	concentration
Soft	< 160 mg/L
Moderately hard	160-320 mg/L
Hard	320-460 mg/L
Very hard	>460 mg/L

Total hardness of the River Nile water is about 100 – 150 mg/L.

2.1.5 ACIDITY AND pH

Acidity is the base neutralizing capacity of water. The acidity of water is controlled by strong mineral acids (H₂SO₄, HCl, HNO₃), weak acids such as carbonic, humic and fluvic acid and hydrolyzing salts of metals (e.g. iron, aluminum).

pH is a measure of the acid balance of a solution and is related to the concentration of H⁺ ions in the aqueous solution.

$$pH = \log\left(\frac{1}{[H^+]}\right)$$
$$= -\log[H^+]$$

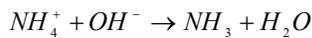
where [H⁺] = Hydrogen ion concentration in meq/L

The pH value is always between 0 and 14. A pH of 7 is neutral (same concentration of H⁺ as OH⁻ ions). A pH lower than 7 is an acid solution, while a pH higher than 7 is a base solution.

pH is an important variable in water quality assessments as it influences many biological and chemical processes within a water body and all processes associated with water supply and treatment. At a given temperature, pH indicates the intensity of the acidic or basic character of a solution. In unpolluted waters, pH is principally controlled by the balance between CO_2 , CO_3^{2-} , and HCO_3^- ions as well as other natural compounds such as humic and fluvic acids.

Changes in pH affect the natural acid-base balance of a water body and this change indicate the presence of certain effluents, particularly when continuously measured. Diurnal variations in pH can be caused by the photosynthesis and respiration of algae in eutrophic waters.

pH toxicity is affected by many factors. Ammonium salts are not very toxic at low pH values but under alkaline conditions ammonia can be quite harmful to fish. The reaction that causes this change in toxicity is shown below.



The effect of pH on fish production is shown in Figure 3.

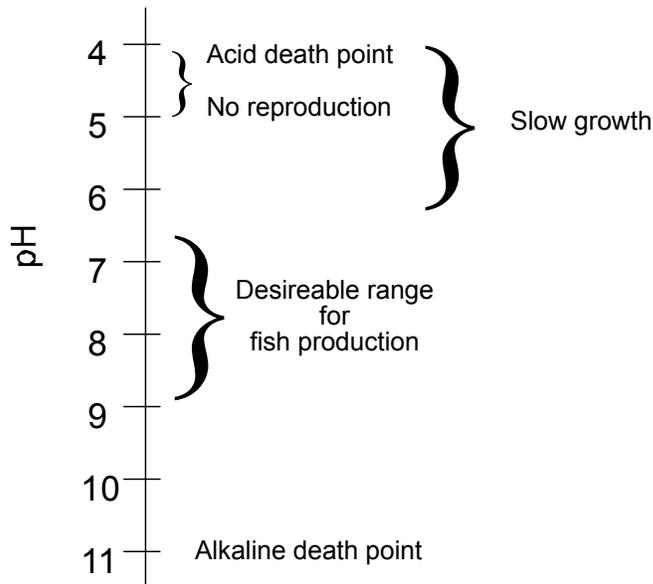


Figure 3: Effect of pH on fish production.

2.1.6 METALS

All metals are soluble in water to some extent. While excessive amounts of any metal may present health hazards, only those metals that are harmful in relatively small amounts are commonly labeled toxic, other metals fall into the non-toxic group. Sources of metals in natural water include dissolution from natural deposits and discharges of domestic, industrial or agricultural wastewater. Laboratory conditions are usually needed to measure metals.

2.1.6.1 Nontoxic metals

In addition to the hardness ions calcium and magnesium, other nontoxic metals commonly found in water include sodium, iron manganese, aluminum, copper, and zinc. Sodium, by far the most common non-toxic

metal found in natural waters, is abundant in the earth's crust and is highly reactive with other elements. The sodium salts are a health hazard to cardiac and kidney patients. Sodium is also corrosive to metal surfaces and, in large concentrations, is toxic to plants.

Iron and manganese quite frequently occur together and present no health hazards at concentrations normally found in natural waters. Iron concentrations of 0.3 mg/L and manganese concentrations as low as 0.05 mg/L can cause color problems. Occasionally, some bacteria use iron and manganese compounds as an energy source, and the resulting slime growth may produce taste and odor problems for drinking water.

When significant quantities of iron are encountered in natural water systems it is usually associated with chloride (FeCl_2), bicarbonate ($\text{Fe}(\text{HCO}_3)_2$) or sulfate ($\text{Fe}(\text{SO}_4)$) and exists in a reduced state. In the presence of oxygen, the ferrous (Fe^{2+}) ion is oxidized to the ferric (Fe^{3+}) ion and forms an insoluble compound with hydroxide $\{\text{Fe}(\text{OH})_3\}$ thus, significant quantities of iron will usually be found only in systems devoid of oxygen such as groundwater or perhaps the bottom layers of stratified lakes. In anoxic groundwater with a pH of 6 to 8, ferrous iron (Fe^{2+}) concentration can be as high as 50 mg/L and concentration of 1 to 10 mg/L are common. Groundwater is clear when first brought from a well but becomes cloudy and then orange in color as oxidation immediately occurs with the precipitation of ferric hydroxide. Consequently, obtaining representative sample for iron determination from groundwater presents special difficulties.

Similarly, manganese ions (Mn^{2+} and Mn^{4+}) associated with chloride, nitrates, and sulfates are soluble, while oxidized compounds (Mn^{3+} and Mn^{5+}) are virtually insoluble.

High iron concentration in groundwater is widely reported from developing countries, where iron is often an important water quality issue. Similar problems can be found in anoxic water for Mn^{2+} , although the concentrations reached are usually ten times less than ferrous iron.

The other nontoxic metals are found granularly in very small quantities in natural water systems, and most would cause taste problems long before toxic levels were reached. However, copper and zinc are synergistic and when both are present even in small quantities, may be toxic to many biological species.

2.1.6.2 Toxic Metals

Toxic metals are harmful to humans and other organisms in small quantities. Toxic metals that may be dissolved in water include arsenic, barium, cadmium, chromium, lead, mercury and silver. Cumulative toxic metals as arsenic, cadmium, lead and mercury are particularly hazardous. These metals are concentrated by the food chain, thereby posing the greatest danger to organisms near the top of the chain.

Fortunately, toxic metals are present in only minute quantities in most natural water systems. Although natural sources of all the toxic metals exist, significant concentration in water can usually be traced to mining, industrial, or agricultural sources. The toxicity of metals in water depends on the degree of oxidation of a given metal ion together with the forms in which it occurs (e.g. the maximum allowable concentration of Cr^{5+} in Russia is 0.001 mg/L where as for Cr^{3+} it is 0.5 mg/L). As a rule, the ionic form of a metal is the most toxic form. The toxicity is reduced if the ion is bound into complexes with natural organic matter such as fluvic and humic acids. Under certain conditions, metallo-organic, low molecular compounds formed in natural waters, exhibit toxicity greater than the uncombined forms (e.g. methyl mercury which is formed from elemental mercury by aquatic micro-organisms). Metals in natural waters can exist in truly dissolved, colloidal and suspended forms, consequently the toxicity and sedimentation potential of metal change depending on their forms.

2.2 ORGANIC CHEMICAL WATER-QUALITY PARAMETERS

Many organic materials are soluble in water. Organic material in natural water systems may come from natural sources or may result from human activities. Most natural organic matter consists of the decay products of organic solids, while synthetic organics are usually the result of wastewater discharges or agricultural practices.

In agriculture, organics are usually not considered a threat for crop production when natural waters are used as the water source. However, when wastewater is reused, more attention is paid to organic components of water. Also, drainage water effluent and its effect on the environment must be monitored to maintain a sustainable agricultural system. The organic component in that case is important (think about pesticide runoff, dissolved oxygen, over-fertilization etc).

Dissolved organics in water are usually divided into two broad categories: biodegradable and non-biodegradable (refractory).

2.2.1 BIODEGRADABLE ORGANICS

Biodegradable material consists of organics that can be utilized for food by naturally occurring micro-organisms. In dissolved form, these materials usually consist of starch, fat, protein, alcohol, acid, aldehyde, and ester. They may be the end product of the initial microbial decomposition of plant or animal tissue, or they may result from domestic or industrial wastewater discharges. Although some of these materials can cause color, taste, and odor problems, the principal problem associated with biodegradable organics is a secondary effect resulting from the action of micro-organisms on these substances.

Microbial utilization of dissolved organics can be accompanied by oxidation (addition of oxygen to, or removal of hydrogen from the organic molecule) or by reduction (addition of hydrogen to, or removal of oxygen from the organic molecule). Although it is possible for the two processes to occur simultaneously, the oxidation process is by far more efficient and is predominant when oxygen is available. In aerobic (oxygen present) environments, the end products of microbial decomposition of organics are stable and acceptable compounds. Anaerobic (oxygen absent) decomposition results in unstable and objectionable end-products. Should oxygen later become available, anaerobic end-products will be oxidized to aerobic end-products. The oxygen-demanding nature of biodegradable organics is important in natural water systems. When oxygen utilization occurs more rapidly than oxygen can be replenished by transfer from the atmosphere, anaerobic conditions will affect the ecology of the system.

2.2.1.1 Biological Oxygen Demand (BOD)

The amount of oxygen consumed during microbial utilization of organics is called the biological oxygen demand (BOD). The BOD determination is a measure of the amount of oxygen required by micro-organisms to decompose the organic matter in a water sample under a specific set of conditions. Additionally, BOD is an empirical test in which standardized laboratory procedures are used to determine the relative oxygen requirements of wastewater, effluent and polluted water. The test measures the oxygen required for the biochemical degradation of organic material, carbonaceous demand and the oxygen used to oxidize inorganic material such as sulfides and ferrous iron. It also may measure the oxygen used to oxidize reduced forms of nitrogen (carbonaceous demand).

The BOD is measured by determining the oxygen consumed from a sample placed in an air-tight container kept in a controlled environment for a pre-defined period of time. In the standard test, a 300 ml BOD bottle is used and the sample is incubated at 20 °C for 5 days (BOD₅). Light must be excluded from the incubator to prevent algal growth that may produce oxygen in the bottle. Because the saturation concentration for oxygen in water at 20 °C is approximately 9 mg/L, dilution of the sample with oxygen-saturated water is

necessary to measure BOD values greater than just a few milligrams per liter. The BOD of the diluted sample is calculated by

$$BOD = \frac{DO_i - DO_f}{P}$$

where DO_i , and DO_f are the initial and final dissolved-oxygen concentrations (mg/L) and P is the fraction (decimal) of the sample in the 300 mg/L bottle (dilution factor). Ranges of BOD covered by various dilutions are shown in Table 4. These values assume an initial dissolved-oxygen concentration of 9 mg/L in the mixture with a minimum of 2 and maximum of 7 mg/L of O_2 being consumed. Calculations of BOD from this testing procedure are illustrated in Box 4.

Table 4: Ranges of BOD values covered by various dilutions

By using percent mixtures		By direct pipetting into 300-mL bottles	
%mixture	Range of BOD	mL	Range of BOD
0.01	20,000-70,000	0.02	30,000-105,000
0.02	10,000-35,000	0.05	12,000-42,000
0.05	4,000-14,000	0.10	6,000-21,000
0.1	2,000-7,000	0.20	3,000-10,500
0.2	1,000-3,500	0.50	1,200-4,200
0.5	400-1,400	1.0	600-2,100
1.0	200-700	2.0	300-1,050
2.0	100-350	5.0	120-420
5.0	40-140	10.0	60-210
10.0	20-70	20.0	30-105
20.0	10-35	50.0	12-42
50.0	4-14	100.0	6-21
100.0	0.7-300	300.0	0-7

Source: From Sawyer and McCarty (19xx).

Box 4: Detemination of BOD

The BOD of a wastewater is suspected in the range from 50 to 200 mg/L. Three dilutions are prepared to cover this range, based on information from Table 4. The procedure is the same in each case. First, the sample is placed in the standard BOD bottle and is then diluted to 300 ml with organic-free oxygen-standard water.

The sample sizes are determined from column 3 and 4 in Table 4. For the expected range of 50 to 200 mg/L BOD, a sample size of 5, 10 or 20 ml is suggested. From column 1 and 2, it can be seen that for the expected range, a mixture percentage of 2-10% is recommended. Diluting all samples to 300 ml results in sample mixes of 2, 3 and 7%, respectively (P fraction as percentage).

The initial dissolved oxygen is determined and the bottles tightly closed with a stopper and placed in the incubator at 20 °C for 5 days, after which the dissolved oxygen is again determined.

Wastewater ml	DO _i mg/L	DO _f mg/L	O ₂ used mg/L	P fraction	BOD ₅ mg/L
5	9.2	6.9	2.3	0.0167	138
10	9.1	4.4	4.7	0.033	142
20	8.9	1.5	7.4	0.067	110

If the third value is disregarded (the final DO being less than 2.0 mg/L, outside the range of the values in Table 4) the average BOD of the wastewater is 140 mg/L.

Chemical oxygen demand (COD) is a measure of the total amount of oxygen which is required to completely oxidize all the organic matter in a sample (using strong chemical oxidant) to CO₂ and water. Therefore, the COD of water increases with increasing organic matter concentrations. In samples from a specific source, COD can be related empirically to BOD, organic carbon or organic matter. The COD test is useful for monitoring and control after correlation has been established with BOD values.

2.2.1.2 Chlorophyll

The green pigment chlorophyll (which exists in the three forms: chlorophyll a, b and c) is present in most photosynthetic organisms and provides an indirect increase of algal biomass and an indication of the trophic status of a water body. Chlorophyll determination is usually included in assessment programs for lakes, and reservoirs and is important for the management of water used for drinking water, since excessive algae growth makes water unpalatable or more difficult to treat.

In water with little input of sediment from the catchment, or with little re-suspension, chlorophyll can give an approximate indication of the quality of material suspended in the water column. The growth of planktonic algal in a water body is related to the presence of nutrients (principally nitrate and phosphates), temperature and light. Therefore, concentration of chlorophyll fluctuates seasonally, daily or even with water depth.

It is known that water bodies with low level of nutrients (oligotrophic) have low level of chlorophyll (< 2.5 ug/l), whereas high nutrient content (eutrophic) have high levels of chlorophyll (5-14 ug/l), although levels in excess of 300 mg/l also occur.

Chlorophyll fluoresces red when excited by blue light and this property can be used to measure chlorophyll levels and indicate algae biomass. Direct and continuous, measurement of chlorophyll fluorescence can be made with a fluorimeter or spectrophotometrically.

2.2.2 *NON BIODEGRADABLE ORGANICS*

Some organic material are resistant to biological degradation. Tannic and lignic acids, cellulose, and phenols are often found in natural water systems. These constituents of woody plants biodegrade so slowly that they are usually considered refractory. Molecules with exceptionally strong bonds (some of the polysaccharides) and ringed structures (benzene) are essentially non biodegradable.

An example is the detergent compound alkylbenzenesulfonate (ABS) which, with its benzene ring, does not biodegrade. Being a surfactant, ABS causes frothing and fowling in wastewater treatment plants and increases turbidity by stabilizing colloidal suspensions. This problem was largely alleviated when detergent manufacturers switched to a linearalkylsulfonate (LAS) compound, which is biodegradable. Many of the organics associated with petroleum and with its refining and processing also contain benzene and are essentially non-biodegradable.

Some organics are non-biodegradable and are toxic to organisms. These include organic pesticides, some industrial and hydrocarbon compounds that have combined with chlorine. Pesticides, including insecticides and herbicides, have found widespread use in modern society in both urban and agricultural setting. Root application practices and, subsequent wash off by rainfall and runoff may result in contamination of surface streams. Organic insecticides are usually chlorinated hydrocarbons (i.e., aldrin, dieldrin, endrin, and lindane), while herbicides are usually chlorophenoxy (i.e. 2,4- dichlorophenoxyacetic acid and 2,4,5-trichlorophenoxypropionic acid). Many of the pesticides are cumulative toxins and cause severe problems at the higher end of the food chain. An example is the near-extinction of the brown pelican that feeds on fish and other macroaquatic species by the insecticide DDT.

Measurement of non-biodegradable organics is usually done by the chemical oxygen demand (COD) test. Non-biodegradable organics may also be estimated from a total organic carbon (TOC) analysis. Both COD and TOC measure the biodegradable fraction of the organics, thus the BOD must be subtracted from the COD or TOC to quantify the non-biodegradable organics. Specific organic compounds can be identified and quantified through analysis by gas chromatography

2.3 NUTRIENTS

Nutrients are elements essential to the growth and reproduction of plants and animals, and aquatic species depend on the surrounding water to provide their nutrients. Although a wide variety of minerals and trace elements can be classified as nutrients, those required in most abundance by aquatic species are carbon, nitrogen and phosphorus. In agriculture, potassium is another necessary nutrient; N-P-K fertilizers consist of nitrogen (N), phosphorous (P) and potassium (K). Carbon is readily available from many sources. Carbon dioxide is available from the atmosphere. Alkalinity and decay products of organic matter all supply carbon.

2.3.1 *Nitrogen*

Nitrogen gas (N_2) is the primary component of the atmosphere and is extremely stable. It will react with oxygen under high-energy conditions (electrical discharges or flame incineration) to form nitrogen oxides. Nitrogen is a constituent for proteins, chlorophyll, and many other biological compounds. Upon the death of plants or animals, complex organic matter is broken down to a simple form by bacterial decomposition. Proteins, for instance, are converted to amino acids and further reduced to ammonia (NH_3). If oxygen is present the ammonia is oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-). The nitrate can then be transformed into living organic matter by photosynthetic plants (Figure 4).

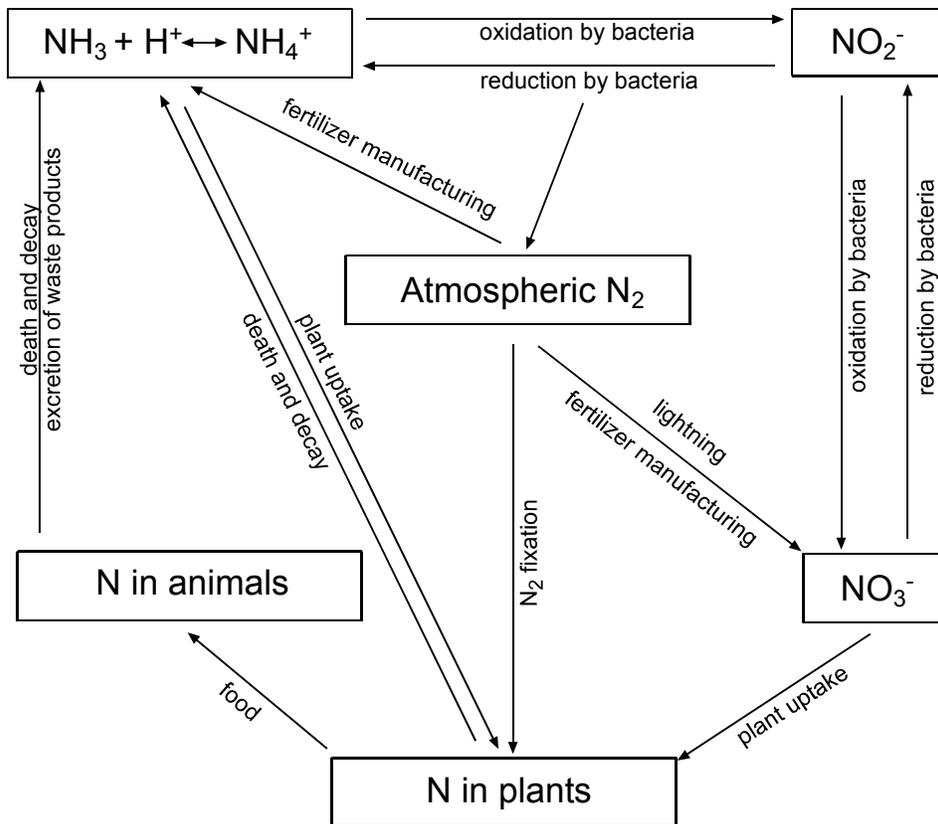
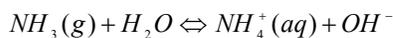


Figure 4: The nitrogen cycle

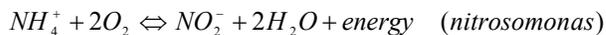
Other sources of nitrogen in aquatic systems include animal wastes, chemical discharges (particularly chemical fertilizers), and wastewater discharges. Nitrogen from these sources is discharged directly into streams or may enter wastewater through surface runoff or groundwater discharge. Nitrogen compounds can be oxidized to nitrate by soil bacteria and may be carried into the groundwater by percolating water. Once in the aquifer, nitrate moves freely with the groundwater flow. Groundwater contamination by nitrogen from animal feedlots and septic-tank drain fields has been recorded in numerous instances. It is always possible to indicate from the different species of nitrogen present in polluted water how recently pollution occurred. Presence of organic nitrogen or ammonia indicates that pollution is recent with ties to raw sewage, whereas presence of nitrate alone indicates that pollution must have taken place a long time ago.

In addition to the groundwater contamination, nitrogen can have other serious consequences. Ammonia is a gas at temperatures and pressures normally found in natural water systems. The gas (NH₃) exists in equilibrium with the aqueous ionic form; ammonium (NH₄⁺)



The hydrogen concentration of the water, and thus the pH, controls the relative abundance of each species. Oxidation of NH₃ and NH₄⁺ to nitrite and nitrate by aquatic microbes (nitrification demand process) results in an additional biochemical oxygen demand.

Nitrification does not remove ammonia but converts it to the nitrate form, thereby eliminating toxicity to fish life and reducing the nitrogen oxygen demand (NOD) of the polluted water. Ammonia oxidation to nitrate is a two-phase process performed by autotrophic bacteria with nitrite as an intermediate product.



These aerobic reactions yield energy for metabolic functions such as synthesis of carbon dioxide (CO₂) into new cells. Conversion of ammonia to nitrite is the rate limiting step that controls the overall reaction, therefore nitrite concentrations normally do not build up to significant levels. Temperature, pH and dissolved oxygen are important parameters in nitrification kinetics (processes).

Ammonia

Unpolluted waters contain small amount of ammonia and ammonia compounds, usually less than 0.2 mg/L NH₃-N, but may reach 2-3 mg/L NH₃-N. Higher concentration could be an indication of organic pollution from domestic sewage, industrial water and fertilizer run-off. Ammonia is therefore a useful indicator for organic pollution.

Nitrite and Nitrate

Natural sources of nitrate to surface waters include igneous rocks, land drainage and plant and animal debris. Natural levels, which seldom exceed 0.1 mg/L NO₃-N, may be enhanced by municipal and industrial wastewater, including leachate from waste disposal sites and sanitary landfill. In rural and suburban areas the use of inorganic nitrate fertilizers can be an important source. Seasonal fluctuations in nitrate in natural streams occur with aquatic plant growth and decay.

When influenced by human activity, surface waters normally contain nitrate concentration up to 5 mg/L NO₃-N, but often less than 1 mg/L NO₃-N. Levels in excess of 5 mg/L NO₃-N usually indicate pollution by human or animal waste or fertilizer runoff. In cases of extreme pollution, concentrations may reach 200 mg/L NO₃-N.

As the World Health Organization (WHO) recommended maximum limit for drinking water is 10 mg/L NO₃-N, water with higher concentrations represent a significant health risk. In standing water (e.g. lakes) levels of nitrate in excess of 0.2 mg/L NO₃-N tend to stimulate algal growth and indicate possible eutrophic conditions. Nitrite concentrations in freshwaters are usually very low, 0.001 mg/L NO₂-N and rarely higher than 1 mg/L NO₂-N. High nitrite concentrations are generally indicative of industrial effluents and are often associated with unsatisfactory microbiological quality of water. Determination of nitrite plus nitrate in surface waters gives a general indication of the nutrient status and level of organic pollution. Consequently, these species are included in most basic water quality surveys and multipurpose or background monitoring programs, and are specifically included in programs monitoring the impact of organic or relevant industrial inputs.

Organic nitrogen

Organic nitrogen consists mainly of protein substances (e.g. amino acids, nucleic acids and urine) and the product of their biochemical transformations (eg. humic acid and fluvic acid). Organic nitrogen is formed in water mainly by phytoplankton and bacteria. Cycled within the food chain, the concentration is subject to the seasonal fluctuation of the biological community.

2.3.1.1 Impacts

In the aquatic environment, increasing ammonia concentration in the water is highly toxic to fishes. Also increasing nitrite and nitrate cause methemoglobinemia (also known as blue baby syndrome) in fish blood where fish died (suffocate) from lack of oxygen. Nitrate poisoning in infant animals, including humans, can cause serious problems and even death. Apparently, the lower acidity in an infant's intestinal tract permits growth of nitrate-reducing bacteria that convert the nitrate to nitrite, which is then absorbed into the blood stream. Nitrite has a greater affinity for hemoglobin than oxygen and thus replaces oxygen in the blood complex. The body is denied essential oxygen and, in extreme cases, the victim suffocates. Because oxygen starvation results in a bluish discoloration of the body, nitrate poisoning has been referred to as the "blue baby" syndrome, although the correct term is methemoglobinemia. Once the flora of the intestinal

tract has fully developed, usually after the age of 6 months, nitrate conversion to nitrite and subsequent methemoglobinemia from drinking water is seldom a problem. Fortunately, the natural oxidation of nitrite to nitrate occurs quickly so that significant quantities of nitrites are not found in natural water.

2.3.1.2 Measurement

Tests for nitrogen forms in water commonly include analysis for ammonia (including both ammonia and ammonium), nitrate, and organic nitrogen. The results of the analyses are usually expressed as milligrams per liter of the particular species as nitrogen. Tests for ammonium and organic nitrogen are more common on wastewater and other polluted waters while the test for nitrate is the most common on clean water samples and treated wastewater. Ammonia is measured using a colorimeter. Nitrite determination is difficult due to interference from other substances present in water. One part of the water sample can be chemically analyzed for total inorganic nitrogen and the other for nitrite (spectrophotometrically). The nitrate concentration is obtained from the difference between the two values. Organic nitrogen is usually determined using the Kjeldhal method which gives total ammonia nitrogen plus total organic nitrogen (Kjeldhal N). The difference between the total nitrogen and the inorganic forms gives the total organic nitrogen content. Samples must be filtered and analyzed within 24 hours since organic nitrogen is rapidly converted to ammonia.

2.3.2 *Phosphorous*

Phosphorous is an essential nutrient for living organisms and exists in water bodies as both dissolved and particulate species. In aquatic environment, phosphorous appears as phosphate (PO_4^{3-}). It is generally the limiting nutrient for algae growth and therefore controls the primary productivity of a water body. In natural water and wastewater, phosphorous occurs mostly as dissolved orthophosphates, condensed phosphates (Pyre-, meta- and polyphosphates) and organically bound phosphates. Like nitrogen, phosphates pass through the cycle of decomposition and photosynthesis. Changes between these forms occur continuously due to decomposition and synthesis of organically bound forms and oxidized inorganic forms. Phosphorous is rarely found in high concentrations in fresh water as it is actively taken up by plants. As a result there can be considerable seasonal fluctuations in concentration in surface waters. It is recommended that phosphate concentrations are expressed as phosphorous (i.e. mg/L $\text{PO}_4\text{-P}$ and not as mg/L PO_4^{3-}). In most natural surface waters, phosphorous ranges from 0.005 to 0.020 mg/L $\text{PO}_4\text{-P}$. Concentrations as low as 0.001 mg/L $\text{PO}_4\text{-P}$ may be found in some pristine waters and as high as 200 mg/L $\text{PO}_4\text{-P}$ in some enclosed saline waters. Average groundwater levels are about 0.02 mg/L $\text{PO}_4\text{-P}$.

2.3.2.1 Sources

Phosphate is a constituent of soil and is used extensively in fertilizer to replace or supplement natural quantities on agricultural lands. Phosphate is also a constituent of animal waste and may become incorporated into the soil in grazing and feeding areas. Runoff from agricultural areas is a major contributor to phosphate in surface waters. The tendency for phosphate to adsorb to soil particles limits its movement in soil moisture and groundwater, but results in its transport into surface waters by erosion.

Municipal wastewater is another major source of phosphate in surface water. Condensed phosphates are used extensively as builders in detergents and organic phosphates are constituents of body waste and food residue. Other sources include industrial waste in which phosphate compounds are used for such purposes as boiler water.

2.3.2.2 Impact

While phosphates are not toxic and do not represent a direct health threat to human or other organisms, they do represent a serious indirect threat to water quality. Phosphate is normally the limiting nutrient in

surface waters. When the available supply is increased, rapid growth of aquatic plants usually results in severe consequences. Phosphate can also interfere with water treatment processes. Concentrations as low as 0.2 mg/L interfere with the chemical coagulation of turbidity.

2.3.2.3 Measurements

Phosphates are measured colorimetrically. Orthophosphates can be measured directly while condensed forms must be converted to orthophosphates by acid hydrolysis. Organic phosphates must be converted to orthophosphates by acid digestion. Results of the analysis are reported as milligrams per liter of phosphate. Careful handling of samples prior to analysis is crucial. For example, acid-washed glass bottles should be used for sampling as bottles washed in phosphate detergent may contaminate samples.

3 Physical water quality indicators

3.1 SUSPENDED SOLIDS

Solids can be dispersed in water in both suspended and dissolved forms. Although some dissolved solids may be perceived by the physical senses, they fall more appropriately under the category of chemical parameters (under the term 'total dissolved solids').

Solids suspended in water may consist of inorganic or organic particles. Inorganic solids such as clay, sand, or other soil constituents are common in surface water. Organic material such as plant fibers and biological solids (algal cells, bacteria, etc.) are also common constituents of surface waters. These materials are often natural contaminants resulting from the erosive action of water. Because of the filtering capacity of the soil, suspended material is seldom a constituent of groundwater.

Other suspended material may result from human use of the water. Domestic wastewater usually contains large quantities of suspended solids that are mostly organic in nature. Industrial use of water may result in a wide variety of suspended impurities of either organic or inorganic nature. Immiscible liquids such as oils and greases are often constituents of wastewater.

Suspended material may be objectionable in water for several reasons. It is aesthetically displeasing and provides adsorption sites for chemical and biological agents. Suspended organic solids may be degraded biologically, resulting in objectionable by-products. Biologically active (live) suspended solids may include disease-causing organisms as well as organisms such as toxin-producing strains of algae.

3.1.1 Measurements

There are several tests available for measuring solids. Most are gravimetric tests involving the mass of residues. The total solids test quantifies all the solids in the water suspended and dissolved, organic and inorganic. This parameter is measured by evaporating a sample to dryness and weighing the residue. The total quantity of residue is expressed as mass per volume, e.g. milligrams per liter (mg/L) on a dry-mass-of-solids basis. An oven set to a drying temperature slightly above boiling (104 °C) is sufficient to drive off the liquid and the water adsorbed to the surface of the particles, while a temperature of 180 °C is necessary to evaporate the occluded water. Note, however, that a temperature of 180 °C may burn some of the organic material and thus underestimate total dissolved solids.

Most suspended solids can be removed from water by filtration. Thus, the suspended fraction of the solids in a water sample can be approximated by filtering the water, drying the residue and filter to a constant weight at 104°C, and determining the mass of the residue retained on the filter. The results of this suspended solids test are also expressed as dry mass per volume (e.g. milligrams per liter). The amount of dissolved solids passing through the filters, also expressed as mass per volume, is the difference between the 'total solids' and 'suspended solids' of a water sample.

It should be emphasized that filtration of a water sample does not precisely divide the solids into suspended and dissolved fractions according to the definitions presented earlier. Some colloids may pass through the filter and be measured along with the dissolved fraction, while some of the dissolved solids adsorb to the filter material. The extent to which this occurs depends on the size and nature of the solids and on the pore size and surface characteristics of the filter material. For this reason, the terms filterable residues and non-filterable residues are often used. Filterable residue passes through the filter along with the water and relates more closely to dissolved solids, while non-filterable residues are retained on the filter and relate more closely to suspended solids. "Filterable residues" and "non-filterable residues" are terms more frequently used in laboratory analysis while "dissolved solids" is more commonly used in water quality management practice. For most practical applications it is not necessary to make a distinction between the two.

Once samples have been dried and measured, the organic content of both total and suspended solids can be determined by burning the residue at 600 °C for 1 hour. The organic fraction of the residues will be converted to carbon dioxide, water vapor, and other gases and will escape. The remaining material will represent the inorganic, or fixed, residue. When organic suspended solids are measured, a filter made of glass fiber or some other material that will not decompose at the elevated temperature must be used. The example in Box 5 illustrates the calculations involved in suspended solids analysis.

Box 5: Determining the concentration of suspended solids

A filterable residue analysis is run on a sample of water. Prior to filtering, the crucible and filter pad are kept overnight in the drying oven, cooled, and the dry mass (tare mass) of the pair determined to be 54.352 g. A sample of 250 ml is drawn through a filter pad contained in the porous-bottom crucible. The crucible and filter pad placed in a drying oven at 104°C and dried until a constant mass of 54.389 g is reached. Determine the suspended solids concentration of the sample.

SOLUTION:

1. Determine the mass of solids removed.

$$\begin{array}{rcl}
 \text{Tare mass + solids} & = & 54.389 \text{ g} \\
 \underline{\text{Tare mass}} & = & \underline{54.352 \text{ g}} \\
 \text{Mass of solids} & = & 0.037 \text{ g} \\
 & = & 37 \text{ mg}
 \end{array}$$

2. Determine the concentration of the solids.

$$\frac{\text{mg solids} * 1000 \text{ mL} / \text{L}}{\text{ml of sample}} = \text{conc. mg} / \text{L}$$

$$\frac{37 \text{ mg} * 1000 \text{ mL} / \text{L}}{250 \text{ ml of sample}} = 148 \text{ mg} / \text{L}$$

Suspended solids, where such material is likely to be organic or biological in nature, is an important quality indicator for wastewater. The suspended solids indicator is used to measure the quality of the wastewater influent, to monitor several treatment processes, and to measure the quality of the effluent. United States Environmental Protection Agency (EPA) has set a maximum suspended solids standard of 30 mg/L for most treated wastewater discharges.

3.2 TURBIDITY

A direct measurement of suspended solids is not usually performed on samples from natural bodies of water or on potable (drinkable) water supplies. The nature of the solids in this water and the secondary effects they produce are more important than the actual quantity. For such waters a test for turbidity is commonly used. Turbidity is a measure of the extent to which light is either absorbed or scattered by suspended material in water. Because absorption and scattering are influenced by both size and surface characteristics of the suspended material, turbidity is not a direct quantitative measurement of suspended solids. For example, one small pebble in a glass of water would produce virtually no turbidity. If this pebble were crushed into thousands of particles of colloidal size, a measurable turbidity would result, even though the mass of solids had not changed.

Most turbidity in surface waters results from the erosion of colloidal material such as clay, silt, rock fragments, and metal oxides from the soil. Vegetable fibers and micro-organisms may also contribute to turbidity. Household and industrial wastewater may contain a wide variety of turbidity-producing material. Soaps, detergents, and emulsifying agents produce stable colloids that result in turbidity. Although turbidity measurements are not commonly run on wastewater, discharges of wastewater may increase the turbidity of natural bodies of water.

3.2.1 Impacts

When turbid water in a small transparent container, such as a drinking glass, is held up to the light, an aesthetically displeasing opaqueness or "milky" coloration is apparent. The colloidal material associated with turbidity provides adsorption sites for chemicals that may be harmful or cause undesirable tastes and odors and for biological organisms that may be harmful. Disinfecting turbid water is difficult because of the adsorptive characteristics of some colloids and because the solids may partially shield organisms from the disinfectant.

In natural water bodies, turbidity may be shown as a brown color to water, depending on the light-absorbing properties of the solids, and may interfere with light penetration and photosynthetic reactions in streams and lakes. Accumulation of turbidity-causing particles in porous streambeds results in sediment deposits that can adversely affect the flora and fauna of the stream.

3.2.2 Measurement

Turbidity is measured photometrically by determining the percentage of light of a given intensity that is either absorbed or scattered. The original measuring apparatus, called a Jackson turbidimeter, was based on light absorption and employed a long tube and standardized candle. The candle was placed beneath the glass tube that was then housed in a black metal sheath so that the light from the candle could only be seen from above the apparatus. The water sample was then poured slowly into the tube until the flame was no longer visible, i.e., complete absorption had occurred. The glass tube was calibrated with readings for turbidity produced by suspensions of silica dioxide (SiO_2), with one Jackson turbidity unit (JTU) being equal to the turbidity produced by 1 mg SiO_2 in 1 L of distilled water.

In recent years this awkward apparatus has been replaced by a turbidity meter in which a standardized electric bulb produces a light that is directed through a small sample vial. In the absorption mode, a photometer measures the light intensity on the side of the vial opposite of the light source, while in the scattering mode, a photometer measures the light intensity at a 90° angle from the light source. Although most turbidity meters in use today work on the scattering principle, turbidity caused by dark substances that absorb rather than reflect light should be measured by the absorption technique. Formazin, a chemical compound, provides more reproducible standards than SiO_2 and has replaced it as a reference. Turbidity meter readings are now expressed as formazin turbidity units (FTU). The term nephelometry turbidity units (NTU) is often used to indicate that the test was run according to the scattering principle.

Turbidity measurements are normally made on "clean" water as opposed to wastewater. Natural water may have turbidities ranging from a few FTU's to several hundred. US-EPA drinking-water standards specify a maximum of 1 FTU, while the American Water Works Association (AWWA) has set 0.1 FTU as its goal for drinking water.

3.3 COLOR

Pure water is colorless, but water in nature is often colored by foreign substances. Water whose color is partly due to suspended matter is said to have apparent color. Color contributed by dissolved solids that remain after removal of suspended matter is known as true color.

3.3.1 Sources

After contact with organic debris such as leaves, conifer needles, weeds, or wood, water picks up tannins, humic acid, and humates and takes on yellowish-brown hues. Iron oxide causes reddish water, and manganese oxide causes brown or blackish water. Industrial waste from textile and dyeing operations, pulp and paper production, food processing, chemical production, and mining, refining, and slaughterhouse operations may add substantial coloration to water in receiving streams.

Colored water is not aesthetically acceptable to the general public. In fact, given a choice, consumers tend to choose clear, non-colored water of otherwise poorer quality over treated potable water supplies with an objectionable color. Highly colored water is unsuitable for laundry, dyeing, papermaking, beverage manufacturing, dairy production and other food processing, and textile and plastic production. Thus, the color of water affects its marketability for both domestic and industrial use.

While true color is not usually considered unsanitary or unsafe, the organic compounds causing true color may create a chlorine demand and thereby seriously reduce the effectiveness of chlorine as a disinfectant. Perhaps more important are the products formed by the combination of chlorine with some color-producing organics. Phenolic compounds, common constituents of vegetative decay products, produce very objectionable taste and odor compounds with chlorine. Additionally, some compounds of naturally occurring organic acids and chlorine are either known to be, or are suspected of being, carcinogens (cancer-causing agents).

3.3.2 Measurement

Although several methods of color measurement are available, methods involving comparison with standardized colored material are most often used. Color-comparison tubes containing a series of standards may be used for direct comparison of water samples that have been filtered to remove apparent color. Results are expressed in true color units (TCU) where one unit is equivalent to the color produced by 1 mg/L platinum in the form of chlorplatinite ions (only for yellow-brown hues). For colors other than yellowish-brown hues, especially for colored waters originating from industrial waste effluent, special spectrophotometric techniques are usually employed.

In fieldwork, instruments employing colored glass disks that are calibrated to the color standards are often used. Because biological and physical changes occurring during storage may affect color, samples should be tested within 72 h of collection.

Color is not a parameter usually included in wastewater analysis. In potable water analysis, the common practice is to measure only the true color produced by organic acid resulting from decaying vegetation in the water. The resulting value can be taken as an indirect measurement of humic substances in the water.

3.4 TASTE AND ODOR

The terms 'taste' and 'odor' are themselves definitions of this parameter. Because the sensation of taste and smell are closely related and often confused, a wide variety of taste and odors may be attributed to water by consumers. Substances that produce an odor in water will almost invariably impart a taste as well. The converse is not true, as there are many mineral substances that produce taste but no odor.

3.4.1 Sources

Many substances with which water comes into contact in nature or during human use may impart perceptible taste and odor. These include minerals and salts from the soil, end products from biological reactions, and constituents of wastewater. Inorganic substances are more likely to produce tastes unaccompanied by odor. Alkaline material imparts a bitter taste to water, while metallic salts may give a salty or bitter taste.

Organic material, on the other hand, is likely to produce both taste and odor. A multitude of organic chemicals may cause taste and odor problems in water, with petroleum-based products being prime offenders. Biological decomposition of organic material may also result in taste- and odor-producing liquids and gasses in water. Principal among these are the reduced form of sulfur that imparts a "rotten egg" taste and odor. Also, certain species of algae secrete an oily substance that may result in both taste and odor. The combination of two or more substances, neither of which would produce taste or odor by itself, may sometimes result in taste and odor problems. This synergistic effect was noted earlier in the case of organics and chlorine.

Consumers find taste and odor aesthetically displeasing because water is thought of as tasteless and odorless, while this water might actually pose more of a health threat. Odors produced by organic substances may pose more than a problem of simple aesthetics, since some of those substances may be carcinogenic.

3.4.2 Measurement

Direct measurement of materials that produce tastes and odors can be made if the causative agents are known. Several types of analysis are available for measuring taste-producing inorganic components. Measurement of taste- and odor-causing organics can be made using gas or liquid chromatography. Because chromatographic analysis is time-consuming and requires expensive equipment, it is not routinely performed on water samples, but should be done if a problem with organics is suspected. However, because of the synergism mentioned before, quantifying the sources does not necessarily quantify the nature or intensity of taste and odor.

Quantitative tests that employ the human senses of taste and smell can be used for this purpose. An example is the test for the threshold odor number (TON). Varying amounts of odorous water are poured into containers and diluted with enough odor-free distilled water to make a 200 mL mixture. An assembled panel of five to ten "noses" is used to determine the mixture in which the odor is just barely detectable to the sense of smell. The TON of that sample is then calculated, using the formula.

$$TON = \frac{A + B}{A}$$

Where A is volume of odorous water (ml) and B is the volume of odor-free water required to produce a 200 ml mixture. Odor numbers corresponding to various sample volumes are shown in Table 5. Similar tests can be used to quantify taste, or the panel can simply rate the water qualitatively on an "acceptability" scale

Table 5: Threshold odor numbers corresponding to sample volume diluted to 200 ml

Sample volume (A) [ml]	TON
200	1.0
175	1.1
150	1.3
125	1.6
100	2.0
75	2.7
67	3.0
50	4.0
40	5.0
25	8.0
10	20.0
2	100
1	200

Although odors can be a problem with wastewater, the taste and odor parameter is only associated with potable water. US-EPA does not have a maximum standard for TON. A maximum TON of 3 has been recommended by public health services and serves as a guideline rather than a legal standards.

3.5 TEMPERATURE

Temperature is not used to evaluate directly either potable water or wastewater. It is, however, one of the most important parameters in natural surface-water systems. The temperature of surface water governs to a large extent the biological species present and their rates of activity and has an effect on most chemical reactions that occur in natural water systems. Temperature also has a pronounced effect on the solubility of gases in water. Temperature of water released from dams and reservoirs has been getting attention, since temperature of the stream below the dam proved an important aspect for the spawning of fish.

3.5.1 Sources

The temperature of natural water systems responds to many factors, the ambient temperature (temperature of the surrounding atmosphere) being the most common. Generally, shallow bodies of water are more affected by ambient temperatures than deeper bodies. The use of water for dissipation of waste heat in industry and the subsequent discharge of the heated water may result in dramatic, temperature changes in receiving streams. Removal of forest canopies and irrigation return flows can also result in increased stream temperature.

Cooler waters usually have a wider diversity of biological species. At lower temperatures, the rate of biological activity, i.e., utilization of food supplies, growth, reproduction, etc., is slower. If the temperature is increased, biological activity increases. An increase of 10 °C is usually sufficient to double the biological activity, when essential nutrients are present. At elevated temperatures and increased metabolic rates, organisms that are more efficient at food utilization and reproduction flourish, while other species decline and are possibly eliminated altogether. Accelerated growth of algae often occurs in warm water and can become a problem when cells cluster into algae mats. Natural secretion of oils by algae in the mats and the decay products of dead algae cells can result in taste and odor problems. Higher-order species, such as fish, are affected dramatically by temperature and by dissolved oxygen levels (affected by temperature).

The relation between temperature and dissolved oxygen levels in a natural stream in Kansas, USA is shown in Figure 5.

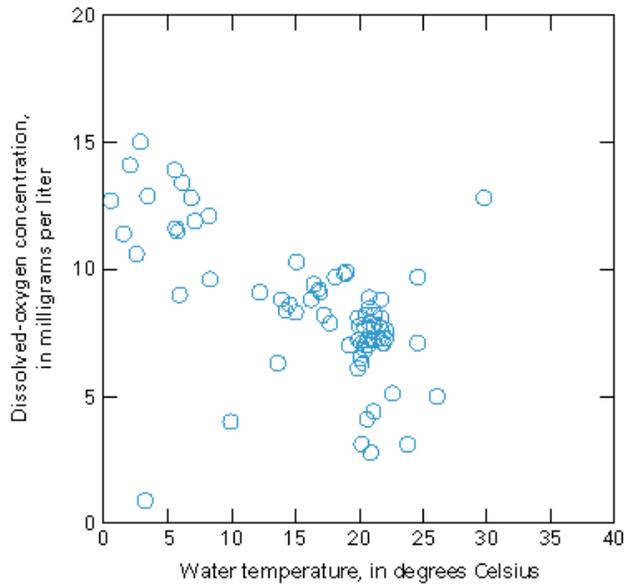


Figure 5: Relation between dissolved oxygen and temperature in Kansas, USA (Trombley, 2001)

Temperature changes affect the reaction rates and solubility levels of chemicals. Most chemical reactions involving dissolution of solids are accelerated by increased temperatures. The solubility of gasses, on the other hand, decreases at elevated temperatures. Because biological oxidation of organics in streams and impoundments is dependent on an adequate supply of dissolved oxygen, decrease in oxygen solubility is undesirable. Temperature also affects other physical properties of water. The viscosity of water increases with decreasing temperature. The maximum density of water occurs at 4 °C, and density decreases on either side of that temperature, a unique phenomenon among water (Figure 6). Both temperature and density have a subtle effect on planktonic micro-organisms in natural water systems.

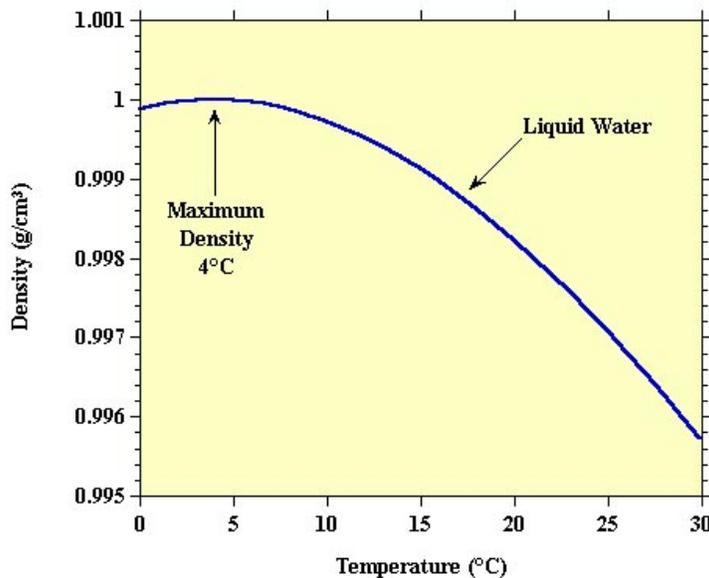


Figure 6: Water density changes over temperature.

4 Biological Water - Quality Parameters

Water may serve as a medium in which literally thousands of biological species spend part, if not all, of their life cycles. Aquatic organisms range in size and complexity from the smallest single-cell micro-organism to the largest fish. All members of the biological community are, to some extent water quality parameters, because their presence or absence may indicate in general terms the characteristics of a given body of water.

Biologists often use a species diversity index (related to the number of species and the relative abundance of organisms in each species) as a qualitative parameters for streams and lakes. A body of water hosting large numbers of species with well balanced numbers of individuals is considered to be a healthy system. Based on their known tolerance for a given pollutant organisms can be used as indicators of the presence of pollutants.

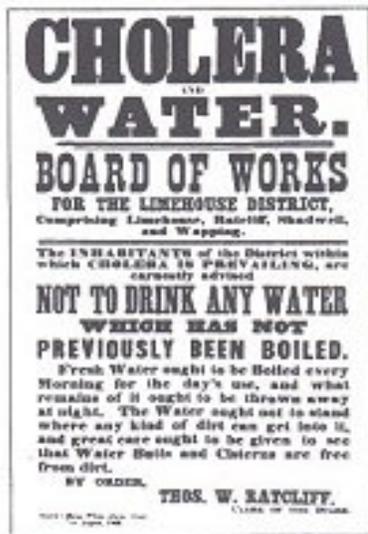
4.1 PATHOGENS

The highest common risk to human health associated with water stems from the presence of disease-causing micro-organisms (pathogens). Many of these pathogens originate from water polluted with human waste. Human feces can contain a variety of intestinal pathogens that cause diseases ranging from mild gastro-enteritis to the serious and possible fatal dysentery, cholera and typhoid. Depending on the prevalence of certain other diseases in a community, other viruses and parasites may also be present. Freshwater also contains other indigenous pathogen including bacteria, fungi, protozoa (single-celled organisms), helminths (parasitic worms) and algae (micro-organisms with photosynthetic pigments), a few are known to produce toxins and transmit or cause diseases. The characteristics of the primary waterborne pathogen are listed in Table 6.

Table 6: Common waterborne pathogens

Organism	Disease
<u>Bacteria</u>	
<i>Francisella tularensis</i>	Tularemia (deer fly fever)
<i>Leptospirae</i>	Leptospirosis (Weil's disease, swineherd's disease, hemorrhagic jaundice)
<i>Salmonella paratyphi</i> (A, B, C)	Paratyphoid (enteric fever)
<i>Salmonella typhi</i>	Thyphoid fever, enteric fever
<i>Shigella</i> (<i>S. flexneri</i> , <i>S. sonnei</i> , <i>S. dysenteriae</i> , <i>S. boydii</i>)	Shigellosis (bacillary dysentery)
<i>Vibrio comma</i> (<i>Vibrio cholerae</i>)	Cholera (Asiatic, Indian, El Tor)
<u>Viruses</u>	
Enteric cytopathogenic human orphan (ECHO)	Aseptic meningitis, epidemic exanthema, infantile diarrhea
Poliomyelitis (3 types)	Acute anterior poliomyelitis, infantile paralysis
Unknown viruses	Infectious hepatitis
<u>Protozoa</u>	
<i>Entamoeba histolytica</i>	Amebiasis (amebic dysentery, amebic enteritis, amebic colitis)
<i>Giardia lamblia</i>	Giardiasis (<i>Giardia</i> enteritis, lambliaosis)
<u>Helminths (parasitic worms)</u>	
<i>Dracunculus medinensis</i>	Dracontiasis (drcunculiasis; dracunculosis medina; serpent, dragon or guinea-worm infection)
<i>Echinococcus</i>	Echinococcoses (hydatidosis; granulosis; dog tapeworm)
Schistosoma (<i>S. mansoni</i> , <i>S. japonicum</i> , <i>S. haematoblum</i>)	Schistosomiasis (bilharziasis or "Bill Harris" or "blood fluke" disease)

Sewage, urban runoff and domestic wastewater are widely discharged to water bodies, particularly rivers. Pathogens associated with these discharges subsequently become distributed through the water body presenting a risk to downstream water user. Typical municipal raw sewage can contain 10 to 100 million coliform bacteria (bacteria originating from the gut) per 100 ml and 1 to 50 million *Escherichia coli* or *focal streptococci* per 100 ml. Different levels of treatments may reduce this by a factor of 10 - 100 and these concentrations will be reduced further after dilution by the receiving waters. The survival of microbiological pathogens, once discharged into a water body, is highly variable depending on the quality of the receiving waters, particularly the turbidity, oxygen levels, nutrients and temperature. *Salmonella bacilli* have been reported in excess of 50 miles downstream of the point source, indicating an ability to survive, under the right conditions, for several days. Once in a water body, micro-organisms often become adsorbed onto sand, clay and sediment particles. Counts of bacteria of fecal origin in rivers and lakes around the world that suffer little human impact vary from < 1 to 3,000 organisms per 100 ml. However, water bodies in area of high population density can have counts up to 10 million organisms per 100 ml. Natural groundwater should contain no fecal bacteria unless contaminated, whereas surface waters, even in remote mountain areas, contain up to one hundred per 100 ml. To avoid human infection, the WHO recommended concentration for drinking water is zero organisms per 100 ml. Detection of other pathogens, particularly viruses, is less common partly due to the lack of appropriate available methodology.



Enteroviruses are typically found in raw sewage at a much lower concentration than bacterial pathogens. Measured as plaque forming units (PFU's) they rarely occur at more than 1000 units per liter.

4.1.1 Bacteria

The word bacteria comes from the Greek word meaning “rod” or “staff”, a shape characteristic of most bacteria. Bacteria are single-cell micro-organisms, usually colorless, and are the lowest form of life capable of synthesizing protoplasm from the surrounding environment. In addition to the rod shape (bacilli) mentioned above, bacteria may also be spherical (cocci) or spiral-shaped (spirilla). Gastrointestinal disorders are common symptoms of most diseases transmitted by waterborne pathogenic bacteria. Cholera, the disease that ravaged Europe during the eighteenth and nineteenth century, is transmitted by *Vibrio comma*. Among the most violent of the waterborne bacterial diseases, cholera causes vomiting and diarrhea that without treatment results in dehydration and death. Symptoms of typhoid, a disease transmitted by the waterborne pathogen, *Salmonella typhosa*, include gastrointestinal disorders, high fever, ulceration of the intestines, and possible nerve damage. Although immunization of individuals and

disinfection of water supplies have eliminated cholera and typhoid in most parts of the world, areas of developing countries where overcrowding and poor sanitary conditions prevail still experience occasional outbreaks of these two diseases. Temporary lapses in good sanitary practices sometimes result in outbreaks of gastroenteritis caused by some of the other bacterial pathogens listed in Table 6.

4.1.2 Viruses

Viruses are the smallest biological structures known to contain all the genetic information necessary for their own reproduction. They are so small that they can only be “seen” with the aid of an electron microscope. Viruses are obligate parasites that require a host in which to live. Symptoms associated with waterborne viral infections usually involve disorders of the nervous system rather than of the gastrointestinal tract. Waterborne viral pathogens are known to cause poliomyelitis and infectious hepatitis, and several other viruses are known to be, or suspected of being, waterborne.

Immunization of individuals has reduced the incidence of polio to a few isolated cases each year in developed nations. Outbreaks of hepatitis are more common, with around 60,000 cases reported in the United States each year. Most of the hepatitis cases result from people eating shellfish contaminated by viruses from polluted waters, although an occasional outbreak will occur at campgrounds or other facilities where crowds gather and where water-supply protection and sanitary facilities are poor.

Although standard disinfecting practices are known to kill viruses, confirmation of effective viral disinfection is difficult, owing to the small size of the organism and the lack of quick and conclusive tests for viable virus organisms. The uncertainty of viral disaffection is a major obstacle to direct recycling of wastewater and is a cause of concern regarding the increasing practice of land application of wastewater.

4.1.3 Protozoa

The lowest forms of animal life, protozoa are unicellular organisms, more complex in their functional activity than bacteria or viruses. They are complete, self-contained organisms that can be free-living or parasitic, pathogenic or nonpathogenic, microscopic or macroscopic. Highly adaptable, protozoa are widely distributed in natural waters, although only a few aquatic protozoa are pathogenic.

Protozoa infections are usually characterized by gastrointestinal disorders of a milder order than those associated with the bacterial infections. Protozoa infections can be serious nonetheless, as illustrated by an epidemic in Chicago in 1933 in which over 1400 people were affected and 98 deaths resulted when drinking water was contaminated by sewage containing *Entombed histolytica*. Many oases of giardiasis, or backpackers disease, have been reported in recent years among people that drink untreated water from surface streams. This infection is caused by *Giardia lamblia*, a protozoa that may be carried by wild animals living in or near natural water systems.

Under adverse environmental circumstances, aquatic protozoa from cysts are difficult to deactivate by disinfection. Usually complete treatment, including filtration, is necessary to remove protozoa cysts.

4.1.4 Helminths

The life cycles of helminths, or parasitic worms, often involve two or more animal hosts, one of which can be human, and water contamination may result from human or animal waste that contain helminths. Contamination may also be via aquatic species of other hosts, such as snails or insects. While aquatic systems can be the vehicle for transmitting helminthal pathogens, modern water treatment methods are very effective in destroying these organisms. Thus, helminths pose hazards primarily to those people who come into direct contact with untreated water. Sewage plant operators, swimmers in recreational lakes polluted by sewage or storm water runoff from cattle feedlots, and farm laborers employed in agricultural irrigation operations are at particular risk.

4.2 INVERTEBRATES

Benthic invertebrates are small animals, such as clams, worms, and crustaceans that live on or in the bottom substrate of a water body. These organisms are an important food source for many fish and crustaceans. In addition, benthic organisms can be important organisms for monitoring the adverse effects from anthropogenic impacts (NOAA, 2001). Benthic invertebrate biomonitoring has long been a tool of choice in assessing and monitoring the impacts of anthropogenic stress in aquatic systems. Benthic invertebrates are longer lived than most planktonic organisms, and thus can integrate the effects of environmental conditions over longer periods of time. Additionally, they are relatively sedentary and are therefore easier to sample than nektonic organisms, such as fish (EPA, 1997).

In the United Kingdom a Biological Monitoring Working Party (BMWP) was created to develop an indexing system for algae and invertebrates to be used as indicators for water quality in river systems, without the need of chemical analysis. Over time, this indexing system has been adjusted several times (Hawkes, 1997).

Table 7 shows the revised scoring index suggested by Walley and Hawkes (1996). The higher the BMWP score for a family, the less tolerant (the more sensitive) it is to organic pollution. In other words, the occurrence of an insect family with a high score in a water sample is an indication of high quality water.

In the original BMWP score system, if a given family is found in a sample taken from the river bed, its score contributes to the overall score for that site. Each family contributes only once to the sum of the scores, even though the occurrence of that family might be more than once. A more reliable method is however a weighted score, where the total BMWP score is divided by the number of families that contributed to that score. This is indicated by the equation

$$ASPT = \frac{1}{N_t} \sum_{t=1}^{N_t} B_t$$

Where ASPT = Average score per taxon, B_t = BMWP family score of family t that is present in the sample, N_t = number of BMWP families present in the sample (Walley and Hawkes, 1997)).

Zwart and Trivedi (1995) created a taxonomy key for biological water quality determination based on the BMWP method. The taxonomy key aids the user in determining the family of an invertebrate through a step-wise questionnaire.

Table 7: BMWP revised scoring system (Walley and Hawkes, 1996)

Common name	Family	Revised BMWP Score
Flatworms (TRICLADIDA)	<i>Planariidae</i>	4.2
	<i>Dendrocoelidae</i>	3.1
Snails (MOLLUSCA)	<i>Neritidae</i>	7.5
	<i>Viviparidae</i>	6.3
	<i>Valvatidae</i>	2.8
	<i>Hydrobiidae</i>	3.9
	<i>Lymnaeidae</i>	3.0
	<i>Physidae</i>	1.8
	<i>Planorbidae</i>	2.9
Limpets and Mussels (MOLLUSCA)	<i>Ancylidae</i>	5.6
	<i>Unionidae</i>	5.2
	<i>Sphaeriidae</i>	3.6
Worms (OLIGOCHAETA)	<i>Oligochaeta</i>	3.5
Leeches (HIRUDINA)	<i>Piscicolidae</i>	5.0
	<i>Glossiphoniidae</i>	3.1
	<i>Hirudidae</i>	0.0
	<i>Erpobdellidae</i>	2.8
Crayfish, Shrimps and Slaters (CRUSTACEA)	<i>Asellidae</i>	2.1
	<i>Corophiidae</i>	6.1
	<i>Gammaridae</i>	4.5
	<i>Astacidae</i>	9.0
Mayflies (EPHEMEROPTERA)	<i>Siphonuridae</i>	11.0
	<i>Baetidae</i>	5.3
	<i>Heptageniidae</i>	9.8
	<i>Leptophlebiidae</i>	8.9
	<i>Ephemerellidae</i>	7.7
	<i>Potamanthidae</i>	7.6
	<i>Ephemeridae</i>	9.3
Stoneflies (PLECOPTERA)	<i>Taeniopterygidae</i>	10.8
	<i>Nemouridae</i>	9.1
	<i>Leuctridae</i>	9.9
	<i>Capniidae</i>	10.0
	<i>Perlodidae</i>	10.7
	<i>Perlidae</i>	12.5
	<i>Chloroperlidae</i>	12.4
Damsel flies (ODONATA)	<i>Platycnemidae</i>	5.1
	<i>Coenagriidae</i>	3.5
	<i>Lestidae</i>	5.4
	<i>Calopterygidae</i>	6.4
Dragon flies (ODONATA)	<i>Cordulegasteridae</i>	8.6
	<i>Aeshnidae</i>	6.1
	<i>Libellulidae</i>	5.0
Bugs (HEMIPTERA)	<i>Hydrometridae</i>	5.3
	<i>--Mesoveliidae</i>	4.7
	<i>Gerridae</i>	4.7
	<i>Nepidae</i>	4.3
	<i>Naucoridae</i>	4.3
	<i>Aphelocheiridae</i>	8.9
	<i>Notonectidae</i>	3.8
	<i>Pleidae</i>	3.9
<i>Corixidae</i>	3.7	
Beetles (COLEOPTERA)	<i>Hygrobiidae</i>	2.6
	<i>Dytiscidae</i>	4.8
	<i>Gyrinidae</i>	7.8
	<i>Hydrophilidae</i>	5.1
	<i>Halplidae</i>	4.0
	<i>Scirtidae</i>	6.5
	<i>Dryopidae</i>	6.5
	<i>Elmidae</i>	6.4
	<i>Chrysomelidae</i>	4.2
<i>Curculionidae</i>	4.0	

Alder flies (MEGALOPTERA)	<i>Sialidae</i>	4.5
Caddis flies (TRICHOPTERA)	<i>Rhyacophilidae</i>	8.3
	<i>Philopotamidae</i>	10.6
	<i>Polycentropidae</i>	8.6
	<i>Psychomyiidae</i>	6.9
	<i>Hydropsychidae</i>	6.6
	<i>Hydroptilidae</i>	6.7
	<i>Phryganeidae</i>	7.0
	<i>Limnephilidae</i>	6.9
	<i>Molannidae</i>	8.9
	<i>Beraeidae</i>	9.0
	<i>Odontoceridae</i>	10.9
	<i>Leptoceridae</i>	7.8
	<i>Goeridae</i>	9.9
	<i>Lepidostomatidae</i>	10.4
<i>Brachycentridae</i>	9.4	
<i>Sericostomatidae</i>	9.2	
True flies (DIPTERA)	<i>Tipulidae</i>	5.5
	<i>Chironomidae</i>	3.7
	<i>Simuliidae</i>	5.8

5 Hydrological variables

Knowledge of the hydrological regime of a water body is essential when discussing water quality analyses. Discharge measurements, for example, are necessary for mass flow or mass balance calculations and as inputs for water quality models.

5.1 VELOCITY

The velocity (sometimes referred to as the flow rate) of a water body can significantly affect its ability to assimilate and transport pollutants. Thus, measurement of velocity is extremely important in any assessment program. It enables the prediction of movement of compounds (particularly pollutants) within water bodies, including groundwater. For example, knowledge of water velocity enables the prediction of the time of arrival, downstream, of a contaminant accidentally discharged upstream.

Water velocity can vary within a day, as well as from day to day and season to season, depending on hydrometeorological influences and the nature of the catchment area. It is important, therefore, to record the time when measurements are taken and every attempt should be made to measure velocity at the same sites as other water quality samples are collected. Velocity (m/s) is determined with current meters or tracers (e.g. dyes). Measurements are usually averaged over a period of 1-2 minutes.

5.2 DISCHARGE

The discharge is the volume flowing for a given period of time. For rivers, it is usually expressed as m^3/s or m^3/h . The amount of suspended and dissolved matter in a water body depends on the discharge and is a product of the concentration and the discharge. Natural substances arising from erosion (suspended matter) increase exponentially in concentration when river discharge increases. Substances introduced into a water body at a point source tend to occur at decreasing concentration with increasing river discharge. If a pollutant is introduced into a river at a constant rate, the concentration in the receiving water can be estimated from the quality input and the river discharge. Sedimentation and re-suspension can, however, affect this simple relationship.

Discharge can be estimated from the product of the velocity and the cross-sectional area of the river. It should be measured at the time of sampling and preferably at the same position as water samples are taken. As the cross-sectional area affects the discharge, multiple discharge measurements are needed. Measurements of depth across a transect of the water body can be used to obtain an approximate cross-sectional area.

5.3 WATER LEVEL

Measurement of water level is important to determine the hydrological regime of lakes, reservoirs and groundwater and the interaction between groundwater and surface water. Measurement of the water level is necessary for mass flow calculations in lakes and groundwater and must be measured at the time and place of water sampling.

Water can flow to or from an aquifer which is in continuity with a river, depending on the relative water levels in the river and aquifer. Low water levels in the river can induce groundwater flow to the river, and high water levels can reverse the flow and produce losses from the river to the aquifer. Similarly, when groundwater levels are low (or deep) surface water infiltrates downwards to the water table. Depending on the relative water levels in the aquifer and river, stretches which gain or lose may occur in the same river.

Also a particular stretch may be gaining at one time of year and losing at another, as river levels change with the seasons. As the river water and groundwater may be of very different quality, significant variation in water quality may be experienced in wells close to rivers, and in the river itself. Measurement of groundwater levels is particularly important in relation to salt intrusion. However, water is in a constant state of motion as depicted in the hydrologic cycle Figure 7.

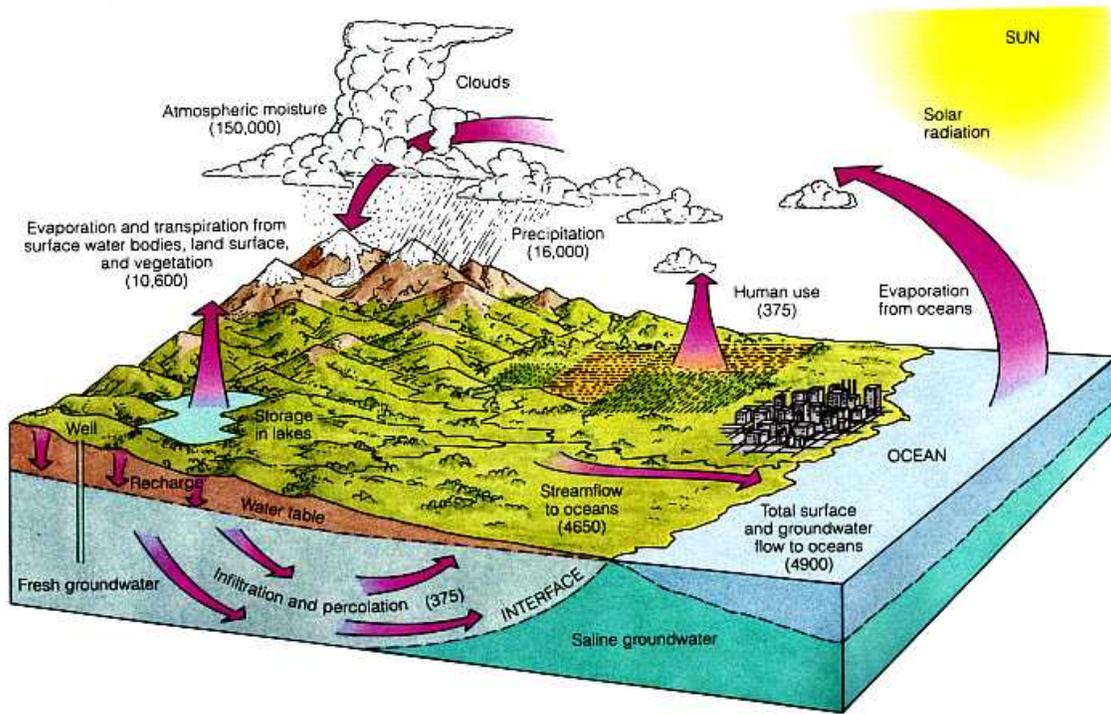


Figure 7: Hydrologic cycle

6 Water Quality Monitoring Programs

6.1 INTRODUCTION

Monitoring is an indispensable activity for water management and planning. In addition, monitoring is required for research purposes. As monitoring is relatively expensive and / or laborious, much attention should be paid to the design of the monitoring programme. Many monitoring programmes fail, because inappropriate (irrelevant) or incomplete data are being collected, data are being collected at the wrong locations, or data are being collected at the wrong time or time intervals.

A monitoring programme should, therefore, incorporate the following three issues:

- Parameters (quantitative / qualitative), i.e. the *indicators*
- Locations (and depths); *spatial resolution*;
- Frequencies; *temporal resolution*.

The monitoring programme should also address:

- Measuring method / sampling protocol;
- Equipment;
- Data processing and quality control;
- Data storage and management.

The monitoring programme principally depends on the following two aspects:

- Monitoring objectives;
- Physical environment.

These aspects will be elaborated in more detail in Paragraph 6.2 and 6.3, respectively.

6.2 MONITORING OBJECTIVES

General considerations

Firstly, the general monitoring objectives should be identified, either being water planning, water management or research. Water planning, generally, requires *extensive data* with a relatively *long time span*, in order to detect trends and variabilities. Water management may require less data (short time span), but the data should be *more frequent* to enable the water manager to make the right decisions and interventions (this especially applies for daily water management). In addition to a higher *temporal resolution*, (daily) water management often requires a higher *spatial resolution* too. Monitoring for research purposes involves specific additional requirements, which will not be elaborated in this manual.

General objectives

Monitoring programmes can have the following general objectives:

- inventory of existing water quality;
- detect long-term trends and assess water quality variability;
- assess the impact of historical events and measures;
- detect sources of pollution;
- enforce water quality standards;
- warn the water users (*early warning* system).

Specific objectives

Within the framework of the general objectives, more explicit, specific monitoring objectives should be defined. These monitoring objectives very much depend on the various *water uses* in the area and the relative importance of the individual water uses. Various water uses may have different objectives. Sometimes, *international obligations* are also involved.

It is often difficult to clearly prescribe the specific monitoring objectives, as these objectives should not only incorporate the interests of (short and long-term) water uses, but also the required level of accuracy, risks and all kind of practicalities with respect to daily water management. Some of these aspects are difficult to quantify, yet it is important to try to set monitoring objectives that go beyond generalities, in order to be able to design and optimise a monitoring programme.

A monitoring programme should be *efficient*, which means that a maximum amount of relevant information is obtained at minimum costs, and *effective*, which means that all (as much as possible) relevant information is obtained. Correlation between data (both in time series and in spatial data) should be minimised. The required effectiveness is related to the acceptable *risk of failure* of the monitoring system and the consequences of such a failure.

Examples of water uses that are subject to risks with respect to water quality are:

- humans and cattle (health risks);
- aquatic ecosystems;
- agriculture (crop water);
- (irrigation) equipment and water infrastructure (e.g. corrosion, blocking, clogging);
- industrial processes;
- a-biotic natural resources (e.g. adverse effects on soils, groundwater);

It is obvious that water that is being used for human consumption will need a more intensive monitoring programme, also involving specific risk parameters for human health, than water that is being used as cooling water for an industrial plant. The drinking water for a city obviously requires more intensive monitoring than drinking water for a single family. Irrigation water may impose specific requirements in terms of SAR and EC, which may not be critical parameters for a specific ecosystem., etc.

6.3 PHYSICAL ENVIRONMENT

The monitoring programme cannot be established without extensive knowledge of the area. This involves both knowledge on the (existing, past and future) *land and water use* and knowledge on the *physical setting* of the area (topography, climate, soils, surface water, groundwater).

Land and Water Use

Knowledge of the land and water use is required to *identify (potential) sources of pollution* and to *identify the relevant parameters* to be monitored. For example, the composition of the effluent from agricultural land is strongly related with the cropping pattern and farm practises (together with rainfall, soils and drainage). Entirely different water quality parameters may be involved for pasture land, arable land and (different types of) horticulture. In agricultural areas, salinity, (certain) nutrients, (certain) pesticides and / or specific toxic elements may be relevant.

In mining areas, sulphates, acidity and heavy metals are often relevant parameters, thus requiring an entirely different monitoring programme. In industrial areas a wide range of parameters can be involved, depending on the type of industry and the way that the effluent is treated.

In urban areas nitrate may be a relevant parameter to monitor, depending on the sewerage facilities and / or the sanitary system.

The land and water use, therefore, provides information on the water quality parameters involved and their possible concentrations.

It is noted that the land and water use may impact on the water quality as *point sources* (e.g. effluent of factories, treatment plants and mines, waste sites), *line sources* (e.g. agricultural land that drains to surface water, a leaking canal discharging to groundwater) and *diffuse sources* (e.g. atmospheric deposition, deep groundwater seepage). Each type of source should be monitored in a different way. Point sources should be monitored at the discharge location. Line sources should be monitored immediately downstream of the source. Diffuse sources should be monitored with a network of evenly spread measuring locations.

It should be noted that diffuse sources may sometimes exist in a much wider area than (or even outside of) the area that is to be managed. For example, the water quality may be directly or indirectly impacted by atmospheric deposition of acids and nutrients.

Physical setting

Knowledge on the physical setting of the area allows for a first assessment of the (*background*) *water quality* and to assess *how the system will respond* to certain activities or measures.

The background water quality is the result of a variety of (past or present) interactions in the physical environment, such as the interaction between water (groundwater and surface water) and rocks or soils, the interaction between groundwater and surface water, the interaction with the atmosphere, etc. For example, in areas with carbonate rocks and soils, often highly alkaline water is found. Water in coastal areas may be brackish or saline. Water in volcanic areas (or volcanic rocks) may contain elevated fluoride concentrations (which can cause severe health problems).

The physical setting also provides information on the *dynamics* of the water system, i.e. how the water system responds to events. For example, the outlet of a small catchment generally reacts faster and more directly on rainfall events than a large catchment's outlet, a catchment with a high drainage intensity reacts differently on rainfall than a catchment with few surface water courses, a phreatic aquifer has other dynamics than a confined aquifer, water from a forest area reacts differently than water from a city, a mountainous area reacts differently than a plain, etc, etc.

The properties of the concerned water quality parameter also need to be considered. There are large differences with respect to the mobility (adsorption / desorption) of chemical compounds and their subject to chemical reactions. Hazardous chemical compounds may not be immediately found in the water, while they accumulate in the soils, thus being a future water quality "time bomb".

In conclusion: the dynamics of the entire physical environment, both in time and distance, obviously imposes requirements with respect to the measuring frequency and locations.

6.4 PARAMETERS

The water quality parameters to be monitored should be selected on the basis of the monitoring objectives and the physical environment. Parameters are the indicators for water quality, describing a certain state or use of the water system.

For daily qualitative water management it is common practice to develop *water quality criteria*, which

generally consist of the *maximum allowable concentrations* for a set of parameters (for the distinctive water uses). Most countries have quality criteria for drinking water, while there are also water quality criteria or guidelines for livestock, irrigation and (various) aquatic ecosystems. The WHO guidelines can also be applied.

With the knowledge on the physical environment the (expected) water composition in terms of occurring parameters and the expected concentrations can be assessed. For daily water management at least the parameters that could occur in concentrations that conflict with the water quality criteria should be monitored. It can be decided to monitor additional parameters that impose severe risks, although they are not expected to occur in hazardous concentrations. It is noted that in many countries monitoring programmes are prescribed (by law) for some of the water uses, for example drinking water.

For long term water planning, the monitoring objectives not only depend of the (current) water uses, but also on long-term water management objectives. This implies that other parameters than those that are currently relevant, should be included in the monitoring programme.

6.5 LOCATION AND FREQUENCY

The locations and frequencies of monitoring depend on:

- the spatial and temporal variability of the parameter;
- the required level of effectiveness (risks involved);
- the required time for implementing mitigating measures.

The spatial and / or temporal variability of a parameter results that individual measurements are less representative (in time and in space). Spatial variability of water quality parameters is typical for heterogeneous areas (in terms of the physical environment). In these areas, generally, a higher monitoring density is required in comparison with homogeneous areas. For example, extensive areas with the same soils and same land use can often be monitored with a lower density monitoring network, as each measurement is expected to be fairly representative for the area.

The required frequency principally depends on the dynamics of the physical environment. Even in homogeneous areas the system dynamics can be great and water quality parameters can show a large temporal variability. For example the leaching and discharge of phosphates from soils in agricultural areas often shows peaks in the beginning of the wet season, pollution control dams may overflow after great storm events, etc.

In general, the dynamics of groundwater systems is much less than surface water systems. In addition, large surface water systems (such as lakes) are less dynamic than small surface water systems. A general guideline is that the dynamics of the system is inversely proportional to the volume of the system. A more precise formulation is that inflows into a system with storage properties are more variable than outflows. As a consequence, the monitoring of water quality parameters should occur more frequently in small volume systems than in large volume systems, while monitoring a water quality parameter at an upstream location requires a higher frequency than monitoring at a downstream location.

There are no simple rules to determine monitoring locations and frequencies. A system analysis together with a statistical analysis would be required to quantify the spatial and temporal variability. Together with the monitoring objectives the monitoring programme can then be established.

Routine water quality monitoring in rivers and streams generally requires frequencies varying from permanent monitoring to two-weekly monitoring (sometimes in combination with more frequent monitoring). Frequencies of less than 1x/month are, generally, not applied. Depending on the monitoring objectives, risks and the volume, monitoring in lakes can occur less frequent. Generally -order of

magnitude- monthly to bi-annual monitoring is applied. Routine groundwater monitoring generally occurs bi-monthly to bi-annually (unless there are specific conditions).

Mitigation

The monitoring programme should also anticipate corrective or mitigative measures. If water from the river is used for drinking water, the water quality should be measured at a sufficient distance upstream that measures can be taken in time (e.g. closure of the intake). For example, if the water flows with 0.5 m/second, while the sampling and analysing requires a full day, the sampling should occur from approximately 50 km upstream. This example shows that much more frequent sampling and analysing would be required. Sometimes mitigating measures may take much time. To replace groundwater abstraction wells and all related infrastructures may require as much as 10-25 years. The groundwater quality monitoring system should then be designed such, that any non correctable deterioration of the resource is detected 10-25 years ahead.

6.6 SAMPLING

The methodology to collect (and handle) water samples depends very much on the parameters that are to be determined. Physical, chemical and microbiological parameters require their own specific equipment and sampling techniques. Organic compounds are to be handles in a different way than inorganic compounds.

There are many national and international standards for water quality sampling. The ISO 5667 standard is a comprehensive, internationally acknowledged standard that should, where possible, followed. Table 9 presents a summary of ISO 5667.

Table 9. General water quality sampling standards (ISO 5667).

ISO number	Year	
ISO 5667-1	1980/1996	Part 1: Guidance on the design of sampling programmes
ISO 5667-2	1991	Part 2: Guidance on sampling techniques
ISO 5667-3	2003	Part 3: Guidance on the preservation and handling of water samples
ISO 5667-4	1987	Part 4: Guidance on sampling from lakes, natural and man-made
ISO 5667-5	1991	Part 5: Guidance on sampling of drinking water and water used for food and beverage processing
ISO 5667-6	1990	Part 6: Guidance on sampling of rivers and streams
ISO 5667-7	1993	Part 7: Guidance on sampling of water and steam in boiler plants
ISO 5667-8	1993	Part 8: Guidance on the sampling of wet deposition
ISO 5667-9	1992	Part 9: Guidance on sampling from marine waters
ISO 5667-10	1992	Part 10: Guidance on sampling of waste waters
ISO 5667-11	1993	Part 11: Guidance on sampling of groundwaters
ISO 5667-12	1995	Part 12: Guidance on sampling of bottom sediments
ISO 5667-13	1997	Part 13: Guidance on sampling of sludges from sewage and water-treatment works
ISO 5667-14	1998	Guidance on quality assurance of environmental water sampling and handling
ISO 5667-15	1999	Part 15: Guidance on preservation and handling of sludge and sediment samples
ISO 5667-16	1998	Part 16: Guidance on biotesting of samples
ISO 5667-17	2000	Part 17: Guidance on sampling of suspended sediments
ISO 5667-18	2001	Part 18: Guidance on sampling of groundwater at contaminated sites

Some general remarks on surface water and groundwater sampling can be made. In general, before the water sample is taken, the sampling equipment (in particular the bottles) should be cleansed with the water

that is to be sampled (hence not with distilled water).

Rivers and streams

Water samples from streams and rivers should be taken from a representative section. Unless for specific ecological purposes, the sample should not be taken from or near the surface (to avoid floating compounds), near the bottom or near banks. Stagnant waters should also be avoided. If there are doubts on the representativeness of a single sample (such as in stagnant waters), more samples should be collected.

Diurnal water quality fluctuations can occur, especially when the river quality is impacted on by point sources. Sampling times must then be chosen with care. It is obvious that knowledge on the physical environment is required to be able to select the appropriate sampling times, e.g. when the highest concentrations are expected.

Lakes

In lakes utmost attention should be paid to the locations of the inflows. Sampling near these inflows should be avoided. Isolated bays, sections with certain water plants and sections with pronounced wind action can also result in non representative water quality of the lake. In addition, lakes often show a vertical stratification of water quality (especially deep lakes). Bottom layers may then have a higher density than top layers, while bottom layers may also contain less oxygen or even become anaerobic.

In the case of vertical stratification, monitoring locations should be sampled at, at least, three depths: 1 metre below the water surface, 1 metre above the lake bottom and at, at least, one intermediate point. To assess whether stratification plays a role, one may simply measure the temperature and dissolved oxygen at different depths in the lake (this can easily be done with field equipment). Temperature and oxygen are, generally, adequate indicators for stratification.

In the case that (temperature) stratification occurs, it is recommended that sampling occurs, as much as possible, at a fixed time, to avoid bias by diurnal water quality fluctuations.

Groundwater

Groundwater samples are, generally, taken from groundwater observation wells or production wells. In order to take a representative sample, the (stagnant) water in the observation well should be removed before the sample is taken (this does not apply when light non-aqueous liquids, floating on groundwater, are to be detected). A bailer or pump can be used for this purpose. As a rule of thumb, three times the contents of the well should be pumped before the sample is taken. This means that a volume of water of $3 \cdot 0.25 \cdot \pi \cdot d^2 \cdot H$ should be abstracted.

$$\approx \boxed{2.4 \cdot d^2 \cdot H} \quad (d \text{ is the diameter of the well and } D \text{ the -saturated- depth}).$$

For example, approximately 1400 litres should be abstracted from a 6-inch, 50-metres deep well *before the sample is taken* (!).

6.7 PRESERVATION AND HANDLING OF WATER SAMPLES

Generally some time elapses before a water sample is analysed by the laboratory. During this time, the sample should be properly handled and stored. Water quality monitoring can easily fail, if the proper procedures with respect to the preservation and handling of water samples are not complied with. For this reason, national and international guidelines have been developed for the preservation and handling of water samples (see Table 9).

Some general remarks can be made. It is obvious that it should be avoided that any chemical equilibrium in the water sample changes (or any chemical reactions occur) after that the sample has been taken. As temperature has a major influence on hydrochemical equilibria, water samples should be put in a cooler box and stored in a fridge.

The chemistry of groundwater samples and water samples from greater depths in lakes are often not 'in equilibrium' with the atmosphere. Groundwater samples are therefore, generally, subject to changes in the carbonate-bicarbonate equilibrium. Carbon dioxide may leave the sample, thus inducing changes of the pH, alkalinity and total inorganic carbon. If the pH increases, mobile metals may precipitate or adsorb to the sample bottle. Another process is that oxygen from the atmosphere enters the sample and oxidises ferrous iron and other compounds that can be present in anoxic groundwater. This obviously changes the water composition, including the alkalinity.

To prevent changes in the chemical composition, the parameters subject to changes should, where possible, determined in the field, for example the pH, the temperature, oxygen and the electrical conductivity (EC). Other parameters (such as the major cations, heavy metals) should be conserved. This can be done by adding acid to the water sample until the pH is below 2. By acidifying the sample bacterial growth is stopped, adsorption and precipitation (of metals and cations) is stopped and oxidation processes halted.

If a sample is acidified, the water sample should firstly be filtered to avoid that suspended solids become dissolved by the acid. As different laboratories require different preservation methods, good co-ordination with the laboratory is required.

6.7 LABORATORY ANALYSIS

The laboratory procedures are not included in this manual. It is, however, obvious, that the analysing work should be done by a reputable laboratory and by qualified staff. Parameters should, as much as possible, be determined independently. By no way may the concentration of one of the major parameters be calculated from other concentrations (such as sometimes is done for sulphate, which is slightly more difficult to determine).

In many countries, a certification system for laboratories has been implemented. Certified laboratories have to follow a prescribed protocol that covers all activities from the sample intake to the reporting of the analysis results. The analysis is done according to strictly prescribed, acknowledged methods, while internal procedures are aimed at avoiding errors in the handling process (changing samples etc).

If the laboratory analyses have been done by a certified laboratory, there is at least some quality assurance.

6.8 DATA STORAGE AND MANAGEMENT

If the monitoring programme is well designed, the sampling is carried out according to the appropriate standards and the analyses executed by a qualified laboratory, errors may still occur in the further storing and processing of information.

It is common (and good) practice to store monitoring results in a database. As typing errors are unavoidable, data entry is subject to errors. The route from the laboratory to the database should be as short as possible, with minimum bureaucracy. Preferably the (digital) data from the laboratory should be entered directly into the database. The laboratory reporting format and the database entry format should match as much as possible.

If data is to be entered manually (for example historical data), a procedure should be set-up to detect typing

errors. One option is to enter the data by two (independent) typists and thereafter compare the data series.

In addition, data quality control procedures should be established to detect other errors that occurred anywhere in the monitoring process. Statistical analyses can aid to detect unreliable and wrong data. Statistical analyses can also help to optimise the monitoring programme, both in space (for example by calculating correlation coefficients) time (determining auto-correlation) and parameters (by assessing the significance and probability).

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