

**Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring - Second Edition**

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## **Chapter 1\* - AN INTRODUCTION TO WATER QUALITY**

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*\*This chapter was prepared by M. Meybeck and R. Helmer*

### **1.1. Characterisation of water bodies**

Water bodies can be fully characterised by the three major components: hydrology, physico-chemistry, and biology. A complete assessment of water quality is based on appropriate monitoring of these components.

#### **1.1.1. Hydrodynamic features**

All freshwater bodies are inter-connected, from the atmosphere to the sea, via the hydrological cycle. Thus water constitutes a continuum, with different stages ranging from rainwater to marine salt waters. The parts of the hydro-logical cycle which are considered in this book are the inland freshwaters which appear in the form of rivers, lakes or groundwaters. These are closely inter-connected and may influence each other directly, or through intermediate stages, as shown in Table 1.1 and Figure 1.1. Each of the three principal types of water body has distinctly different hydrodynamic properties as described below.

*Rivers* are characterised by uni-directional current with a relatively high, average flow velocity ranging from 0.1 to 1 m s<sup>-1</sup>. The river flow is highly variable in time, depending on the climatic situation and the drainage pattern. In general, thorough and continuous vertical mixing is achieved in rivers due to the prevailing currents and turbulence. Lateral mixing may take place only over considerable distances downstream of major confluences.

*Lakes* are characterised by a low, average current velocity of 0.001 to 0.01 m s<sup>-1</sup> (surface values). Therefore, water or element residence times, ranging from one month to several hundreds of years, are often used to quantify mass movements of material. Currents within lakes are multi-directional. Many lakes have alternating periods of stratification and vertical mixing; the periodicity of which is regulated by climatic conditions and lake depth.

*Groundwaters* are characterised by a rather steady flow pattern in terms of direction and velocity. The average flow velocities commonly found in aquifers range from 10<sup>-10</sup> to 10<sup>-3</sup> m s<sup>-1</sup> and are largely governed by the porosity and permeability of the geological material.

As a consequence mixing is rather poor and, depending on local hydrogeological features, the ground-water dynamics can be highly diverse.

There are several transitional forms of water bodies which demonstrate features of more than one of the three basic types described above and are characterised by a particular combination of hydrodynamic features. The most important transitional water bodies are illustrated in Figure 1.1 and are described below.

**Table 1.1.** The hydrological cycle: water volumes, residence times and fluxes

	Total cycle volume		Freshwater volume only (%)	Freshwater volume without icecaps and glaciers (%)	Residence times
	(10 <sup>6</sup> Km <sup>3</sup> )	(%)			
Oceans and seas	1,370	94			~4,000 years
Lakes and reservoirs	0.13	< 0.01	0.14	0.21	~10 years
Swamps and marshes	< 0.01	< 0.01	< 0.01	< 0.01	1-10 years
River channels	< 0.01	< 0.01	< 0.01	< 0.01	~2 weeks
Soil moisture	0.07	< 0.01	0.07	0.11	2 weeks-1 year
Groundwater	60	4	66.5	99.65	2 weeks-50,000 years
Icecaps and glaciers	30	2	33.3		10-1,000 years
Atmospheric water	0.01	< 0.01	0.01	0.02	~10 days
Biospheric water	< 0.01	< 0.01	< 0.01	< 0.01	~1 week
<i>Fluxes</i>					
Evaporation from oceans	425				
Evaporation from land	71				
Precipitation from oceans	385				
Precipitation from land	111				
Run-off to oceans	37.4				
Glacial ice	2.5				

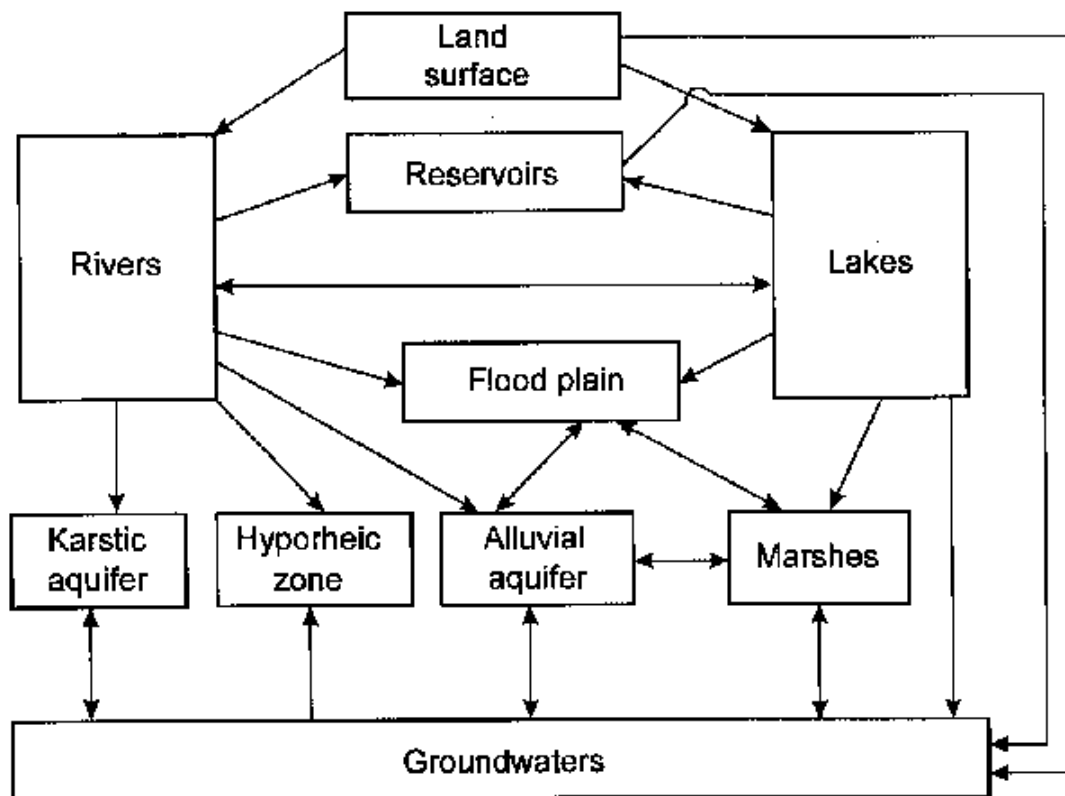
Source: Modified from Nace, 1971 and various sources

*Reservoirs* are characterised by features which are intermediate between rivers and lakes. They can range from large-scale impoundments, such as Lake Nasser, to small dammed rivers with a seasonal pattern of operation and water level fluctuations closely related to the river discharge, to entirely constructed water bodies with pumped in-flows and out-flows. The cascade of dams along the course of the River Dnjepr is an example of the interdependence between rivers and reservoirs. The hydrodynamics of reservoirs are greatly influenced by their operational management regime.

*Flood plains* constitute an intermediate state between rivers and lakes with a distinct seasonal variability pattern. Their hydrodynamics are, however, determined by the river flow regime.

*Marshes* are characterised by the dual features of lakes and phreatic aquifers. Their hydrodynamics are relatively complex.

**Figure 1.1. Inter-connections between inland freshwater bodies (intermediate water bodies have mixed characteristics belonging to two or three of the major water bodies)**

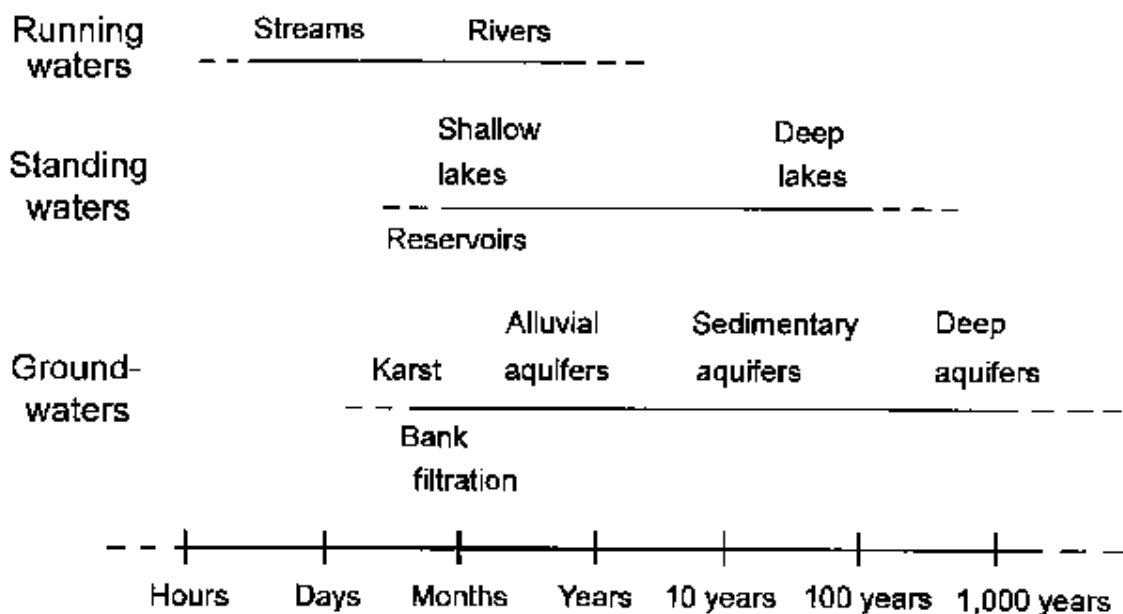


*Alluvial and karstic aquifers* are intermediate between rivers and groundwaters. They differ, generally, in their flow regime which is rather slow for alluvial and very rapid for karstic aquifers. The latter are often referred to as underground rivers.

As a consequence of the range of flow regimes noted above, large variations in water residence times occur in the different types of inland water bodies (Figure 1.2). The

hydrodynamic characteristics of each type of water body are highly dependent on the size of the water body and on the climatic conditions in the drainage basin. The governing factor for rivers is their hydrological regime, i.e. their discharge variability. Lakes are classified by their water residence time and their thermal regime resulting in varying stratification patterns. Although some reservoirs share many features in common with lakes, others have characteristics which are specific to the origin of the reservoir. One feature common to most reservoirs is the deliberate management of the inputs and/or outputs of water for specific purposes. Groundwaters greatly depend upon their recharge regime, i.e. infiltration through the unsaturated aquifer zone, which allows for the renewal of the ground-water body. Further details for each of these water bodies are available in Chapters 6, 7, 8 and 9.

**Figure 1.2. Water residence time in inland freshwater bodies (After Meybeck et al., 1989)**



It cannot be over-emphasised that thorough knowledge of the hydrodynamic properties of a water body must be acquired before an effective water quality monitoring system can be established. Interpretation of water quality data cannot provide meaningful conclusions unless based on the temporal and spatial variability of the hydrological regime.

### 1.1.2. Physical and chemical properties

Each freshwater body has an individual pattern of physical and chemical characteristics which are determined largely by the climatic, geomorphological and geochemical conditions prevailing in the drainage basin and the underlying aquifer. Summary characteristics, such as total dissolved solids, conductivity and redox potential, provide a general classification of water bodies of a similar nature. Mineral content, determined by the total dissolved solids present, is an essential feature of the quality of any water body resulting from the balance between dissolution and precipitation. Oxygen content is another vital feature of any water body because it greatly influences the solubility of

metals and is essential for all forms of biological life. For a complete description of chemical water quality variables see Chapter 3.

The chemical quality of the aquatic environment varies according to local geology, the climate, the distance from the ocean and the amount of soil cover, etc. If surface waters were totally unaffected by human activities, up to 90-99 per cent of global freshwaters, depending on the variable of interest, would have natural chemical concentrations suitable for aquatic life and most human uses. Rare (between 1 and 10 per cent and between 90 and 99 per cent of the global distribution) and very rare (< 1 per cent and > 99 per cent of the global distribution - see section 1.3, Figure 1.4) chemical conditions in freshwaters, such as occur in salt lakes, hydrothermal waters, acid volcanic lakes, peat bogs, etc., usually make the water unsuitable for human use (see section 1.3). Nonetheless, a range of aquatic organisms have adapted to these extreme environments. In many regions groundwater concentrations of total dissolved salts, fluoride, arsenic, etc., may also naturally exceed maximum allowable concentrations (MAC) (see section 9.2.6).

Particulate matter (PM) is a key factor in water quality, regulating adsorption-desorption processes. These processes depend on: (i) the amount of PM in contact with a unit water volume, (ii) the type and character of the PM (e.g. whether organic or inorganic), and (iii) the contact time between the water and the PM. The time variability of dissolved and particulate matter content in water bodies results mainly from the interactions between hydro-dynamic variability, mineral solubility, PM characteristics and the nature and intensity of biological activity.

### **1.1.3. Biological characteristics**

The development of biota (flora and fauna) in surface waters is governed by a variety of environmental conditions which determine the selection of species as well as the physiological performance of individual organisms. A complete description of biological aspects of water quality is presented in Chapter 5. The primary production of organic matter, in the form of phytoplankton and macrophytes, is most intensive in lakes and reservoirs and usually more limited in rivers. The degradation of organic substances and the associated bacterial production can be a long-term process which can be important in groundwaters and deep lake waters which are not directly exposed to sunlight.

In contrast to the chemical quality of water bodies, which can be measured by suitable analytical methods, the description of the biological quality of a water body is a combination of qualitative and quantitative characterisation. Biological monitoring can generally be carried out at two different levels:

- the response of individual species to changes in their environment or,
- the response of biological communities to changes in their environment.

Water quality classification systems based upon biological characteristics have been developed for various water bodies. The chemical analysis of selected species (e.g. mussels and aquatic mosses) and/or selected body tissues (e.g. muscle or liver) for contaminants can be considered as a combination of chemical and biological monitoring. Biological quality, including the chemical analysis of biota, has a much longer time dimension than the chemical quality of the water since biota can be affected by chemical,

and/or hydro-logical, events that may have lasted only a few days, some months or even years before the monitoring was carried out.

## **1.2. Definitions related to water quality**

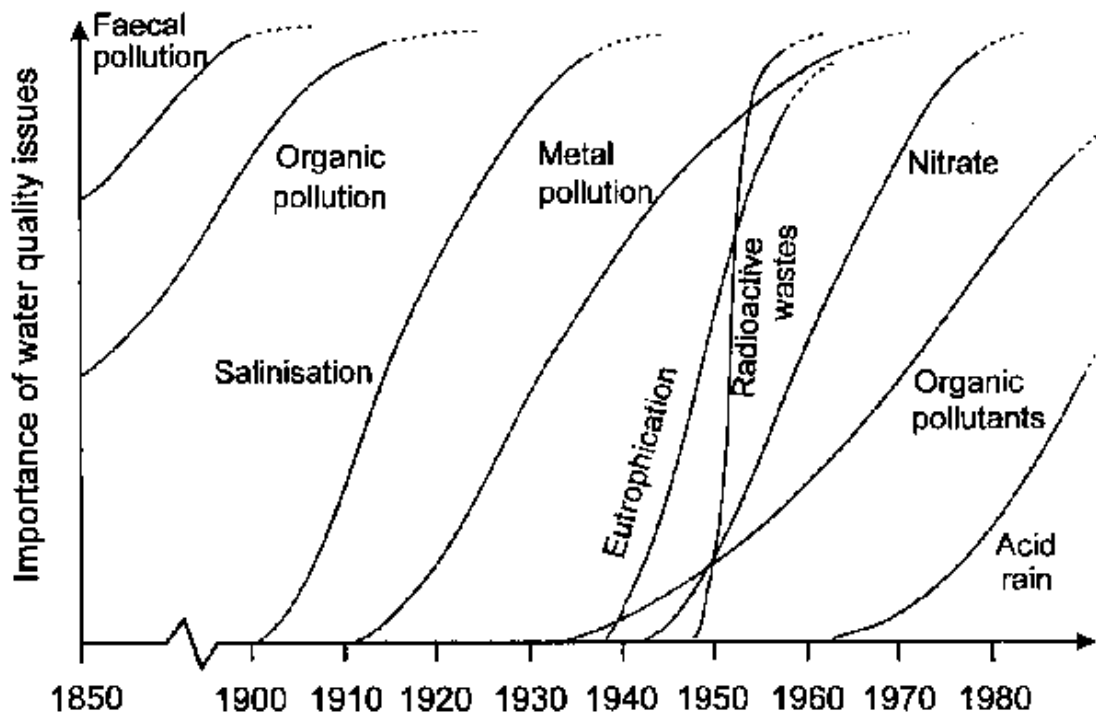
In view of the complexity of factors determining water quality, and the large choice of variables used to describe the status of water bodies in quantitative terms, it is difficult to provide a simple definition of water quality. Furthermore, our understanding of water quality has evolved over the past century with the expansion of water use requirements and the ability to measure and interpret water characteristics. Figure 1.3 demonstrates the evolutionary nature of chemical water quality issues in industrialised countries. For the purposes of this guidebook the following definitions have been accepted:

<b>Term</b>	<b>Definition</b>
QUALITY of the aquatic environment	<ul style="list-style-type: none"> <li>• Set of concentrations, speciations, and physical partitions of inorganic or organic substances.</li> <li>• Composition and state of aquatic biota in the water body.</li> <li>• Description of temporal and spatial variations due to factors internal and external to the water body.</li> </ul>
POLLUTION of the aquatic environment	<p>Introduction by man, directly or indirectly, of substances or energy which result in such deleterious effects as:</p> <ul style="list-style-type: none"> <li>• harm to living resources,</li> <li>• hazards to human health,</li> <li>• hindrance to aquatic activities including fishing,</li> <li>• impairment of water quality with respect to its use in agricultural, industrial and often economic activities, and</li> <li>• reduction of amenities<sup>1</sup></li> </ul>

<sup>1</sup> as defined by GESAMP (1988)

The physical and chemical quality of pristine waters would normally be as occurred in pre-human times, i.e. with no signs of anthropogenic impacts. The natural concentrations (governed by factors described in section 1.1.2) could, nevertheless, vary by one or more orders of magnitude between different drainage basins. In practice, pristine waters are very difficult to find as a result of atmospheric transport of contaminants and their subsequent deposition in locations far distant from their origin. Before pristine waters reach the polluted condition, two phases of water quality degradation occur.

**Figure 1.3. The sequence of water quality issues arising in industrialised countries (After Meybeck and Helmer, 1989)**



The first phase shows an alteration in water quality with evidence of human impact but without any harm to the biota or restriction of water use. Such changes may only be detectable by repeated chemical measurements over long time spans. Typical examples are when  $\text{Cl}^-$  concentrations change from a few  $\text{mg l}^{-1}$  to  $10 \text{ mg l}^{-1}$  (as in Lake Geneva where average concentrations went from  $2 \text{ mg l}^{-1}$  in 1960 to  $6 \text{ mg l}^{-1}$  at present) or when  $\text{N-NO}_3^-$  concentrations change from  $0.1 \text{ mg l}^{-1}$  to  $0.2 \text{ mg l}^{-1}$ . The next phase consists of some degradation of water quality and possible restriction of specific water uses because recommended water quality guidelines (local, regional or global) may be exceeded. Once maximum acceptable concentrations for selected variables in relation to water use have been exceeded, or the aquatic habitat and biota have been markedly modified, the water quality is usually defined as polluted (see example in section 6.7.3).

Description of the quality of the aquatic environment can be carried out in a variety of ways. It can be achieved either through quantitative measurements, such as physico-chemical determinations (in the water, particulate material, or biological tissues) and biochemical/biological tests (BOD measurement, toxicity tests, etc.), or through semi-quantitative and qualitative descriptions such as biotic indices, visual aspects, species inventories, odour, etc. (see Chapters 3, 4 and 5). These determinations are carried out in the field and in the laboratory and produce various types of data which lend themselves to different interpretative techniques (see section 10.3.1). For the purpose of simplicity the term “water quality” is used throughout this book, although it refers to the overall quality of the aquatic environment.

The terms monitoring and assessment are frequently confused and used synonymously. For the purpose of this guidebook and its companion handbook (Bartram and Ballance, 1996) the following definitions are used:

Term	Definition
Water quality ASSESSMENT	The overall process of evaluation of the physical, chemical and biological nature of water in relation to natural quality, human effects and intended uses, particularly uses which may affect human health and the health of the aquatic system itself.
Water quality MONITORING	The actual collection of information at set locations and at regular intervals in order to provide the data which may be used to define current conditions, establish trends, etc.

Water quality assessment includes the use of monitoring to define the condition of the water, to provide the basis for detecting trends and to provide the information enabling the establishment of cause-effect relationships. Important aspects of an assessment are the interpretation and reporting of the results of monitoring and the making of recommendations for future actions (see Chapter 2). Thus there is a logical sequence consisting of three components: monitoring, followed by assessment, followed by management. In addition, there is also a feedback loop because management inevitably requires compliance monitoring to enforce regulations, as well as assessments at periodic intervals to verify the effectiveness of management decisions. The principal objective of the global freshwater quality monitoring project, GEMS/WATER, provides an illustrative example of the complexity of the assessment task and its relation to management (WHO, 1991):

- To provide water quality assessments to governments, the scientific community and the public, on the quality of the world's freshwater relative to human and aquatic ecosystem health, and global environmental concerns, specifically:
  - to define the status of water quality;
  - to identify and quantify trends in water quality;
  - to define the cause of observed conditions and trends;
  - to identify the types of water quality problems that occur in specific geographical areas;
 and
- to provide the accumulated information and assessments in a form that resource management and regulatory agencies can use to evaluate alternatives and make necessary decisions.

### ***1.3. Anthropogenic impacts on water quality***

With the advent of industrialisation and increasing populations, the range of requirements for water have increased together with greater demands for higher quality water. Over time, water requirements have emerged for drinking and personal hygiene, fisheries, agriculture (irrigation and livestock supply), navigation for transport of goods, industrial production, cooling in fossil fuel (and later also in nuclear) power plants, hydropower generation, and recreational activities such as bathing or fishing. Fortunately, the largest demands for water quantity, such as for agricultural irrigation and industrial cooling, require the least in terms of water quality (i.e. critical concentrations may only be

set for one or two variables). Drinking water supplies and specialised industrial manufacturers exert the most sophisticated demands on water quality but their quantitative needs are relatively moderate. In parallel with these uses, water has been considered, since ancient times, the most suitable medium to clean, disperse, transport and dispose of wastes (domestic and industrial wastes, mine drainage waters, irrigation returns, etc.).

Each water use, including abstraction of water and discharge of wastes, leads to specific, and generally rather predictable, impacts on the quality of the aquatic environment (see Chapter 3). In addition to these intentional water uses, there are several human activities which have indirect and undesirable, if not devastating, effects on the aquatic environment. Examples are uncontrolled land use for urbanisation or deforestation, accidental (or unauthorised) release of chemical substances, discharge of untreated wastes or leaching of noxious liquids from solid waste deposits. Similarly, the uncontrolled and excessive use of fertilisers and pesticides has long-term effects on ground and surface water resources.

Structural interventions in the natural hydrological cycle through canalisation or damming of rivers, diversion of water within or among drainage basins, and the over-pumping of aquifers are usually undertaken with a beneficial objective in mind. Experience has shown, however, that the resulting long-term environmental degradation often outweighs these benefits. The most important anthropogenic impacts on water quality, on a global scale, are summarised in Table 1.2, which also distinguishes between the severity of the impairment of use in different types of water bodies.

**Table 1.2.** Major freshwater quality issues at the global scale<sup>1</sup>

Issue	Water body			
	Rivers	Lakes	Reservoirs	Groundwaters
Pathogens	xxx	x <sup>2</sup>	x <sup>2</sup>	x
Suspended solids	xx	na	x	na
Decomposable organic matter <sup>3</sup>	xxx	x	xx	x
Eutrophication <sup>4</sup>	x	xx	xxx	na
Nitrate as a pollutant	x	0	0	xxx
Salinisation	x	0	x	xxx
Trace elements	xx	xx	xx	xx <sup>5</sup>
Organic micropollutants	xxx	xx	xx	xxx <sup>5</sup>
Acidification	x	xx	xx	0
Modification of hydrological regimes <sup>6</sup>	xx	x		x

A full discussion of the sources and effects of each of these pollution issues is available in the relevant chapters of Meybeck *et al.*, 1989

xxx Severe or global deterioration found

xx Important deterioration

x Occasional or regional deterioration

0 Rare deterioration

na Not applicable

<sup>1</sup> This is an estimate for the global scale. At a regional scale these ranks may vary greatly according to the stage of economic development and land-use. Radioactive and thermal wastes are not considered here.

<sup>2</sup> Mostly in small and shallow water bodies

<sup>3</sup> Other than resulting from aquatic primary production

<sup>4</sup> Algae and macrophytes

<sup>5</sup> From landfill, mine tailings

<sup>6</sup> Water diversion, damming, overpumping, etc.

Pollution and water quality degradation interfere with vital and legitimate water uses at any scale, i.e. local, regional or international (Meybeck *et al.*, 1989). As shown in Table 1.3, some types of uses are more prone to be affected than others. Water quality criteria, standards and the related legislation are used as the main administrative means to manage water quality in order to achieve user requirements. The most common national requirement is for drinking water of suitable quality, and many countries base their own standards on the World Health Organization (WHO) guidelines for drinking water quality (WHO, 1984, 1993). In some instances, natural water quality (particularly conditions which occur very rarely; see section 1.1.2) is inadequate for certain purposes as defined by recommended or guideline concentrations (Figure 1.4B). However, other water bodies may still be perfectly usable for some activities even after their natural conditions have been altered by pollution. A very comprehensive collection and evaluation of water quality criteria for a variety of uses has been made, and is being regularly updated, by Canadian scientists (Environment Canada, 1987).

**Table 1.3.** Limits of water uses due to water quality degradation

Pollutant	Use						
	Drinking water	Aquatic wildlife, fisheries	Recreation	Irrigation	Industrial uses	Power and cooling	Transport
Pathogens	xx	0	xx	x	xx <sup>1</sup>	na	na
Suspended solids	xx	xx	xx	x	x	x <sup>2</sup>	xx <sup>3</sup>
Organic matter	xx	x	xx	+	xx <sup>4</sup>	x <sup>5</sup>	na
Algae	x <sup>5,6</sup>	x <sup>7</sup>	XX	+	xx <sup>4</sup>	x <sup>5</sup>	x <sup>8</sup>
Nitrate	xx	x	na	+	xx <sup>1</sup>	na	na
Salts <sup>9</sup>	xx	xx	na	xx	xx <sup>10</sup>	na	na
Trace elements	xx	xx	x	x	x	na	na
Organic micropollutants	xx	xx	x	x	?	na	na
Acidification	x	xx	x	?	x	x	na

xx Marked impairment causing major treatment or excluding the desired use

x Minor impairment

0 No impairment

na Not applicable

+ Degraded water quality may be beneficial for this specific use

? Effects not yet fully realised

<sup>1</sup> Food industries

<sup>2</sup> Abrasion

<sup>3</sup> Sediment settling in channels

<sup>4</sup> Electronic industries

<sup>5</sup> Filter dogging

<sup>6</sup> Odour, taste

<sup>7</sup> In fish ponds higher algal biomass can be accepted

<sup>8</sup> Development of water hyacinth (*Eichhomia crassipes*)

<sup>9</sup> Also includes boron, fluoride, etc.

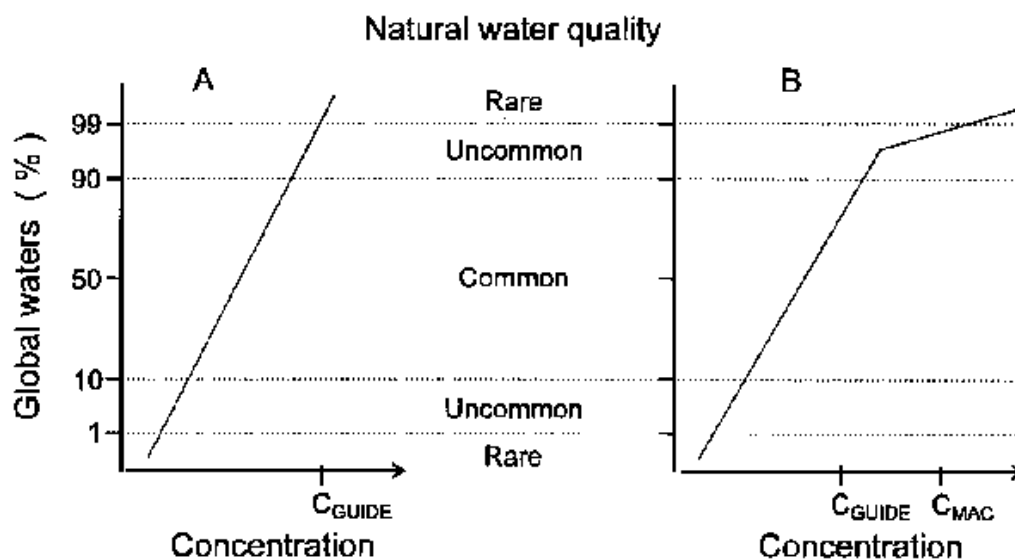
<sup>10</sup> Ca, Fe, Mn in textile industries, etc.

Due to the complexity of factors determining water quality, large variations are found between rivers or lakes on different continents or in different hydroclimatic zones. Similarly, the response to anthropogenic impacts is also highly variable. As a consequence, there is no universally applicable standard which can define the baseline chemical or biological quality of waters. At best, a general description of some types of rivers, lakes or aquifers can be given.

Although the major proportion of all water quality degradation world-wide is due to anthropogenic influences, there are natural events and environmental catastrophes which can lead, locally, to severe deterioration of the aquatic environment. Hurricanes, mud flows, torrential rainfalls, glacial outbursts and unseasonal lake overturns are just a

few examples. Some natural events are, however, aggravated by human activities, such as soil erosion associated with heavy rainfall in deforested regions. Restoration of the natural water quality often takes many years, depending on the geographical scale and intensity of the event. The eruption of Mount Saint Helens, USA in 1980, and the subsequent mud flows, are still having a profound effect on downstream water quality (D. Rickert, US Geological Survey, pers. comm.).

**Figure 1.4. A schematic representation of the statistical distribution of natural waters on a global scale and their suitability for different uses as defined by guideline and maximum allowable concentrations (MAC). A. An element of single natural origin (e.g.  $K^+$ ) and with concentrations always within guideline values. B. An element of more than one natural origin (e.g.  $Na^+$ ) which can occur in concentrations which restrict its use or are too high for most purposes**



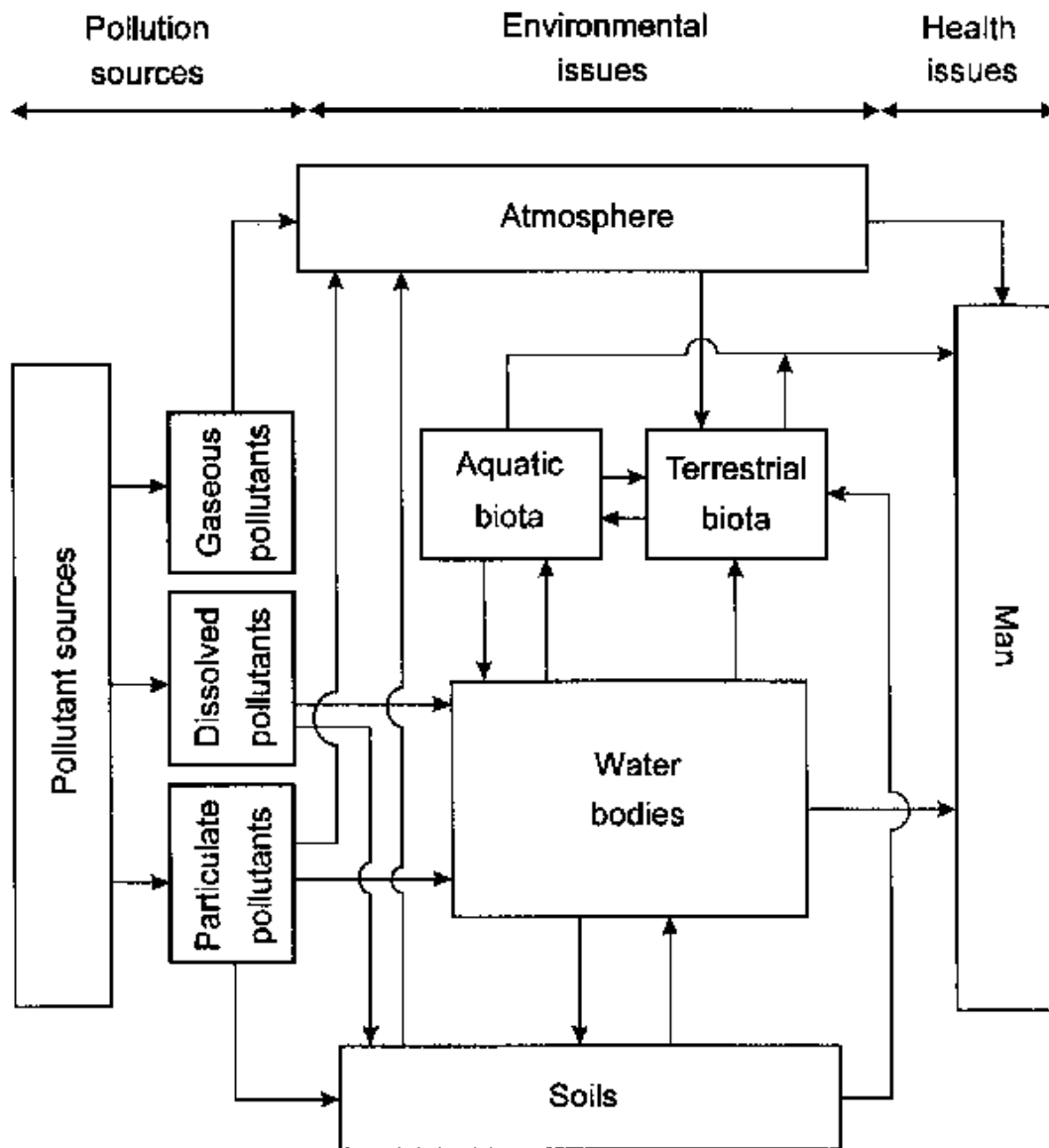
### 1.4. Pollutant sources and pathways

In general, pollutants can be released into the environment as gases, dissolved substances or in the particulate form. Ultimately pollutants reach the aquatic environment through a variety of pathways, including the atmosphere and the soil. Figure 1.5 illustrates, in schematic form, the principal pathways of pollutants that influence freshwater quality.

Pollution may result from point sources or diffuse sources (non-point sources). There is no clear-cut distinction between the two, because a diffuse source on a regional or even local scale may result from a large number of individual point sources, such as automobile exhausts. An important difference between a point and a diffuse source is that a point source may be collected, treated or controlled (diffuse sources consisting of many point sources may also be controlled provided all point sources can be identified). The major point sources of pollution to freshwaters originate from the collection and discharge of domestic wastewaters, industrial wastes or certain agricultural activities, such as animal husbandry. Most other agricultural activities, such as pesticide spraying or fertiliser application, are considered as diffuse sources. The atmospheric fall-out of

pollutants also leads to diffuse pollution of the aquatic environment. The various sources of major pollutant categories are summarised in Table 1.4 and examples of pollution sources for groundwater are presented in Table 9.7.

**Figure 1.5. Potential pollutant pathways related to the aquatic environment**



#### *Atmospheric sources*

The atmosphere is proving to be one of the most pervasive sources of pollutants to the global environment. Significant concentrations of certain contaminants are even being observed in Arctic and Antarctic snow and ice, with high levels of bioaccumulation magnified through the food chain to mammals and native human populations (see Chapter 5). Sources of anthropogenic materials to the atmosphere include:

- combustion of fossil fuels for energy generation,

- combustion of fossil fuels in automobiles, other forms of transport, heating in cold climates and industrial needs (e.g. steel making),
- ore smelting, mainly sulphides,
- wind blown soils from arid and agricultural regions, and
- volatilisation from agriculture, from waste disposal and from previously polluted regions.

**Table 1.4.** Anthropogenic sources of pollutants in the aquatic environment

Source	Bacteria	Nutrients	Trace elements	Pesticides/herbicides	Industrial organic micro pollutants	Oils and greases
<i>Atmosphere</i>		x	xxxG	xxxG	xxxG	
<i>Point sources</i>						
Sewage	xxx	xxx	xxx	x	xxx	
Industrial effluents		x	xxxG		xxxG	xx
<i>Diffuse sources</i>						
Agriculture	xx	xxx	x	xxxG		
Dredging		x	xxx	xx	xxx	x
Navigation and harbours	x	x	xx		x	xxx
<i>Mixed sources</i>						
Urban run-off and waste disposal	xx	xxx	xxx	xx	xx	xx
Industrial waste disposal sites		x	xxx	x	xxx	x

x Low local significance

xx Moderate local/regional significance

xxx High local/regional significance

G Globally significant

These sources, together, provide an array of inorganic and organic pollutants to the atmosphere which are then widely dispersed by weather systems and deposited on a global scale. For example, toxaphene and PCBs (poly-chlorinated biphenyls) have been described in remote lake sediments from Isle Royale, Lake Superior (Swaine, 1978) and in high Arctic ice (Gregor and Gummer, 1989). In the former case, the source was postulated as the southern USA and Central America, whereas in the latter case, the source was believed to be Eastern Europe and the former USSR. Deposition of pollutants from the atmosphere, either as solutes in rain or in particulate form, occurs evenly over a wide area; covering soils, forests and water surfaces, where they become entrained in both the hydrological and sedimentary (erosion, transport and deposition)

cycles. This may be termed secondary cycling, as distinct from the primary cycle of emission into the atmosphere, transport and deposition.

### *Point sources*

By definition a point source is a pollution input that can be related to a single outlet. Untreated, or inadequately treated, sewage disposal is probably still the major point source of pollution to the world's waters. Other important point sources include mines and industrial effluents.

As point sources are localised, spatial profiles of the quality of the aquatic environment may be used to locate them. Some point sources are characterised by a relatively constant discharge of the polluting substances over time, such as domestic sewers, whereas others are occasional or fluctuating discharges, such as leaks and accidental spillages. A sewage treatment plant serving a fixed population delivers a continuous load of nutrients to a receiving water body. Therefore, an increase in river discharge causes greater dilution and a characteristic decrease in river concentration. This contrasts with atmospheric deposition and other diffuse sources where increased land run-off often causes increased pollutant concentrations in the receiving water system.

### *Non-atmospheric diffuse sources*

Diffuse sources cannot be ascribed to a single point or a single human activity although, as pointed out above, they may be due to many individual point sources to a water body over a large area. Typical examples are:

- Agricultural run-off, including soil erosion from surface and sub-soil drainage. These processes transfer organic and inorganic soil particles, nutrients, pesticides and herbicides to adjacent water bodies.
- Urban run-off from city streets and surrounding areas (which is not channelled into a main drain or sewer). Likely contaminants include derivatives of fossil fuel combustion, bacteria, metals (particularly lead) and industrial organic pollutants, particularly PCBs. Pesticides and herbicides may also be derived from urban gardening, landscaping, horticulture and their regular use on railways, airfields and roadsides. In the worst circumstances pollutants from a variety of diffuse sources may be diverted into combined storm/sewer systems during storm-induced, high drainage flow conditions, where they then contribute to major point sources.
- Waste disposal sites which include municipal and industrial solid waste disposal facilities; liquid waste disposal (particularly if groundwater is impacted); dredged sediment disposal sites (both confined and open lake). Depending on the relative sizes of the disposal sites and receiving water bodies, these sources of pollution can be considered as either diffuse or point sources, as in the case of groundwater pollution (see Table 9.7).
- Other diffuse sources including waste from navigation, harbour and marina sediment pollution, and pollution from open lake resource exploitation, in particular oil and gas (e.g. Lakes Erie and Maracaibo).

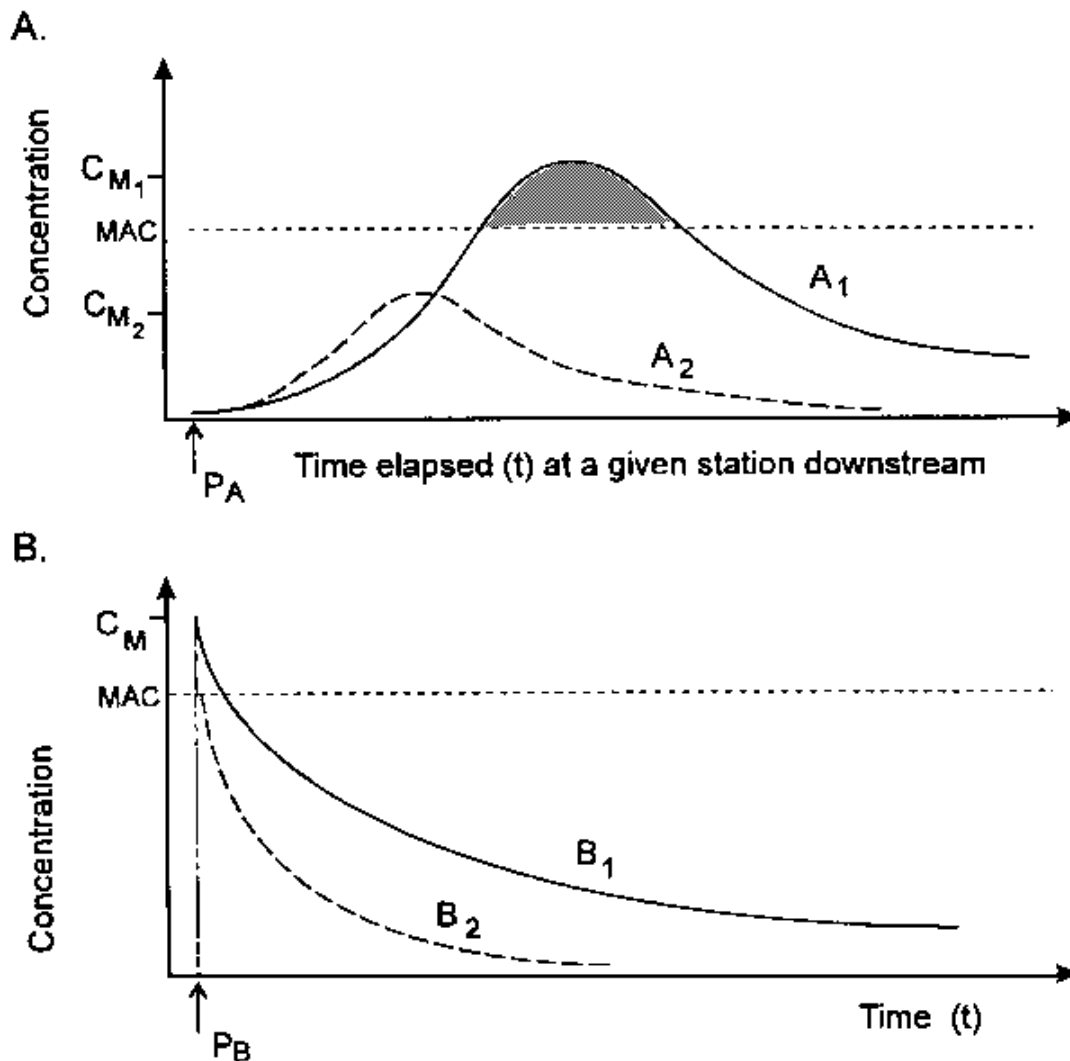
The time variability of pollutant release into the aquatic environment falls into four main categories. Sources can be considered as permanent or continuous (e.g. domestic wastes from a major city and many industrial wastes), periodic (e.g. seasonal variation associated with the influx of tourist populations, or food processing wastes), occasional (e.g. certain industrial waste releases), or accidental (e.g. tank failure, truck or train accidents, fires, etc.). The effects of these various types of pollutants on receiving water bodies are rather different. The continuous discharge of municipal sewage, for example, may be quite acceptable to a river during high discharge periods when dilution is high and biodegradation is sufficient to cope with the pollution load. During low discharges, however, pollution levels and effects may exceed acceptable levels in downstream river stretches. Figure 1.6A shows these two seasonal situations for rivers. The example of the effects of an episodic pollution event on a lake is given in Figure 1.6B which shows the influence of residence time on the elimination of the pollutant from the lake, as measured at its natural outlet. Lake volume and initial dilution are also factors co-determining the prevalence of the pollutant in the lake.

### ***1.5. Spatial and temporal variations***

Spatial variation in water quality is one of the main features of different types of water bodies, and is largely determined by the hydrodynamic characteristics of the water body. Water quality varies in all three dimensions (see section 2.2.1) which are further modified by flow direction, discharge and time. Consequently, water quality cannot usually be measured in only one location within a water body but may require a grid or network of sampling sites.

For practical purposes, i.e. to limit the number of sampling sites and to facilitate the presentation of data, some simplifications to the ideal sampling grid are used. Examples include longitudinal or vertical profiles as shown in Figure 1.7. Two-dimensional profiles are most suitable for observing plumes of pollution from a source, presenting the information either with depth or horizontally in the form of maps. These are particularly applicable to lakes, reservoirs and groundwater aquifers.

Figure 1.6. The influence of hydrodynamic characteristics on the environmental fate of pollutants (CM maximum concentration reached, MAC maximum allowable concentration) A. Schematic response observed at a given river station downstream of a chronic point source of pollution (PA) (non-reactive dissolved substances). High ( $A_2$ ) and low ( $A_1$ ) river discharge. B. Schematic response observed at lake outlets following a single episode of pollution (PB) (non-reactive dissolved substances) for long ( $B_1$ ) and short ( $B_2$ ) residence times in lakes of equal volumes

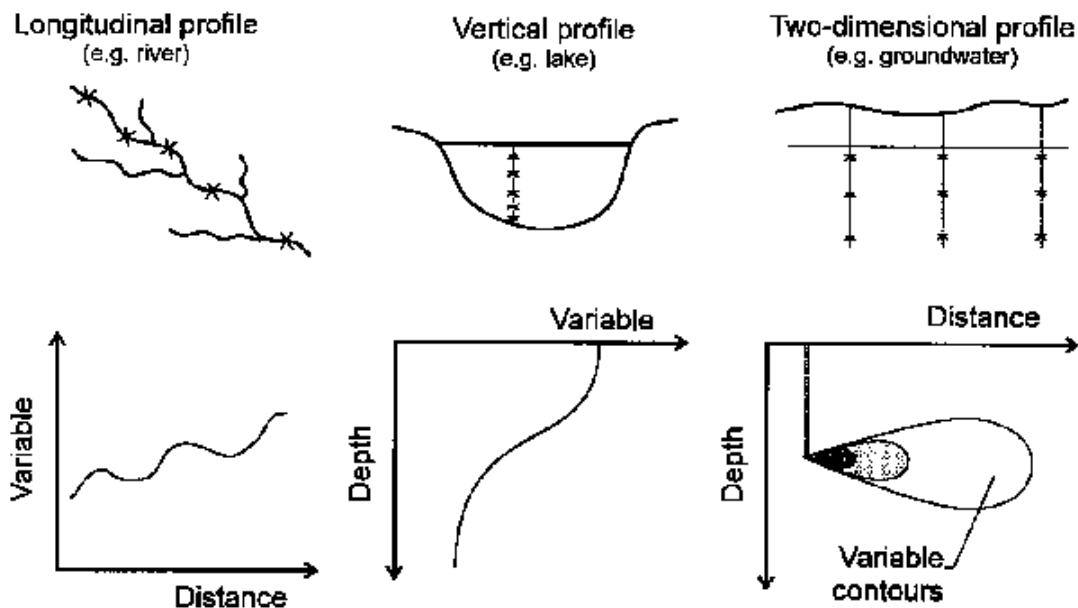


The temporal variation of the chemical quality of water bodies can be described by studying concentrations (also loads in the case of rivers) or by determining rates such as settling rates, biodegradation rates or transport rates. It is particularly important to define temporal variability. Five major types are considered here:

- Minute-to-minute to day-to-day variability resulting from water mixing, fluctuations in inputs, etc., mostly linked to meteorological conditions and water body size (e.g. variations during river floods).

- Diel variability (24 hour variations) limited to biological cycles, light/dark cycles etc. (e.g. O<sub>2</sub>, nutrients, pH), and to cycles in pollution inputs (e.g. domestic wastes).
- Days-to-months variability mostly in connection with climatic factors (river regime, lake overturn, etc.) and to pollution sources (e.g. industrial wastewaters, run-off from agricultural land).
- The seasonal hydrological and biological cycles (mostly in connection with climatic factors).
- Year-to-year trends, mostly due to human influences.

**Figure 1.7 Examples of the description of spatial variations in water quality**



Once the cause of water quality degradation has been removed or reduced (such as the treatment of point sources or the regulation of diffuse sources), the restoration or recovery period of the aquatic environment may take weeks, or even millennia (e.g. some rivers in Wales are still influenced by mine tailings from the Roman period) (Figure 1.8). The temporal and spatial scales of many water quality issues are associated with water residence time (see Figure 1.2). Other issues, however, are hardly linked to water residence time or to water body size; for example, the changes in aquatic habitat downstream of river dams typically last more than 100 years. From the human perspective, a recovery period between 10 and 100 years can be considered as a limited form of reversibility, whereas recovery taking over 100 years can be considered as irreversible degradation of the aquatic environment.

## **1.6. Economic development and water quality**

The continuing increase in socio-economic activities world-wide has been accompanied by an even faster growth in pollution stress on the aquatic environment. Only after a

considerable time lapse, allowing for the public perception of water quality deterioration, have the necessary remedial measures been taken. This historic evolution of water pollution control is reflected schematically in Figure 1.9 which illustrates the general deterioration of the quality of the aquatic environment without any control (AB) and which generally accelerates during industrialisation (BC). If public concern starts early (point B) it takes some time (B-C) for the relevant authorities to initiate control measures. If these measures are insufficient, the rate of increase in pollution is lowered (C-D2), but if the economic activity is still growing, or if the assimilation capacity of the environment (storage, dilution, self purification) is limited, the pollution rapidly reaches the threshold concentration (C-D1) where severe or irreversible damage occurs. If proper action is taken, the pollution reaches a maximum (E) after a time-lag (C-E) which depends on the effectiveness of the control, on the water residence time (evaluation of pollution) and on the pollutant interaction with other “sinks and reservoirs” (including storage). Finally a tolerable environmental level (F) may eventually be reached, although this is not generally equivalent to the pristine level (O).

**Figure 1.8. Schematic representation of the relationship between the spatial scale of water quality issues in different water bodies and the period taken for recovery of aquatic systems after remedial measures have been taken**

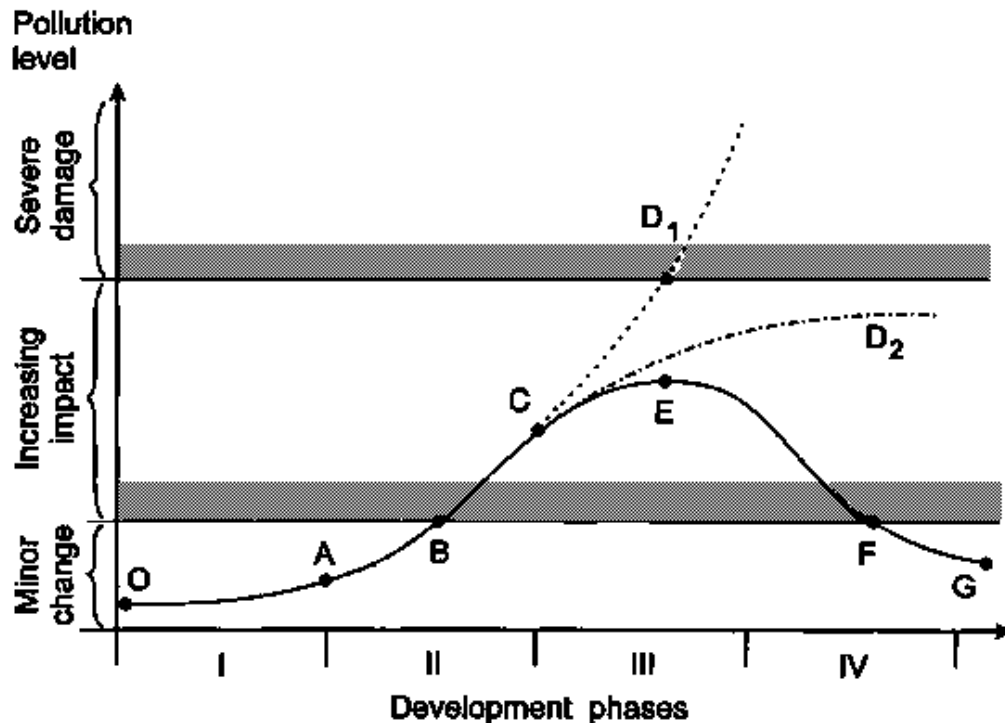
Scale Time of recovery	Local	National	Continental	Global	Reversibility
< 1 year	Rivers				Rapid recovery
1–10 years	Lakes and reservoirs		Acidification		Reversible
10–100 years	Groundwaters		Long range atmospheric pollutant transport		Limited reversibility
> 100 years	Large dams				Irreversible

Four phases of environmental problem development (I to IV) can be identified in relation to progress in socio-economic development (Figure 1.9). In general, this sequence of phases is applicable not only to different types of pollution problems but also to countries at different levels of socio-economic development. A simplified global scheme with three categories of countries can be used for this purpose as follows:

- Highly industrialised countries, which encountered the four phases over a long period of time, starting at about 1850 for some of the issues listed in Figure 1.3.
- Newly industrialising countries, which faced most of the problems in the 1950s or even more recently.

- Low-development countries (with predominantly traditional agricultural economies) which have not yet faced most water quality problems except faecal and organic pollution.

**Figure 1.9 Long-term impact and control of pollution of the aquatic environment (Modified from Meybeck et al., 1989)**



Development phases:

Phase I - a linear increase in low-level pollution with population number (typical pattern for traditional agricultural society)

Phase II - exponential pollution increase with industrial production, energy consumption and agricultural intensification (typical pattern for newly industrialising countries)

Phase III - containment of pollution problems due to the implementation of control strategies (typical pattern for highly industrialised countries)

Phase IV - reduction of pollution problems, principally at the source, to a level which is ecologically tolerable and does not interfere with water uses (desired ultimate situation)

For each of these three categories the occurrence and control of the domestic sewage pollution problem has followed a different time schedule, as indicated in Figure 1.9. The extent to which environmental management services have been installed, and how far they are commensurate with the pollution problems, largely determines the resulting state of the quality of a country's water resources. Furthermore, the different types of pollution problems occur in developing countries in much more rapid succession than in

Europe, due to the modern international trade of chemicals, ubiquitous dispersion of persistent contaminants and changing hydrological cycles, etc. Thus developing countries are, and will be, faced more and more with situations where second and third generation pollution issues appear before much control over “traditional” pollution sources has been achieved.

## **1.7. References**

Bartram, J. and Ballance, R. [Eds] 1996 *Water Quality Monitoring; A Practical Guide to the Design and Implementation of Fresh Water Quality Studies and Monitoring Programmes*. Chapman & Hall, London.

Environment Canada 1987 *Canadian Water Quality Guidelines*. Prepared by the Task Force on Water Quality Guidelines of the Canadian Council of Resource Ministers, Environment Canada, Ottawa.

GESAMP 1988 *Report of the Eighteenth Session, Paris 11-15 April 1988*. GESAMP Reports and Studies No. 33, United Nations Educational, Scientific and Cultural Organization, Paris.

Gregor, D.M. and Gummer, W.D. 1989 Evidence of atmospheric transport and deposition of organochlorine pesticides and polychlorinated biphenyls in Canadian Arctic Snow. *Environ. Sci. Technol.*, **23**, 561-565.

Meybeck, M., Chapman, D. and Helmer, R. [Eds] 1989 *Global Freshwater Quality: A First Assessment*. Blackwell Reference, Oxford, 306 pp.

Meybeck, M. and Helmer, R. 1989 The quality of rivers: from pristine state to global pollution. *Paleogeog. Paleoclimat. Paleoecol.* (Global Planet. Change Sect.), **75**, 283-309.

Nace, R.L. [Ed.] 1971 *Scientific Framework of World Water Balance*. Technical Papers in Hydrology 7, United Nations Educational, Scientific and Cultural Organization, Paris, 27 pp.

Swaine, W.R. 1978 Chlorinated organic residues in fish, water and precipitation from the vicinity of Isle Royale, Lake Superior. *J. Great Lakes Res.*, **4**, 398-407.

WHO 1984 *Guidelines/or Drinking-Water Quality, Volume 2, Health Criteria and other Supporting Information*. World Health Organization, Geneva, 335 pp.

WHO 1991 *GEMS/WATER 1990-2000. The Challenge Ahead*. WHO/PEP/91.2, World Health Organization, Geneva.

WHO 1993 *Guidelines for Drinking-Water Quality, Volume I, Recommendations*. Second edition, World Health Organization, Geneva, 188 pp.

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