Jacques Ganoulis

Risk Analysis of Water Pollution

Second, Revised and Expanded Edition

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Preface to the Second Edition

This second edition of the book brings in new concepts, and approaches to environmental risk analysis with emphasis on water pollution, which have been developed during the last 15 years. The book deals with the quantitative analysis of environmental issues related to the water quality of natural hydrosystems like rivers, lakes, groundwaters and coastal waters. More specifically, issues concerning risk and the reliability of water quality are analysed, mainly from an engineering point of view, and a methodology is developed to evaluate environmental impacts on rivers, groundwater and coastal areas from wastewater disposal and alternative water resources management plans.

According to the new paradigm of water pollution, water quality is closely connected to aquatic ecological and biological characteristics. This is reflected in the new European Union Water Framework Directive (EU WFD 2000/60), where the ecological health of aquatic ecosystems is also an important indicator of 'good water status". In a living environment where there are many risks and where unexpected events may occur, an attempt to apply a rigorous analysis to uncertain and complex environmental issues may appear ambitious. For example what would the effect on algal blooms and eutrophication in a coastal area be, if the pollutant loads from a river doubled? Even in an abiotic environment, issues related to the quality of water resources are complex, unstable and difficult to understand. Even more complicated is the quantitative prediction of coastal water quality from possible climate change (e.g. doubling of the atmospheric CO_2).

It is usually impossible to accurately describe water pollution problems, because available data is incomplete. Mathematical modelling faces difficulties, because of the different types of processes involved, such as hydrodynamic, physico-chemical and biological interactions. Furthermore, the multitude of parameters necessary to describe physico-chemical processes, their physical meaning and their variability in space and time, raises many challenging and intriguing questions.

The study of changes in water quality and the environmental impact of projects related to water resources require adequate methodological tools. Risk and reliability analysis provides a general framework to identify uncertainties and quantify risks. As will be detailed in this book, two main methodologies have so far been developed to analyse natural risks: (a) the stochastic approach and (b) the fuzzy set theory. Stochastic variables and probability concepts are based on frequencies and require large amounts of data. Questions of independence between random variables and validation of stochastic relationships, such as the well-known statistical regression, are usually difficult to resolve. Fuzzy set theory and fuzzy calculus may be used as a background to what should be called ’imprecision theory”. In cases of lack of information or very little data, this book demonstrates how fuzzy numbers and variables may be used for modelling risks. The use of fuzzy regression is a good alternative when statistical regression fails.

Analysis of uncertainties and quantification of risks is not sufficient to formulate and realise environmental projects aiming to improve water quality. It is also important to consider incremental variations in the benefits and costs as functions of risk. This is the risk management issue which will be discussed in relation to the consequences of risk and the decision-making process.

This book started out as lecture notes for a graduate course on risk and reliability in water resources, held at the Division of Hydraulics and Environmental Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki (AUTh). Some of the examples, case studies and research related to this topic go back two decades and are related to the author’s PhD thesis, in which probabilistic modelling was applied to evaluate the risk of the intrusion of a non-wetting fluid into a porous medium.

This book is not exhaustive, nor does it cover all types of water pollution problems. For example questions of water pollution in lakes and reservoirs have been omitted, although such problems are similar to those in semi-enclosed coastal bays and lagoons.

Parts of the first edition of this book were written while the author was on sabbatical leave at the University of Melbourne, Australia, Department of Civil and Agricultural Engineering (1991) and at the ”Laboratoire Enérgetique des Phénomènes de Transfert’ – ENSAM, Bordeaux, France (1992) and accordingly special thanks are given to Professor T. MacMahon, Melbourne, Australia and to Professor M. Combarnous, Bordeaux, France for their support.

The concept of the application of fuzzy set theory to water resources problems emerged from informal discussions with Professor Lucien Duckstein, University of Arizona and Professor Istvan Bogardi, University of Nebraska, USA. I am very grateful for all the information they have provided me with on this matter. I would also like to thank Dr Hans-Joachim Kraus, VCH Publishing Division III, for giving me the opportunity to publish the first edition of this book, and Dr Frank Weinreich, manager of VCH’s Water and Environmental books programme for the opportunity to publish this second edition. Thanks also to Lesley Belfit, Project Editor at VCH, for her help with the design of the book’s cover.

Parts of the first edition of this book were typed by Ms Efi Meimaroglou, Department of Civil Engineering, AUTh, to whom I am very grateful. For the present second edition, my appreciation goes to Petros Anagnostopoulos at the Department of Civil Engineering, AUTh and especially to Katie Quartano at the UNESCO Chair, AUTh for their constructive remarks and technical assistance while reviewing and proof-reading the manuscript.

Thessaloniki, Greece *Jacques Ganoulis*
March 2009

Preface to the First Edition

This book deals with a quantitative analysis of environmental issues related to the water quality of natural hydrosystems. More specifically the questions of risk and reliability in water quality are analysed, from the engineering point of view and a methodology is developed to evaluate environmental impacts on rivers, groundwater and coastal areas from wastewater disposal.

In a biological environment with many risks and unexpected events, an attempt to apply a rigorous analysis to uncertain and complex environmental issues may appear ambitious, if not utopic. In fact, environmental problems related to water resources are complicated, unstable and difficult to understand. What would be, for example, the effect on algal blooms and eutrophication in a coastal area if the pollutant loads from a river doubled? Even more complicated is the quantitative prediction of coastal water quality from a possible climate change (e.g. doubling of the atmospheric CO_2).

Accurate description of water pollution problems is, most of the time, impossible, because available data is incomplete. The different type of the processes involved, such as hydrodynamic, physico-chemical and biological interactions, raise difficulties for mathematical modelling. Furthermore, the multitude of parameters, which are necessary to describe ecosystem's kinetics, their physical meaning and variability in space and time raise a multitude of challenging and intriguing questions.

The study of changes in water quality and the environmental impact of projects related to water resources, requires adequate tools. Engineering risk and reliability analysis provides a general framework to identify uncertainties and quantify risks. As it is shown in this book two main methodologies have been developed so far to analyse natural risks: (a) the stochastic approach and (b) the fuzzy set theory. Stochastic variables and probability concepts are based on frequencies and require large amounts of data. Questions of independence between random variables and validation of stochastic relations, such as the well known statistical regression, are most of the time difficult to resolve. Fuzzy set theory and fuzzy calculus may be used as a background of what we should call "imprecision theory". In this book it is demonstrated how, in case of lack of information or very little data, fuzzy numbers and variables may be used for modelling risks. The use of fuzzy regression is a very good alternative, when statistical regression fails.

Analysis of uncertainties and quantification of risks is not sufficient to formulate and realize environmental projects aiming to improve water quality. It is also important to consider incremental variations of benefits and costs as functions of risk. This is the risk management issue, which is discussed in the book in relation to the consequences of risk and the decision-making process.

The writing of this book started as lecture notes for a graduate course on risk and reliability in water resources, in the Department of Hydraulics and Environmental Engineering, School of Civil Engineering, Aristotle University of Thessaloniki (AUT). Some of the examples, case studies and research related to this topic go back two decades: in relation to the author's PhD Thesis, probabilistic modelling was applied to evaluate the risk of intrusion of a non-wetting fluid into a porous medium.

In this book, no attempt has been made to be exhaustive and cover all types of water pollution problems. For example, questions of water pollution in lakes and reservoirs have been left out, although a similarity exists between such problems and semi-enclosed coastal bays and lagoons.

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The application of fuzzy set theory on water resources problems has emerged, as a concept, from friendly discussions with Prof. Lucien Duckstein, University of Arizona and Prof. Istvan Bogardi, University of Nebraska, USA. I am really thankful for all the information they have provided for me on this matter in the form of papers and lecture notes.

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Thessaloniki, Greece *Jacques Ganoulis*
May 1994

1
Water Resources: Quantity and Quality

Water pollution, together with loss of biodiversity, climate change, energy and socioeconomic issues, is one of the main threats and challenges humanity faces today. Human activities and human-related substances and wastes introduced into rivers, lakes, groundwater aquifers and the oceans modify the environmental water quality and make huge quantities of water unsuitable for various uses. This is the case not only for human-related uses such as drinking, bathing, agricultural irrigation and industrial production but also for terrestrial and aquatic ecosystems for which clean, fresh water is a prerequisite for life.

Water pollution is a serious problem for human health and the environment. The extent of the problem has been confirmed by many reports from UN organisations and related statistics. For example the Global Environment Outlook report (2000) produced by the United Nations' Environment Programme (UNEP) included the following statistics:

- Already one person in five has no access to safe drinking water.
- Polluted water affects the health of 1.2 billion people every year, and contributes to the death of 15 million children less than 5 years of age every year.
- Three million people die every year from diarrhoeal diseases (such as cholera and dysentery) caused by contaminated water.
- Vector-borne diseases, such as malaria, kill another 1.5–2.7 million people per year, with inadequate water management a key cause of such diseases.

Water pollution contributes to the so-called global 'water crisis', because it reduces the available amount of freshwater resources for both people and ecosystems. Freshwater scarcity is already a reality in many parts of the world, not only in developing countries like India, China and many African countries, but also in countries and regions traditionally considered as water rich, such as the USA and Europe. The United Nations (UN) predicts that two-thirds of the world's population will live in water-scarce regions by 2025. The increase in water demand, together with the increase in population in many parts of the world, but mainly the over use of water in areas like agriculture, together with water pollution and climate change are the main driving forces behind this phenomenon.

The quality of water resources and aquatic ecosystem preservation are very much related to the design and operation of hydraulic engineering structures, such as dams, reservoirs and river levees. Until now the design of these structures has paid far greater attention to cost, benefit and safety than to issues of environmental impact. Technical projects such as wastewater treatment plants, management of waste disposal and remediation of contaminated sites, which aim to treat wastewaters and therefore improve water quality, also produce various environmental hazards and risks.

To face real situations of water resources pollution, the efficient application of an environmental impact assessment, including data acquisition, risk analysis and examination of institutional aspects of water resources management, is of crucial importance. In this book the term 'water resources' covers fresh surface water and groundwater, as well as coastal water resources.

Many new techniques for risk assessment and management have been developed recently both in the USA and Europe (Duckstein and Plate, 1987; Ganoulis, 1991c; Haimes *et al.*, 1992; Morel and Linkov, 2006; Hlavinek *et al.*, 2008). These techniques aim to quantify the risks arising from the various uses of water, for example urban water supply, irrigation and industrial processes. However, few of these developments have filtered into academic curricula, and even fewer into engineering practice. The main objective of this book is to present, in a unified framework, methods and techniques of risk and reliability analysis for evaluating the impact on environmental water quality from different water uses, wastewater disposal and water resources management planning.

Risk and reliability analysis has also been used in fields other than engineering, for example in social, economic and health sciences. Risks have been analysed within these disciplines in relation to public policy, administration, financing or public health. Public risk perception, social behaviour and attitudes under risk, risk costs and exposure assessment are some of the major topics of study.

In this book environmental risk and reliability analysis is discussed, as applicable specifically to water pollution in the natural environment. Risk and reliability analysis may also provide a general methodology for the assessment of the safety of water-related engineering projects. In water pollution problems, risk is related to various uncertainties in the fate of pollutants. Thus, risk and reliability assessment of water pollution is a useful tool to quantify these uncertainties and evaluate their effect on water resources. In this respect, the important technical aspects are the management of hydrosystems (rivers, lakes, aquifers and coastal areas) taking into account water quality and environmental impacts, the design of environmental amenities, the management of waste disposal, the optimum operation of wastewater treatment plants and the remediation of contaminated sites.

Important features covered in this book are:

- Uncertainty Analysis of Water Quantity and Quality.
- Stochastic Simulation of Hydrosystems: model selection, water quantity and quality assessment and changes in water quality due to possible climate change in coastal waters, risk of groundwater and river pollution.
- Application of Fuzzy Set Theory in Engineering Risk Analysis.

- Decision Theory under Uncertainty: risk management, risk–cost trade-offs.
- Case Studies.

Environmental water pollution could lead to public health hazards (risk to human health), deterioration of water quality and damage to ecosystems (environmental risk) or may cause economic consequences (economic risk). In this sense, environmental risk and reliability analysis is an interdisciplinary field, involving engineers, chemists, biologists, toxicologists, economists and social scientists. Although there is a strong interaction between these disciplines and for specific applications only team work is appropriate, this book focuses mainly on the technical and engineering aspects of environmental risk.

In this introductory chapter the role of engineering risk and reliability analysis in water pollution problems is further clarified. After stressing the importance of both natural water resources and water quality, environmental risk assessment and management are explained and the organisation of material presented in the following chapters is summarised.

1.1
Water Pollution and Risk Analysis

Risk and reliability have different meanings and are variously applied in different disciplines such as engineering, statistics, economics, medicine and social sciences. The situation is sometimes confusing because terminologies and notions are transferred from one discipline to another without modification or adjustment. This confusion is further amplified as scientists themselves can have different perceptions of risks and use different tools to analyse them.

Risk has different definitions in engineering, economic, social and health sciences. *Risk analysis* is mainly based on the quantification of various uncertainties which may occur in the evolution of different processes. The use of modelling techniques to quantify such uncertainties is an essential part of risk analysis. Furthermore, because preventive and remedial actions should be based on predictions of how processes might develop under uncertainty in the future, probabilistic approaches are more appropriate for this purpose than deterministic methods. Probabilities, and more recently the fuzzy set theory, are suitable tools for quantifying uncertainties which may induce a risk of failure.

Water quantity and quality problems are very much inter-related and should be studied within an integrated framework. Furthermore, water quality is related to the integrity of ecosystems and these should be analysed together. This unified approach has been adopted in this book. After reviewing the importance of water resources and the need for good water quality for sustainable economic development, the management of water resources is analysed. The latter is based on both the design and decision making processes, in which various uncertainties may exist. The concept of quantification of these uncertainties and how one may proceed from the assessment to the management of risks are presented in the following pages and discussed in detail in Chapters 2 and 3.

1.1.1
A Systemic View of Water Resources

The total volume of water on Earth is estimated at 1360 million cubic kilometers or 1338 × 10^6 km^3 (Gleick, 1996 and USGS). This number was derived from a long-term assessment of the average amount of water stored in the hydrosphere, that is, that part of the Earth covered by water and ice, the *atmosphere* and the *biosphere* (all living organisms on Earth). About 70% of the Earth's surface is covered by oceans. The salt water in the seas and oceans represents 97% of the total water on Earth, the remaining 3% being fresh water.

Freshwater is distributed in different components (glaciers, rivers, lakes, groundwater, atmosphere and biosphere) as shown in Table 1.1. From this table it can be seen that the greatest part (68.7%) of total freshwater is trapped in polar glaciers and ice sheets, and is therefore not directly accessible for use. Only 0.3% of the freshwater on Earth is surface water, in the form of lakes (87%) and rivers (2%).

Table 1.1 Distribution of freshwater on Earth.

Source of freshwater (estimate)	Percentage of the total freshwater
Glaciers and permanent snow cover	68.7%
Groundwater	30.1%
Freshwater lakes	0.26%
Rivers	0.006%
Atmosphere	0.004%
Biosphere	0.003%

Water exists in three states: liquid, solid (ice and snow) and gas (water vapour). Due to the energy supplied by the sun, water is permanently being transformed from one state to another, and is in constant motion between oceans, land, atmosphere and biosphere. As shown in Figure 1.1, water in motion constitutes *the hydrologic cycle* through the following hydrological processes, which take place in a permanent manner (UNESCO glossary):

- *Evaporation:* emission of water vapour by a free surface at a temperature below boiling point.
- *Transpiration:* transfer of water vapour from vegetation to the atmosphere.
- *Interception:* process by which precipitation is caught and held by vegetation (canopy and litter structures) and which may then be lost by evaporation without reaching the ground.
- *Condensation:* the change in water phase from a vapour state into a liquid state.
- *Precipitation:* liquid or solid products of the condensation of water vapour falling from clouds or deposited from the air onto the ground. For example rain, sleet, snow, hail.
- *Runoff:* that part of precipitation that appears in surface streams.
- *Infiltration:* flow of water through the soil surface into a porous medium.
- *Groundwater flow:* movement of water in an aquifer.

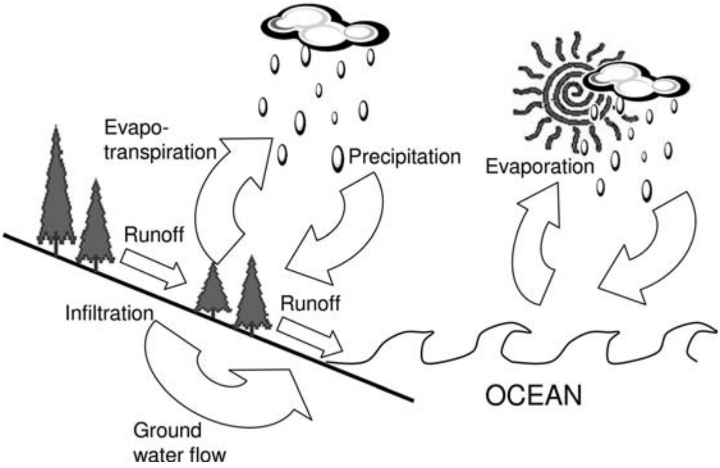

Figure 1.1 The hydrological cycle.

For water resources management in a given hydrological area or at the catchment scale it is necessary to quantify the available water resources for a given time scale. The *water balance* or the *water budget* of a region is the quantification of the individual components of the water cycle during a certain time interval.

What is important for the development of water resources is not the amount of precipitation in an area but rather the so-called *efficient precipitation*. This is the amount of runoff water remaining when *evapotranspiration* is subtracted from the total precipitation. This amount represents the potential water resource and includes the overland flow and water infiltrating the soil. For the EU the mean annual volume of precipitation water is estimated at 1375 km^3/year (97 cm/year) and the efficient precipitation at 678 km^3/year (48 cm/year) (Bodelle and Margat, 1980).

1.1.1.1 Examples of Application

Annual Water Budget of Romania (Table 1.2).

Table 1.2 Annual water budget of Romania (National Institute of Meteorology and Hydrology, Regional Office, Timisoara).

Precipitation	850 mm/year
Runoff	300 mm/year
Evaporation	550 mm/year

Annual Water Budget of Bulgaria (Table 1.3).

Table 1.3 Annual water budget of Bulgaria (Geography of Bulgaria, monograph, Bulgarian Academy of Sciences, 1989).

Precipitation	690 mm/year
Runoff	176 mm/year
Evaporation	514 mm/year

In today's complex economy water resources play a key role. In addition to the fact that fresh water is essential to all kinds of life, it is also used in agriculture and industrial processes. Fresh water is used in settlements to meet domestic demands (Figure 1.2) and also in municipal waste water systems, industrial wastewater treatment plants in agriculture, and for the dissolution and removal of dirt and waste.

A sufficient supply of fresh water has become a necessary condition to ensure economic growth and development. Since it takes 1000 tons of water to produce 1 ton of grain, importing grain is the most efficient way to import water. Countries are, in effect, using grain or other agricultural products to balance their water resources budget.

As demand for water for different uses increases and pollution deteriorates water quality, economic development is put under stress and conflicts result between different 'direct' and 'indirect' users (Figure 1.2). The problem is further exacerbated in regions where long-term droughts have decreased the available amount of water, while the needs for water have increased. At the same time, preservation of good water quality in rivers, lakes, aquifers and coastal waters is necessary to protect public health and ecosystems.

The importance of water resources and problems of water quantity and quality may be better perceived by analysing the economic importance of water and the new

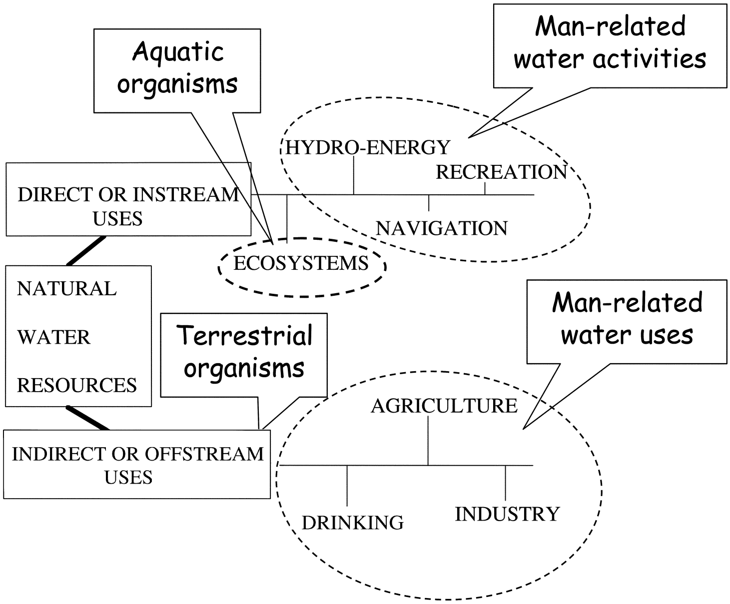

Figure 1.2 Direct and indirect uses of water resources by man and ecosystems.

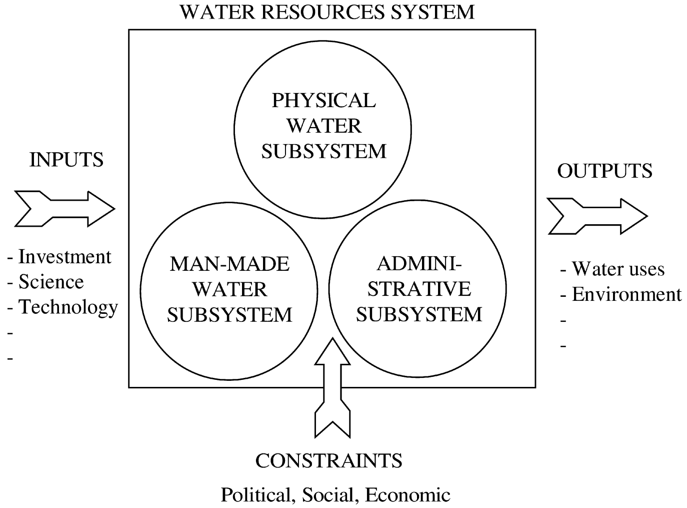

Figure 1.3 Description of a water resources system.

opportunities in the *water market*. In the EU it has been estimated (Williams and Musco, 1992) that the costs of running municipal water supply and wastewater systems alone are 14 billion Euros per year. For the implementation of the municipal wastewater and drinking water directives in the EU, including its new members, several hundred billion Euros will be needed in the near future. To face the problems of future water demand and to combat growing pollution it is expected that the already huge market for water will be expanded further with new technologies, new investments and new management methods.

When considering management issues of water-related problems it becomes apparent that besides scientific and technical components there are also social, economic and institutional components involved (Figure 1.3).

If water resources are defined as a system (Figure 1.3), apart from the natural water subsystem, man-made water subsystems (channels, distribution systems, artificial lakes, etc.), as well as the administrative system, should also be included. These three subsystems are interconnected and are subject to various social, political and economic constraints (Figure 1.3). Inputs to the system are data, investment, science and technology and outputs are water uses, environmental protection, new technologies, and so on.

1.1.2
The New Paradigm of Water Quality

In water resources management water quality plays an increasingly important role, just as important as that of water quantity. In fact, as pollution of surface, coastal and groundwater increases, it has become essential to adopt an integrated approach encompassing both water quantity and quality (Figure 1.4).

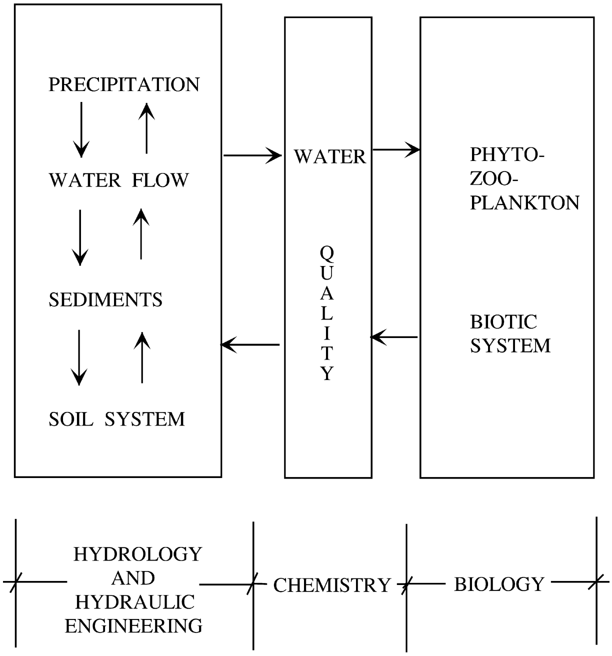

Figure 1.4 Elements of abiotic and biotic water systems.

Furthermore, according to the new paradigm of water quality, the ecological status of a water body should also be taken into consideration. This means that a good status of water biology and healthy aquatic organisms are necessary for obtaining a good status of water quality, and vice versa optimum physico-chemical conditions of water resources are necessary to sustain healthy ecosystems.

This integrated definition of the 'good status of water' was adopted in the new EU-Water Framework Directive 2000/60, which means that the environmental protection of water resources requires joint investigations of both abiotic and biotic elements.

For example in coastal regions, the most serious environmental problems in order of priority are:

(1) Decrease in water transparency as a result of high concentrations of organic elements, suspended matter and nutrients.
(2) Oxygen depletion, due to excessive demand for oxygen from organic matter, nitrogen and phosphorus. As oxygen is an essential requirement for both predatory and non-predatory organisms, a low oxygen concentration may comprise the existence of marine life.
(3) Bacteriological contamination, which poses a threat not only to water but also to shellfish and oysters. This represents a major danger to public health.
(4) Loss of habitat and invasion of tropical species. In the Mediterranean, the appearance of new species of algae is attributed to excessive pollution.

(5) Eutrophication phenomena due to the increase of nutrients, such as nitrogen and phosphorus.

The social causes of these problems are mainly due to the increase in coastal populations and also intensive agricultural, industrial and harbour activities in coastal areas. Preserving water quality in this integrated manner safeguards human well-being and health and at the same time maintains diversity in the biota. In coastal area, fishing and other aquacultures are traditional and very important economic activities, employing and feeding large populations, especially on islands. Tourism forms an important part of the economy in many European countries and is directly related to the quality of marine resources. The importance of these aspects is discussed below.

1.1.2.1 **Human Well-being and Health**

Although water quality has a direct impact on the actual health of urban populations, there are also extremely important indirect impacts through the food chain. Catches of fish and oyster farming in polluted coastal areas may introduce bacterial or toxic metal contamination into the human food chain, causing epidemiological occurrences. Even in cases where contamination remains tolerable, the presence of pollutants may cause abnormal growth of certain algae in the water body, causing oxygen depletion (eutrophication). Fish feeding on these algae may suffer adverse changes in flavour or odour, and become unsuitable for human consumption. In addition, decaying algae produce H_2S and other odorous substances which may affect the well-being of the population living along the water body. The important interplay between water quality and human settlements on the coast is exemplified by the total absence of permanent habitation around the Dead Sea. The quality of water there is so poor that not only does it not attract people, but it actually turns them away.

1.1.2.2 **Ecological Impacts and Biodiversity**

A rich variety of organisms inhabit the world's fresh, coastal and oceanic waters. Generally, these may be divided into producers (e.g. phytoplanktonic diatoms, flagellates, etc.) and consumers of organic matter (e.g. zooplankton, nekton, benthos, etc.). In addition, there are also different types of bacteria, in concentrations ranging from one per litre to more than 10^8 per millilitre. Generally, bacteria do not contribute significantly to nutrient recycling in the water column but mainly in the sediments (Odum, 1971).

Areas containing water play an important role in trapping solar energy and in the transformation of biological matter. Species diversity in the water column is directly related to water quality. Studies by Copeland and Bechtel (1971) have shown a paucity of biodiversity in areas close to effluent outfalls, with the effect diminishing with distance. Also, water toxicity was found to be inversely related to species diversity in the water body.

Copeland (1966) has reported that in polluted waters the levels of various industrial wastes found in fish increase, even when the effluent has not yet reached toxic levels. This is because the reduction in the concentration of dissolved oxygen, caused by the discharge of biological matter around the outfall, forces fish to pump more water through their gills and thus absorb greater quantities of pollutants. This may then have a knock-on effect on the rest of the biota through the food chain.

1.1.2.3 **Fishing and Oyster Farming**

Water quality is very important for fishing and the aqua culture industry, especially shellfish farming. It is well known that organisms living in water accumulate pollutants from the surrounding water in their flesh and pass them into the food chain. This is particularly so for mussels, oysters and other stationary marine animals growing in polluted waters. For this reason, for some time now legislation has stipulated the allowable quality of water for oyster farming.

1.1.2.4 **Tourism**

Regions having a pleasant climate and a rich cultural heritage usually attract tourists. The Mediterranean countries, for example enjoy substantial tourist influxes. It is estimated that as much as one-third of the world tourist traffic concentrates there (Golfi *et al.*, 1993). The coastal strip has become a major attraction for tourist recreation, in the form of bathing, sport fishing and water sports. As a result, tourism has become a major contributor to the local economy.

The tourist economy in these areas, however, is jeopardised by inadequate water infrastructure, such as municipal water supplies and efficient wastewater treatment facilities. This frequently results in deterioration of the quality of coastal water, which was one of the primary factors attracting tourists in the first place. An example of the problems which may result from unsatisfactory water resources management was the damage to the tourist industry on the North Adriatic coast in the late 1980s, due to the occurrence of severe seasonal algal blooms, caused by abnormally high eutrophication and warm ambient temperatures.

If it were not for the substantial amounts of man-made pollution discharged into water bodies in modern times, nature itself would be able to provide a continuous recycling of biological matter in natural waters.

Groundwater contamination is the most critical among the various types of pollution that can occur in the water cycle, because of the long time scales involved and the irreversible character of the damage caused. Due to the very slow movement of groundwater, pollutants can reside for a very long time in the aquifer, and even if the pollutant sources are no longer active the groundwater can remain polluted for centuries. At the same time, because of the complex interaction between pollutants, soil and groundwater, the remediation of contaminated subsurface is a very delicate operation. Usually it is necessary to totally remove and clean the contaminated soil or for biological techniques to be applied over a long period of time.

For surface water resources, in addition to the inherent biological loading from natural recycling of carbonaceous matter, further inputs from the land may arise in the form of

- large amounts of sediments, resulting from increased soil erosion due to the substantial deforestation in historical times, especially in Mediterranean countries;
- inorganic and organic pollutants, mainly nitric or phosphoric fertilisers, pesticides or herbicides used in farming. These result in a substantial contribution and are estimated to account for most of the overall water pollution (USEPA, 1984; ASIWPCA, 1985);
- organic, microbial or toxic man-made pollutants such as heavy metals or greases discharged from sewers.

Of these loads, heavy metals and toxic constituents tend to be chemically inactive and are removed mainly by mechanical or physical processes (e.g. sedimentation, adsorption onto solid particles or surfaces immersed in the water, etc.), whereas organic and other inorganic substances decay via numerous and very complicated chemical and biological processes.

All pollution loads, whether natural or man-made, are subject to the influence of water circulation currents. This results in advection and turbulent dispersion in the water body, following the laws of conservation of mass for each constituent substance in the system.

Advection occurs by turbulent mass transport within the water, while additional diffusion and turbulent dispersion of pollutants takes place. In addition, the pollutants are subject to different types of decay, such as

- chemical, as a result of the oxidising effect of oxygen dissolved in the water, and by mutual neutralisation between acidic and alkaline pollutants;
- biological, arising from metabolism by microbes, phyto- or zooplankton.

Overall, all these processes are extremely complicated and with the exception of water advection and circulation, not understood in any great detail. Therefore, much of the following discussion is based predominantly on empirical findings from experiments.

According to Rafailidis *et al.* (1994) of particular interest to engineers in the field of surface water resources are the concentrations

- The *Carbonaceous Biochemical Oxygen Demand* (CBOD). This is an indicator of the overall 'loading' of the aquatic system due to the oxidation requirements of organic pollutants. It also includes the respiration demand of marine microbes which metabolise organic and fix inorganic matter (e.g. nitrates, inorganic phosphorus, etc.).

- The *Dissolved Oxygen* content (DO). This parameter is more critical because it shows whether there is sufficient oxygen in the water for marine life to survive. The actual DO content reflects the equilibrium between re-aeration at the surface added to photosynthetic oxygen generated by chlorophyll in the water body, minus the biological and any chemical oxygen demand. Generally, most marine fauna will swim away from waters in which DO has fallen to less than about 5 mg/l. Nevertheless, some types of worms have been found to survive in virtually anoxic sediments in river deltas or heavily polluted areas around effluent outfalls.

- The *concentration of nutrients* (ammonia, nitrates, phosphates, inorganic nitrogen or phosphorus) is linked directly to non-point source runoff from agricultural watersheds as a consequence of soil fertilisation, insecticide or pesticide spraying, and so on. Nutrients are metabolised by marine microorganisms and the inorganic elements are fixed to more complex compounds. Algae play a very important role in these processes, enhancing water denitrification (release of N_2 to the atmosphere) or nitrification (capture of N_2 from air).
- *Ammoniac* compounds are antagonistic to nitrates, as both compete for algal uptake. On the other hand, the simultaneous presence of phosphorus enhances algal growth, leading to eutrophication, that is, abnormal growth of algae and marine flora. This is particularly troublesome in enclosed waters (e.g. lakes and lagoons) but also occurs in coastal areas suffering from large pollution inflows and suppressed natural circulation and flushing.
- The *coliform bacteria concentration*. Although these microorganisms are not pathogenic and exist naturally in human intestines, their presence indicates pollution due to urban sewage effluents. However, doubts have been voiced about the suitability of this parameter as an indicator of *pathogenic* potential in coastal waters (Sobsey and Olson, 1983). This is because pathogenic viruses have lower decay rates than coliforms, and can also cause infection at smaller doses. Furthermore, whereas coliforms are of human origin, some opportunistic pathogens (e.g. *Pseudomonas Aeruginosa*, *Legionella Pneumophila*) also often originate from non-fecal sources and can grow naturally in various waters (Bowie *et al.*, 1985). Upon discharge into the water body environmental conditions such as temperature and sunlight determine the eventual fate of coliform bacteria through a multitude of processes (e.g. photo-oxidation, sedimentation, pH, predators, algae, bacteriophages, etc.).
- Apart from the above pollutants, sediments in the water column may also cause environmental problems as they bury benthic flora, or choke the gills of marine invertebrates. In fact, coastal areas at the deltas of large rivers typically suffer from anoxic conditions (Nelsen, 1994) due to oxygen demand from the large sediment and that required for the transport of biological matter. This is in addition to the polluting effects of any other organic or inorganic nutrients carried by the river.

In summary, CBOD in surface waters indicates the overall organic pollution of the water, DO shows whether marine life may be sustained there, and nutrient concentration gives the potential for eutrophication. Coliform counts indicate the danger of disease for humans using the water for bathing or recreation.

1.1.2.5 **Algal and Chlorophyllic Photosynthesis**

Phytoplankton exists in many different forms (e.g. diatoms, green algae, blue-green algae, dinoflagellates, etc.) and form an important part of the water ecosystem determining eventual water quality. Algae are primarily responsible for the uptake of nutrients, which are then recycled through algal respiration and decay.