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Water Resources: Quantity and Quality

Water pollution, together with loss of biodiversity, climate change, energy and socio-economic 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.

Risk Analysis of Water Pollution: Second, Revised and Expanded Edition. Jacques Ganoulis

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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 $1338 \times 10^6\,\text{km}^3$ (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.

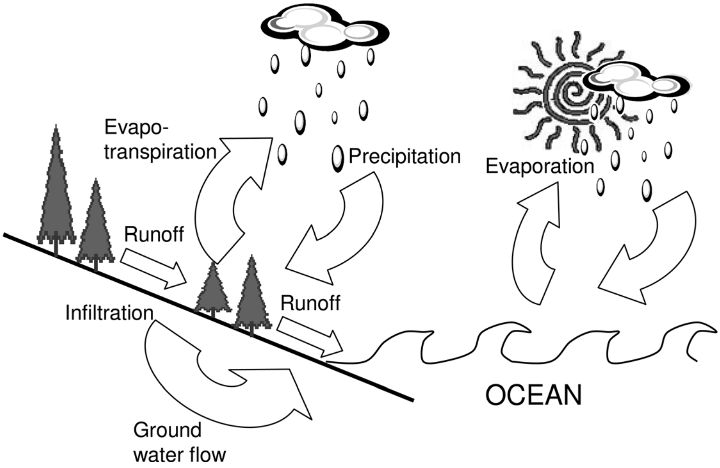

Figure 1.1 The hydrological cycle.

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

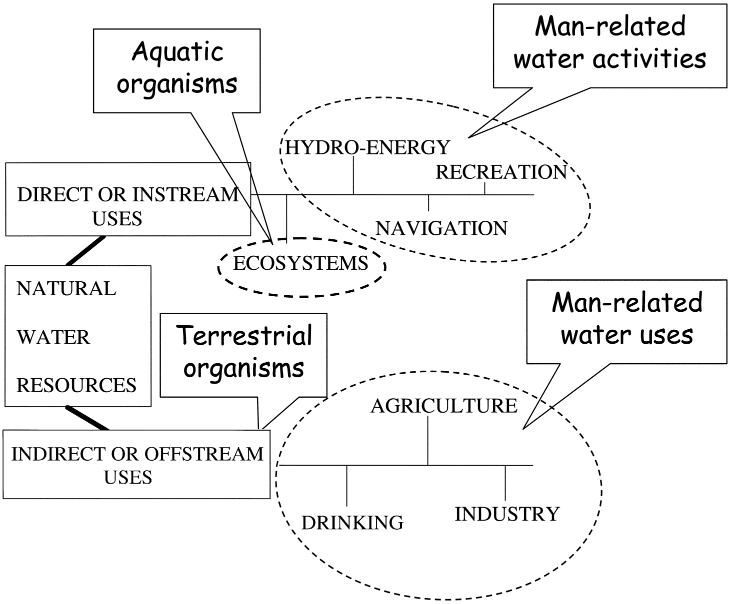

Figure 1.2 Direct and indirect uses of water resources by man and ecosystems.

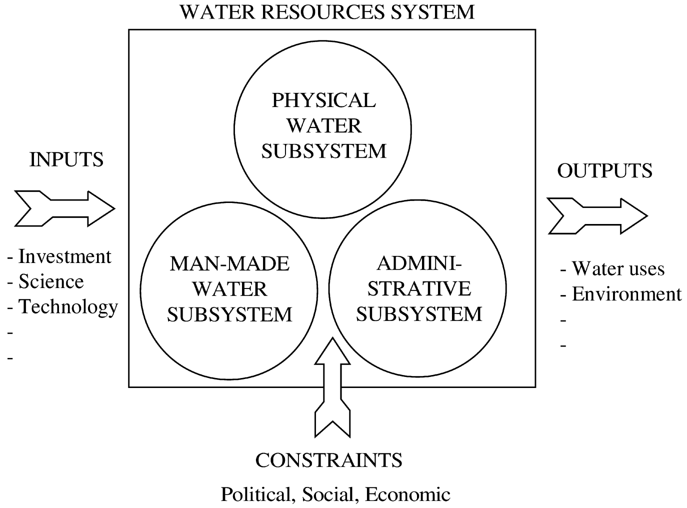

Figure 1.3 Description of a water resources system.

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).

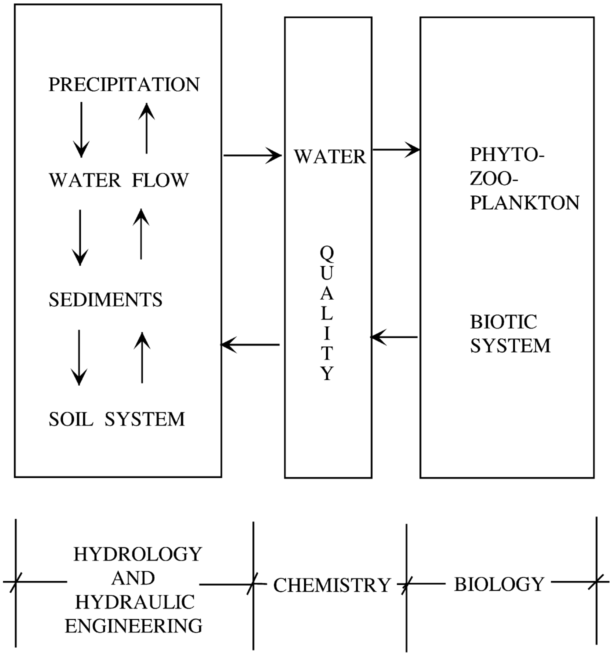

Figure 1.4 Elements of abiotic and biotic water systems.

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.

Photosynthesis by algae in the euphotic zone produces oxygen; this is reversed at night due to respiration.

On the other hand, algae which settle in deeper, oligophotic waters contribute to oxygen depletion there. Algae either take up dissolved CO_2 or produce CO_2 as a by-product of respiration, thus changing water pH and the subsequent chemical interactions in the water. Their presence increases water turbidity, reducing the euphotic depth in the column. On the other hand, phytoplankton constitutes the foundation of the food chain of higher species, virtually supporting the marine animal biota.

Because of the variety of different algae, it is customary to consider algal concentrations in terms of chlorophyll-a concentrations. Algal growth is a function of temperature, solar insolation and nutrients (phosphorus, nitrogen, carbon and silicon for diatoms). Other essential nutrients such as iron, manganese, sulphur, zinc, copper, cobalt, molybdenum and vitamin B_{12} may also be important, especially in oligotrophic waters.

1.1.2.6 **Zooplankton Growth**

Zooplankton are part of the same biomass pool as phytoplankton. Zooplankton dynamics depend on growth, reproduction, respiration, excretion and non-predatory mortality. In contrast to phytoplankton, zooplanktonic organisms are mobile, so settling does not occur. Furthermore, zooplankton migrate vertically following the diurnal cycle, adding another complication to the analysis.

Growth, consumption, respiration and non-predatory mortality are direct functions of temperature. Zooplanktonic animals are typically filter feeders. Therefore, zooplankton growth may be simply considered as being proportional to the available food concentration. Predation is also related to the rates of consumption by higher predators.

1.1.2.7 **Bacteria**

Coliform growth and decay depend mainly upon environmental conditions through a variety of mechanisms. These include physical (e.g. photo-oxidation, coagulation, sedimentation), physico-chemical (e.g. pH, osmotic effects) and biochemical-biological (e.g. nutrient levels, predators, algae, bacteriophages) factors.

The interplay between these factors is poorly understood, especially quantitatively. Because of this limitation, coliform growth and decay have traditionally been assessed on the basis of the first-order approach of the T-90 measured values, that is, the exposure required to ensure 90% mortality. Care must be taken, however, because bacterial decay in the dark is only approximately half of that at midday (Bowie *et al.*, 1985). Apart from this sensitivity to light, measurements have also detected a sensitivity to water salinity. As in all other physico-bio-chemical processes, temperature also plays an important role (Ganoulis, 1992).

1.1.3
Integrated Water Resources Management

Water Resources Management is traditionally defined as a process of effectively allocating an appropriate amount of water to a given sector, such as urban water

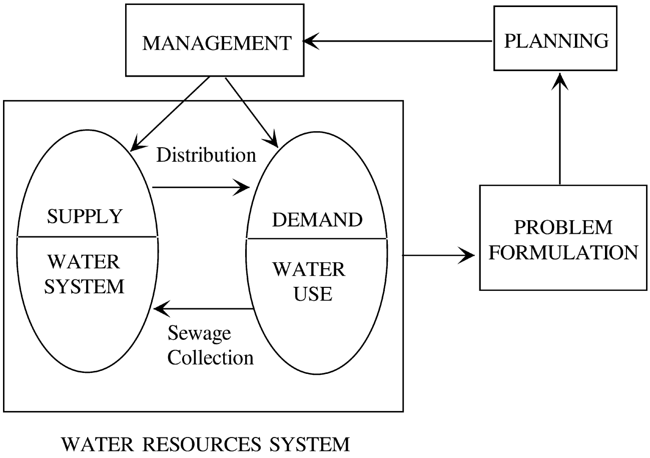

Figure 1.5 Urban water resources management.

supply, agriculture or industry. Adequate decisions should be made and measures taken in order to satisfy the demand for water both in terms of quantity and quality.

In urban water supply for example, decisions on structural and non-structural measures should be taken in order to ensure good drinking water for all citizens. As shown in Figure 1.5, satisfying the demand whilst collecting municipal wastewater and providing adequate treatment for environmental protection, constitute parts of the urban water management problem. Management of urban water resources involves addressing not only technical issues but also many social factors, institutions and administrative procedures.

The main objective of water resources management is to satisfy the demand, given the possibilities and limitations of the water supply. The balance between supply and demand should take into consideration both water quantity and quality aspects as well as the protection of the environment.

As seen in Figure 1.5 water resources management involves problem formulation, planning, implementation of appropriate measures, regulation of both water demand and supply and finally decision making. The various steps involved in this process are described schematically in Figure 1.6. Implementation of the design and decision stages involves the following processes:

Step 1: Identify the problem. Analyse important factors and variables.
Step 2: Determine the objectives in terms of the above variables.
Step 3: Develop a mathematical model correlating input–output variables.
Step 4: Identify alternative options.
Step 5: Select the optimum solution.
Step 6: Employ sensitivity analysis, that is, examine the influence on the results of any change in the value of parameters and the assumptions made.

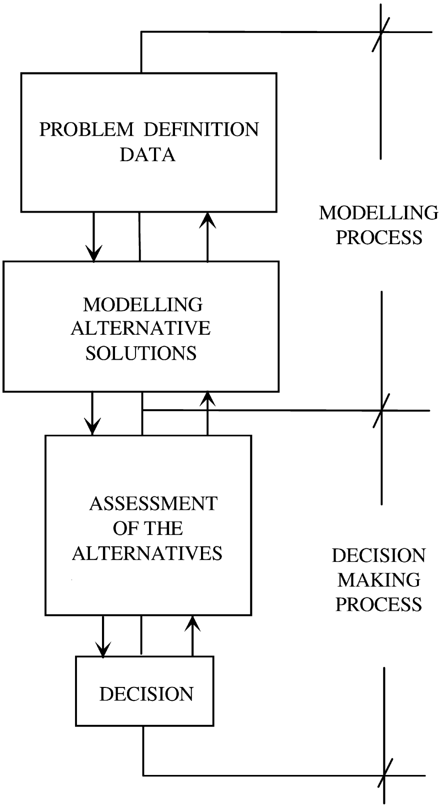

Figure 1.6 Modelling and decision making processes in water resources management.

At the river catchment scale, different uses of water, such as for drinking, agricultural irrigation, hydropower production and industry, often lead to conflicting situations. For example industries producing large amounts of untreated wastewater may pollute groundwater in the surrounding aquifer, which in turn affects the quality of water pumped for drinking purposes. The increase in water pollution from industrial activities may also affect the quality of river water used for irrigation. When groundwater is over-pumped from a series of wells, the groundwater table is lowered and could affect agricultural production, as less water will be available for crop roots. Lowering the water table in a coastal zone may also increase seawater intrusion and soil salinisation, leading to a negative impact on agriculture and ecosystems.

Obviously, when actions are taken for different water uses, as can be seen in the examples above, there is a need to coordinate the various aspects of the related activities, such as between different:

- *sectors of water uses* (water supply, agriculture, industry, energy, recreation, etc.);
- *types of natural resources* (land, water and others);
- *types of water resources* (surface water, groundwater);

- *locations in space* (local, regional, national, international);
- *variations in time* (daily, monthly, seasonal, yearly, climate change);
- *impacts* (environmental, economic, social, etc.);
- *scientific and professional disciplines* (engineering, law, economy, ecology, etc.);
- *water-related institutions* (government, private, international, NGOs, etc.);
- *decision-makers, water professionals, scientists and stakeholders.*

As shown in Figure 1.7, Integrated Water Resources Management (IWRM) can be achieved by coordinating different topics, areas, disciplines and institutions, which can be categorised as being either natural (type of resources, space and time scales) or man-related (sectors, scientific disciplines, impacts, institutions, participants). There is no general rule about the optimum degree of integration and how to achieve it. Concerning the spatial scale and taking into account the hydrological cycle and the water budget, the area of the river basin is the most relevant water management unit. The effect of possible climate change should also be taken into account, although major uncertainties still persist for quantifying such effects.

The need for coordination in Water Resources Management was first recognised in the 1970s and the actual term 'Integrated Water Resources Management' (IWRM) was first coined in 1977 at the UN Conference in Mar del Plata. The term is very broad, and is therefore subject to different definitions.

In the Background Paper No. 4 produced by its Technical Committee (TEC), The Global Water Partnership (GWP) – an NGO based in Stockholm – defines IWRM as 'a process which promotes the coordinated development and management of water, land and related resources to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems'. (GWP, 2000). The 'Tool Box' being developed by GWP promotes IWRM and makes recommendations on how it can be achieved (GWP, 2002, 2004).

The World Water Council (WWC) stated that IWRM is a 'Philosophy that holds that water must be viewed from a holistic perspective, both in its natural state and in balancing competing demands on it – agricultural, industrial, domestic and environmental. Management of water resources and services needs to reflect the interaction between these different demands, and so must be coordinated within and across sectors. If the many cross-cutting requirements are met, and if there can be horizontal and vertical integration within the management framework for water resources and services, a more equitable, efficient and sustainable regime will emerge' (Global Water Partnership, Framework for Action 1999).

At the World Summit in Rio (1992), a special reference was made to IWRM. In the action programme known as Agenda 21 adopted at the Conference, in Chapter 18, Paragraph 18.6 it is stated that "... the holistic management of freshwater as a finite and vulnerable resource, and the integration of sectoral water plans and programmes within the framework of national economic and social policy, are of paramount importance for action in the 1990s and beyond". The fragmentation of responsibilities for water resources development among sectoral agencies is proving, however, to be an even greater impediment to promoting integrated water management than had been anticipated. Effective implementation and coordination mechanisms are required.

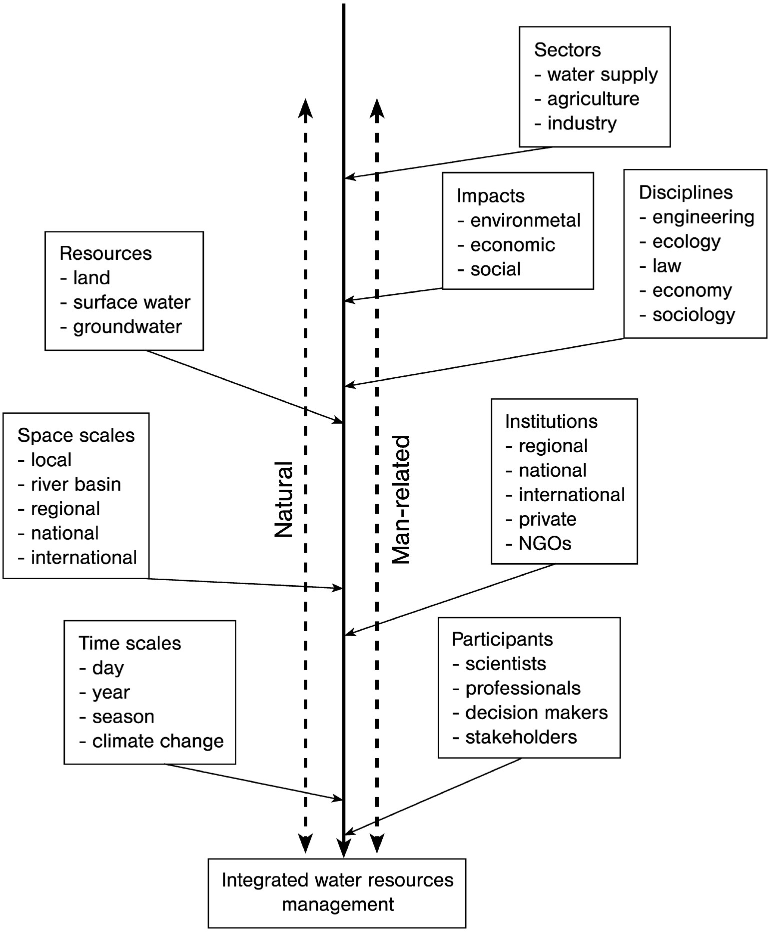

Figure 1.7 Natural and man-related issues of IWRM.

Water resources development and protection, and more particularly IWRM, is one of the main elements for achieving ‘sustainable development’. According to the Brundtland Commission (1987) sustainable development should satisfy current needs without compromising the requirements of future generations. For water resources, sustainable management may be defined as using water for various needs without compromising its hydrologic, qualitative and ecological integrity. Sustainability can be achieved by resolving environmental, economic and social issues related to water management.

Sustainability may be viewed as an ultimate goal, but it is one which is very difficult to achieve. It is therefore important to define quantitative sustainability indices in order to measure and record the progress achieved or the degradation observed in different domains. A risk assessment approach using four risk indices (technical or engineering, economic, environmental and social) is proposed in order to monitor quantitatively the degree to which IWRM achieves sustainable water resources management and sustainable development (Ganoulis, 2001).

1.2
Water Pollution in Transboundary Regions

Two types of border dividing the territory of different states within a river basin are shown in Figure 1.8:

(1) Borders cross the river at a point and divide the river catchment in two areas, the upstream and the downstream. In this case, there is no joint sharing of one river section by the two states. This is the case of the border between Hungary and Serbia at points crossed by the Danube and Tisza Rivers or the border between Greece and the Former Yugoslav Republic of Macedonia (FYROM) crossed by the Vardar/Axios) River near the city of Gevgelia (Figure 1.8a).

(2) Rivers serve as borders between states, as in the case of the lower course of the Danube River, which serves as the border between Bulgaria and Romania (Figure 1.8b); and borders that follow and also cross international rivers.

How the interstate borders follow and/or cross international rivers, and how they divide rivers and river basins, will determine what type of water resources problems exist or will likely arise and need bilateral or multilateral interstate solutions. For transboundary waters, a large number of international agreements for solving various types of interstate water resources problems are available. The most important international treaty is the United Nations Economic Commission for Europe (UNECE) Convention.

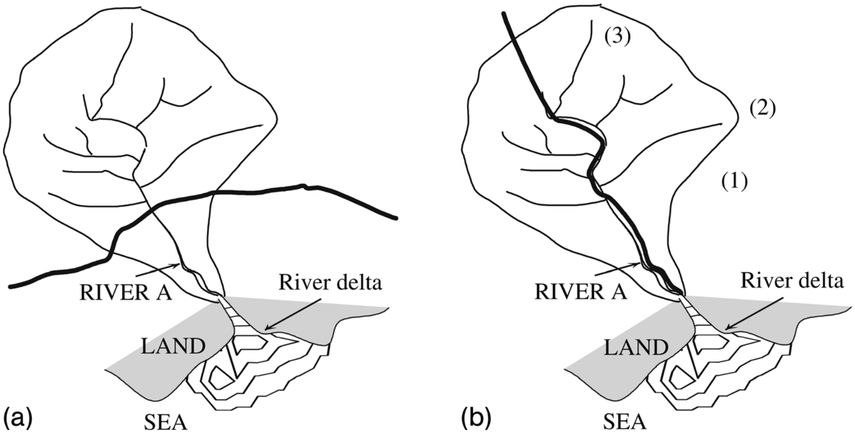

Figure 1.8 Schematic representation of two types of interstate borders: (a) crossing and (b) following a river.

1.2.1
The UNECE Convention (Helsinki, 1992)

Legal name: Convention on the protection and use of transboundary watercourses and international lakes.

The Convention obliges Parties to prevent, control and reduce water pollution from point and non-point sources. It is intended to strengthen national measures for the protection and ecologically sound management of transboundary surface waters and groundwaters. Multilateral cooperation for the protection of natural resources to prevent, control and reduce transboundary impact of surface or groundwaters which mark, cross or are located on boundaries between two or more States.

Transboundary impact means any significant adverse effect on the environment resulting from a change in the conditions of transboundary waters caused by a human activity, the physical origin of which is situated wholly or in part within an area under the jurisdiction of another Party. The Convention also includes provisions for monitoring, research and development, consultations, warning and alarm systems, mutual assistance, institutional arrangements, and the exchange and protection of information, as well as public access to information. In taking protective measures the Parties are advised to be guided by the following principles:

(a) *The precautionary principle,* by virtue of which action to avoid the potential transboundary impact of the release of hazardous substances shall not be postponed on the grounds that scientific research has not fully proved a causal link between those substances on the one hand, and the potential transboundary impact on the other.

(b) *The polluter-pays principle,* by virtue of which costs of pollution prevention, control and reduction measures shall be borne by the polluter.

(c) *Sustainability:* Water resources shall be managed so that the needs of the present generation are met without compromising the ability of future generations to meet their own needs.

The Convention requires that the limits of discharges should be based on *best available technologies* for hazardous substances. Municipal wastewater needs to be biologically treated and best available technologies should be used to reduce nutrient discharges. Appropriate measures and *best environmental practices* must be used for the reduction of nutrients and hazardous substances from non-point sources.

1.3
The EU Water Framework Directive

EU environmental regulation aims at coordinating different measures taken at Community level to tackle particular environmental problems in order to meet established objectives. Key examples of such regulation are the Urban Waste Water Treatment Directive, the Nitrates Directive and the Integrated Pollution Prevention and Control Directive.

In 2000, the EU issued the Water Framework Directive (WFD) in order to ensure an analysis of the state of water bodies and 'a review of the impact of human activity on the status of surface waters and on groundwater'. The analysis and review are to be conducted so as to determine how far each body of water is from the objectives (Directive 2000/60/EC).

The overall objective of the WFD is a 'good status' for all waters to be achieved by December 2015. For surface waters, 'good status' is determined by a 'good ecological' and a 'good chemical status'. This is determined by hydro-morphological (e.g. the condition of habitats), physico-chemical and biological monitoring and analysis. The WFD aims to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which:

- Prevents further deterioration and protects and enhances the status of aquatic ecosystems.
- Promotes sustainable water use based on the long-term protection of available water resources.
- Aims to enhance protection and improvement of the aquatic environment.
- Ensures the progressive reduction of pollution of groundwater and prevents its further pollution.
- Contributes to mitigating the effects of floods and droughts.

Key elements of the WFD include:

- Technical considerations: monitoring, river basin planning, and management.
- Institutional: adopt the river basin as a single system for water management.
- Environmental: water quality and ecosystems.
- Water economics.
- Public participation.

The WFD requires that River Basin Management Plans (RBMPs) are produced for each River Basin District (RBD) by 2009. These will be strategic management documents, developed via the river basin planning process, which will integrate the management of the water and land environment. Preparation will involve a process of analysis, monitoring, objective setting and consideration of the measures to maintain or improve water status.

Under the WFD, environmental monitoring programmes are required and specific objectives for water quality are set up. The WFD operates using a cyclical management process. This process begins by identifying water bodies in each RBD and describing their natural characteristics. The second stage is to assess the pressures and impacts on the water environment. This assessment identifies those water bodies that are unlikely to achieve the environmental objectives set out in the Directive by 2015.

The Directive calls for the application of economic principles (e.g. the recovery of the costs of water services and the polluter pays principle), approaches and tools (e.g. cost effectiveness analysis), and for the consideration of economic instruments (e.g. water pricing) for achieving its environmental objective in the most effective manner.

The WFD recognises the value and importance of involving all those with an interest in the water and land environment in how the WFD is put into practice. In certain areas (e.g. the development of RBMPs), stakeholder involvement is an inherent part of the Directive.

1.4
Uncertainties in Water Resources Management

Although rather the exception, there are situations in water resources engineering that may be considered as deterministic. As the uncertainties are low, a deterministic approach relating input and output suffices in these cases. Take, for example, the water supply from a reservoir operated with a gate. As shown in Figure 1.9, there is a deterministic relationship between the flow rate and the water height in the reservoir. In such cases there is no reason to use risk and reliability techniques, because the situation is predictable.

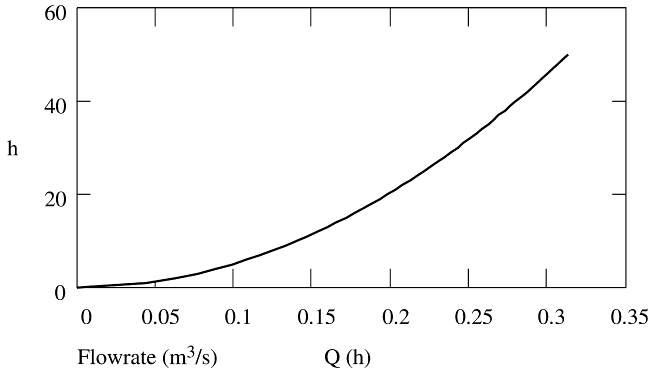

Figure 1.9 Water height expressed as a deterministic function of flow rate.

When the reservoir is filled by an inflow which varies with time, uncertainties in the variation of water height in the reservoir is no longer deterministic, as shown in Figure 1.10.

When uncertainties are important and influence the output of the water system, it becomes more appropriate to use risk analysis. Otherwise, traditional engineering modelling and simulation should be applied. Water resources engineering risk and reliability can be classified into three main categories:

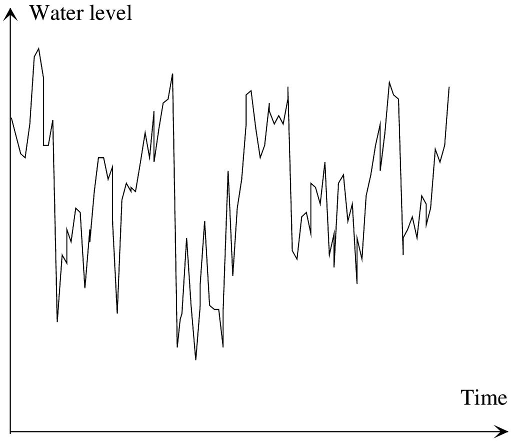

Figure 1.10 Stochastic variation of the water level in a reservoir.

(1) structural reliability (dams, flood levees and other hydraulic structures),
(2) water supply reliability (problems of water quantity),
(3) water pollution risk (problems of water quality).

In all three areas, uncertainties are mainly due to the spatial and temporal variability associated with hydrological variables. In addition to these uncertainties, which arise from the definition of the physical problem, other types of uncertainties are added, such as those related to the use of methods and tools to describe and model the physical problem (i.e. sampling techniques, data acquisition, data analysis and mathematical modelling). This book deals with the third group of problems, the risk to environmental water quality.

Four different types of uncertainties may be distinguished:

(1) Hydrologic uncertainty
This refers to the various hydrological events such as precipitation, river flow, coastal currents, water quality, and so on.

(2) Hydraulic uncertainty
These are uncertainties related to hydraulic design and hydraulic engineering structures.

(3) Economic uncertainty
This refers to all fluctuations in prices, costs and investments that may affect the design and optimisation processes.

(4) Structural uncertainty
This means all deviations due to material tolerances and other possible technical causes of structural failure.

Methods and tools able to quantify such uncertainties should be incorporated into the design and decision processes.

1.5
Environmental Risk Assessment and Management

According to the European Commission (EC) directive 85/337 relative to environmental impact studies, the design of water resources management projects should proceed in five steps:

1. Define the environmental impact of the project.
2. Analyse adverse environmental effects which cannot be avoided if the project is implemented.
3. Alternatives to the proposed action.
4. Relationships between local short-term water uses and maintenance of a long-term productivity.
5. Irreversible commitment of resources which would be involved in the project.

As shown in Figure 1.11, application of environmental risk analysis consists of two main parts
(1) the assessment of risk, and
(2) risk management.

The assessment of risk is mainly based on modelling of the physical system, including forecasting its evolution under risk. Although the main objective of risk

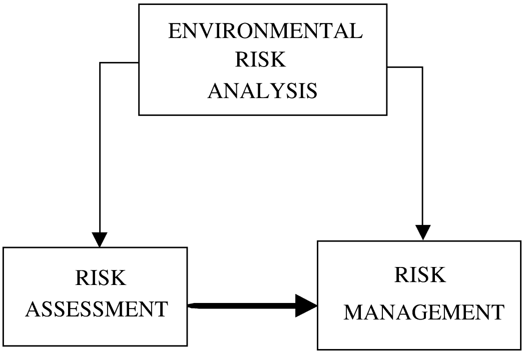

Figure 1.11 Risk assessment and risk management as elements of environmental risk analysis.

analysis is the management of the system, it is not possible to do this if risk has not been quantified first.

The risk assessment phase involves the following steps:
Step 1: Risk or hazard identification
Step 2: Assessment of loads and resistances
Step 3: Uncertainty analysis
Step 4: Risk quantification

When it is possible to assess risk under a given set of assumptions, the process of risk management may begin.

The various steps needed for risk management are:
Step 1: Identification of alternatives and associated risks
Step 2: Assessment of costs involved in various risk levels
Step 3: Technical feasibility of alternative solutions
Step 4: Selection of acceptable options according to the public perception of risk, government policy and social factors
Step 5: Implementation of the optimal choice

Because of the human and social questions involved, risk management is the most important part of the whole process and is also the most difficult to develop. From an engineering point of view, theories and algorithms of optimisation under uncertainty, multi-criterion optimisation and decision making under risk are all applicable.

Apart from the stochastic approach, the fuzzy set theory may be applied. Although the use of fuzzy sets in sequential decision-making was formulated more than two decades ago by Bellman and Zadeh (1970), no realistic application has yet been put forward for hydrology and water resources engineering. The reason for this may be that a solid background in both fuzzy set theory and water resources engineering is required. However the calculations are much simpler than in classical dynamic programming, as applied for example, in reservoir operation or groundwater management. It is quite natural to describe extreme events (especially droughts) as fuzzy or hybrid numbers.

Here we may distinguish between
(a) design or planning problems, and
(b) operational problems.

In *planning* problems, a set of discrete alternatives (also called options, actions, schemes, decisions, etc.) is defined and rated with a set of *performance indices* or *figures of merit* which are usually deterministic, stochastic or fuzzy. These usually also include non-numerical criteria. The recommended multi-objective procedure (Tecle *et al.*, 1988) consists of

(1) defining the type of objectives-specifications-criteria-preferences (weights, scales, etc.);
(2) defining the alternatives, which should be distinct, not just marginally different;
(3) using the input uncertainty characterisation/quantification to rate each alternative in terms of the selected criteria, including risk-related figures of merit. Using value functions to quantify the non-numerical criteria;

(4) selecting at least one multi-criterion decision-making technique to rank the alternatives;
(5) evaluating the ranking, for example by comparing the results of application of different techniques (Duckstein *et al.*, 1991), and performing a sensitivity analysis.

The trade-off between criteria or indicators may be carried out in a hierarchical manner: at first, ecological indicators may be traded off to yield a composite index of risk, and then the economic indicators may be followed to yield a composite cost index. At the second stage the two composite indices are then traded off. At each level, fuzzy numbers may be combined or compared, using for example, a measure of the distance between them.

In *operational* problems, it is customary to include only numerical criteria and use a sequential decision making scheme such as dynamic programming (Parent *et al.*, 1991).

Taking into account the above considerations, the presentation of material in this book is arranged along two main paths. The first comprises the main elements of risk analysis, which rank from the simpler to the more advanced such as

(1) identification of hazards,
(2) risk quantification, and risk management.

The second path follows the traditional engineering approach, that is

(1) analysis of inputs,
(2) modelling, and evaluation of outputs.

This book then combines the two paths. The material illustrates recent concepts and techniques of risk and reliability analysis in water resources engineering planning and management with emphasis on water quality problems.

1.6
Aim and Organisation of the Book

Risk and reliability is still a relatively new subject as applied to water resources and environmental engineering. As a contribution to understanding and using this powerful tool, the present volume aims to serve as a textbook. This is the main reason for having included numerical examples of applications, questions and problems on the various topics covered by the book and also characteristic case studies, illustrating the use of risk assessment techniques in environmental water quality. The general framework of engineering risk analysis is presented from the traditional engineering (conceptual modelling) rather than from the systems engineering point of view. Methods and tools from stochastic modelling and fuzzy set theory are applied to environmental problems related to water pollution.

In May 1985, a NATO Advanced Study Institute (ASI) was held in Tucson, Arizona, USA for the purpose of classifying various concepts of engineering reliability and risk in water resources. In the edited volume of the meeting (Duckstein and Plate, 1987) a general systems engineering framework is provided for the calculation of engineering risk and reliability in water resources. Reliability investigations are presented in two groups: reliability in hydraulic structures and reliability in water supply systems. In the same volume, the last chapter is devoted to decision making under uncertainty and under multiple objectives.

Six years later (May 1991), another NATO ASI was held in Porto Carras, Greece. This ASI may be considered as a continuation and extension of the initial endeavour. The main purpose was to provide a unified approach to risk and reliability in both water quantity and water quality problems, reflecting at the same time concepts and techniques that have emerged recently. The book published after the meeting (Ganoulis, 1991c), illustrates the steps to be followed in a systematic framework for the analysis and management of risks in water resources engineering problems. Methods and tools for risk quantification and management, recent developments, new techniques and case studies are presented for risk-based engineering design in water resources and water pollution problems. Whilst less importance is placed on structural reliability and standard techniques for reservoir management under 'non-crisis' conditions, more attention is placed on the methodologies for the quantification and management of risks related to a broad spectrum of problems. Such methodologies range from the hydrologic estimation of exceeding probability (Bobée, Ashkar and Perreault, 1991) and the stochastic estimation of pollution risk in rivers (Plate, 1991), coastal waters (Ganoulis, 1991d) and groundwater (Bagtzoglou, Tompson and Doudherty, 1991) to new techniques, such as the 'envelope' approach for dynamic risk analysis (Haimes *et al.*, 1991) and the fuzzy set approach (Duckstein and Bogardi, 1991). These techniques appear to be applicable to both scientific and decision making aspects of water resources and environmental engineering.

Although many theoretical developments have occurred in recent years (Morel and Linkov, 2006; Hlavinek *et al.*, 2008), progress made both in the understanding and application of Risk and Reliability analysis in Water Resources and Environmental Engineering remains slow. The main reasons for this seem to be the large amount of data required and the lack of engineers trained to deal with phenomena of a stochastic nature, including optimum cost/benefit decisions under uncertainty. To the author's knowledge, no other textbook is actually available in the current literature that presents the various aspects of risk and reliability in environmental impact analysis and water quality problems in a unified and comprehensive framework.

The purpose of this book is to present in a unified manner, methods and techniques to evaluate the impacts and risks on environmental water quality from alternative water management plans and wastewater or pollutant disposal into the aquatic environment. The book covers uncertainty analysis of water quantity and quality data, stochastic simulation in hydraulic/water resources/environmental engineering, decision theory under uncertainty and case studies. Methods for risk analysis of extremes in hydrology and risk assessment of groundwater, river and coastal pollution are also presented. In this second edition, questions and numerical exercises are added at the end of each chapter and information to help answer these questions and resolve the numerical applications are given in Appendix C.

This book may be of interest to engineers (civil, chemical and environmental), hydrologists, chemists, biologists, graduate students, researchers and professionals working on the issues of environmental water quality.

The assessment of risk in water resources problems should be based on the proper identification of the particular situation. This means that the most significant loads, parameters and boundary conditions of the problem should be identified, together with uncertainties which may give rise to a risk of environmental threat. This process is that of *risk identification* and it is analysed in Chapter 2. Two main methodologies have been developed so far for uncertainty analysis, namely the probabilistic approach and the fuzzy set theory. Basic concepts and the main rules for stochastic and fuzzy calculus are presented in this chapter, together with illustrative examples mainly taken from water quality and water pollution applications.

Risk assessment may be accomplished by the *quantification of risk*. This is very important for engineering applications and forms the background for risk management. Methods and techniques to quantify risks, not only in water resources but in a broader area of engineering, are presented in Chapter 3. In this chapter 'loads' and 'resistances' are described either as stochastic or as fuzzy variables. With the exception of some simple cases, where direct calculation of risk is possible, the environmental system is usually modeled by means of either the stochastic or the fuzzy set approach. The general frameworks for stochastic and fuzzy modelling are described in Chapter 3 and methodologies, such as the Monte Carlo simulation, are also illustrated for risk quantification.

Chapter 4 deals more specifically with the *risk assessment* of water pollution. The assessment of pollution risks in coastal, river and aquifer systems is analysed by appropriate mathematical modelling, describing transport, dispersion and physico-chemical reactions of the pollutants. To quantify uncertainties due to different variabilities such as advection, dispersion and initial conditions the random walk simulation is used.

Chapter 5 deals with *risk management*. Here the risks have been identified and, as far as possible, quantified. Various criteria are defined to characterise risk, including performance indices related to the effects of uncertainty. Some of these criteria may be probabilistic or fuzzy. In any case, risk management provides the means with which to investigate the mitigation of the consequences of risks. For this purpose, trade-offs may be made at increasingly high levels between the various risk indicators. For example at one level an environmental risk index may be traded off against a technical risk index, and at a higher level an overall risk index may be traded off against an overall economic risk index.

A very important demonstration of how risk analysis can be useful when facing new and challenging problems, such as the implications in engineering works from possible coastal pollution and eutrophication due to climate change, is given in Chapter 6, with the case of the Gulf of Thermaikos (Macedonia, Greece). Some other characteristic risk-related *case studies* are presented in this chapter, namely the coastal pollution in the Gulf of Thermaikos and its interactions with the optimum design of the sewage treatment plant of the city, the risk assessment of pollution with nitrates from the river Axios (Macedonia, Greece) and the groundwater salinisation of the Campaspe aquifer (Victoria, Australia).

1.7
Questions and Problems – Chapter 1

Water Pollution and Risk Analysis

A Systemic View of Water Resources

(a) What percentage of the Earth's surface is covered by oceans?
(b) What percentage of the total water on Earth is fresh water?
(c) What percentage of the total freshwater on Earth is surface water?
(d) What percentage of the total freshwater on Earth is groundwater?
(e) Explain why water is the most valuable resource on Earth.
(f) What is the main characteristic of the hydrological cycle?
(g) Define efficient precipitation.
(h) Is the water balance equation generally valid and what are its limitations?

(1) In a catchment area of 0.7 Gm^2, the mean annual rainfall is 670 mm and the correspondent evapotranspiration 520 mm. (a) Assuming negligible storage, determine the total runoff (surface and underground) in mm and km^3; (b) determine the catchment's annual water budget in km^3; (c) calculate the evapotranspition rate as a percentage of the rainfall. What can you conclude if you compare this to the global average percentage evapotranspiration rate?

(2) The surface area of a reservoir is $0.9 \times 10^6\,\text{m}^2$. The average inflow is $0.15\,\text{m}^3/\text{s}$ and the mean annual evaporation rate is 1500 mm/year. Calculate: (a) the daily evaporation rate in mm and m^3; (b) the change in storage per year in mm and m^3/year. Does the storage capacity increase or decrease? (c) The time needed to raise the water level by 1 m.

The New Paradigm of Water Quality

(a) How are water quantity and water quality interrelated?
(b) What is the meaning of the new water quality paradigm?
(c) How is biological assessment a useful tool for assessing the status of water quality?

Integrated Water Resources Management (IWRM)

(a) What is the best space scale at which IWRM should take place?
(b) What are the main reasons for adopting the IWRM process?
(c) Give examples of the benefits of using IWRM.
(d) Do you consider water to be a human right or a human need?
(e) In your opinion should water be considered as a commodity or a social requirement?

Water Pollution in Transboundary Regions

(a) How can 'fair' water allocation be implemented in a transboundary river basin?
(b) Equity and efficiency are notions closely related to water allocation. What are the parameters that should be taken into account in order to achieve equity and efficiency?
(c) Should higher value uses of water take priority over lower value uses?

The EU Water Framework Directive

(a) What is the definition of 'good status of water' in the EU WFD?
(b) How can 'good water status' be achieved?
(c) Enumerate the key elements of the EU-WFD.

Uncertainties in Water Resources Management (WRM)

(a) What are the causes of uncertainties in WRM?
(b) What is the relationship between uncertainties and risk?
(c) Describe at least four different types of uncertainties in WRM.

Environmental Risk Assessment (ERA) and Environmental Risk Management (ERM)

(a) What is the difference between ERA and ERM?
(b) Describe at least four steps necessary to achieve ERA.
(c) Describe at least five steps necessary to achieve ERM.