Wetlands for Water Pollution Control

Second Edition

Miklas Scholz
The University of Salford, Salford, UK

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About the Author

Prof. Miklas Scholz, Cand Ing, BEng (equiv), PgC, MSc, PhD, CWEM, CEnv, CSci, CEng, FHEA, FIEMA, FCIWEM, FICE, Fellow of IWA, holds the Chair in Civil Engineering at The University of Salford (Figure 1). He is the Head of the Civil Engineering Research Group. Prof. Scholz has shown individual excellence evidenced by world-leading publications, postgraduate supervision, and research impact. His main research areas (Figure 2) in terms of publication output are as follows: treatment wetlands (20%), integrated constructed wetlands (ICW; 15%), sustainable flood retention basins (SFRB; 5%), permeable pavement systems (5%), decision support systems (5%), ponds (5%), and capillary suction time (5%). About 45% and 40% of his research are in water resources management and wastewater treatment, respectively. The remaining 10% is in capillary processes and water treatment.

He has published four books and more than 176 journal articles covering a wide range of topics (Figure 2). Between 2009 and 2015, he topped the publication list in terms of numbers for all members of the staff at The University of Salford. Prof. Scholz's total journal article publications in

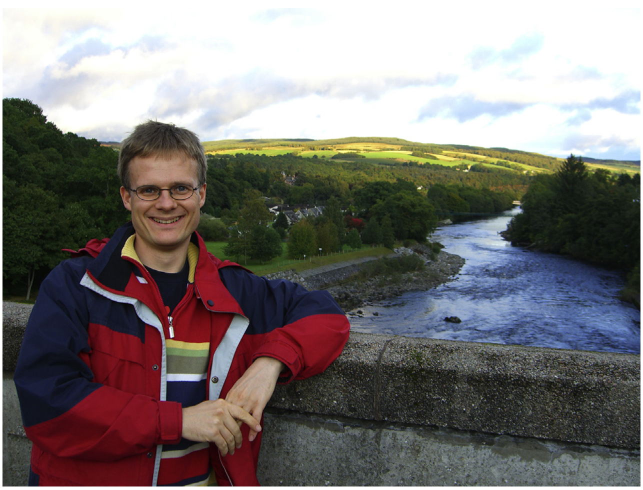

FIGURE 1 Miklas Scholz on top of a sustainable flood retention basin near Perth, Scotland, UK. *(Picture taken by Åsa Hedmark.)*

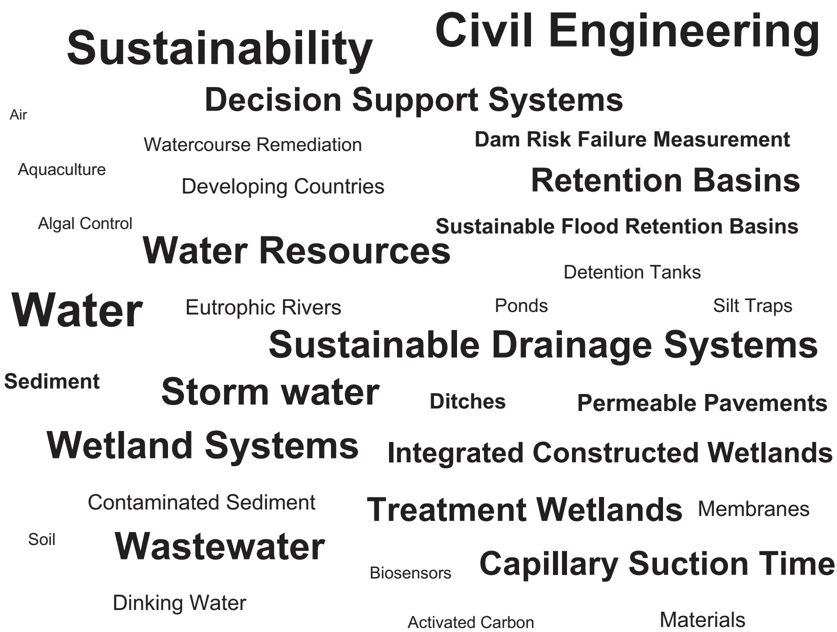

FIGURE 2 Overview of research areas and their corresponding relative importance and linkages between them.

recent years are as follows: 2009, 13 articles; 2010, 19 articles; 2011, 13 articles; 2012, 21 articles; 2013, 17 articles; and 2014, 15 articles.

He publishes regularly in the following journals with high impact factors: *Bioresource Technology, Building and Environment, Construction and Building Materials, Desalination, Ecological Engineering, Environmental Modelling & Software, Environmental Pollution, Industrial & Engineering Chemistry Research, Journal of Chemical Technology and Biotechnology, Journal of Environmental Management, Landscape and Urban Planning, Science of the Total Environment and Water Research*.

Prof. Scholz has total citations of more than 2845 (above 2122 citations since 2010), resulting in an h-index of 28 and an i10-Index of 64. Prof. Scholz is Editor-in-Chief of 13 journals, including the Web of Science-listed journal Water (impact factors for 2014: 1.428). He has membership experience on 35 influential editorial boards. Prof. Scholz was a member of the Institute of Environmental Management and Assessment (IEMA) Council between 2008 and 2015.

Miklas has a currently active (on-going) grant income of usually £270,000. His grant income over any past six years is typically £1,500,000. These figures include research and other grants, as well as consultancy.

His sustainable flood retention basin (SFRB) concept assesses the multi-functionality of all large water bodies, with particular reference to their flood and diffuse pollution control potential. A novel and unbiased classification system allows all stakeholders to clearly define the purpose of a water body that can be classed as an SFRB. Communication among stakeholders regarding the most appropriate management of SFRB is greatly enhanced. Moreover, the SFRB concept addresses the need to assess the flood control potential of all European water bodies as part of new legislation.

His research has led to the incorporation of findings into national and international guidelines on wetland and sustainable drainage systems (SuDS). The greatest impact has been made in the area of integrated constructed wetlands (ICW) in Ireland, Northern Ireland, Scotland, and England. Prof. Scholz contributed to the design guidelines of wetland systems as a research consultant. The guidelines assist designers and managers in all aspects of ICW planning, design, construction, maintenance, and management. Moreover, specific guidelines were written for ICW and used by farmers to treat farmyard runoff in Scotland and Northern Ireland and in Ireland. These guidelines are specifically mentioned in national legislation.

The new guidelines on SFRB and ICW have led to the international uptake of both the SFRB and ICW concepts and the researched hybrid SuDS. This work has particularly benefited the British Isles and Central and Northern Europe. For example, ICW are now being constructed in Belgium, Germany, the United States, and China.

Preface

The first edition of this work, entitled Wetland Systems to Control Urban Runoff, was published by Elsevier in 2006. It follows that the released material is now at least nine years old. This is not a major problem for most of the material, which has a long shelf-life. However, about 30% of the book required updating to make it more relevant for today's market.

This revised edition has both a more detailed and a broader view of the subject area. More detail has been added to some chapters to account for technological advances in treatment units and scientific progress in areas such as molecular microbiology. Furthermore, the subject area has been broadened to account for more multidisciplinary approaches, such as the ecosystem services concept, to solve engineering science challenges with a holistic angle. In order to realize this new approach, both updating and expansion (nine new chapters) of the current content were required. The second edition has therefore been expanded by about 40%, making it more competitive in a market where readers have more choice and flexibility due to advances in technology and the open access policy.

Because the second edition has a much broader focus, it is therefore entitled Wetland Systems to Control Pollution, attracting a wider audience of academics and practitioners. The revised and expanded book covers broad water and environmental engineering aspects relevant for the drainage and treatment of storm water and wastewater, providing a descriptive overview of the complex "black box" treatment systems and general design issues involved.

The fundamental science and engineering principles are explained to address the student and the professional market. Standard and novel design recommendations for, predominately, constructed wetlands and related sustainable drainage systems are provided to account for the interests of professional engineers and environmental scientists. The latest research findings in wastewater treatment and runoff control are discussed to attract academics and senior consultants, who should recommend the proposed textbook to final year and postgraduate students and graduate engineers, respectively.

The revised book deals comprehensively not only with the design, operation, maintenance, and water quality monitoring of traditional and novel wetland systems but also with the analysis of asset performance and modeling of treatment processes and performances of existing infrastructure—predominantly in developed but also in developing countries—and the sustainability and economic issues involved.

The textbook is essential for undergraduate and postgraduate students, lecturers, and researchers in the civil and environmental engineering, environmental science, agriculture, and ecological fields of sustainable water management. It should be used as a reference for the design, operation, and management of wetlands by engineers and scientists working for the water industry, local authorities, nongovernmental organizations, and governmental bodies. Moreover, consulting engineers should be able to apply practical design recommendations and to refer to a large variety of practical international case studies, including large-scale field studies.

The basic scientific principles outlined in the revised edition should be of interest to all concerned with the built environment, including town planners, developers, engineering technicians, agricultural engineers, and public health workers. The book is written for a wide readership, but sufficient hot research topics are also addressed in nine completely new chapters to guarantee a long shelf-life for the book.

Solutions to pressing water quality problems associated with constructed treatment wetlands, integrated constructed wetlands, farm constructed wetlands and stormwater ponds, and other sustainable biological filtration and treatment technologies linked to public health engineering are explained. Case study topics are diverse: wetlands, including natural wetlands and constructed treatment wetlands; sustainable water management, including sustainable drainage systems; and specific applications such as wetlands treating hydrocarbon and piggery wastewater. The research projects are multidisciplinary, holistic, experimental, and modeling-oriented.

The book is predominantly based on experiences gained by the author over the last 14 years. Original material published in articles in more than 170 high-ranking journals and presented in 200 key conference papers has been revisited and analyzed. Experience the author gained as an editorial board member of more than 30 relevant peer-reviewed journals guarantees that the textbook contains sufficient material that fills gaps in knowledge and understanding, and that it documents the latest cutting-edge research in areas such as sustainable drainage.

The book tries to integrate natural and constructed wetlands and sustainable drainage techniques into traditional water and wastewater systems used to treat surface runoff and associated diffuse pollution. Chapters 1–4 introduce water quality management and water and wastewater treatment fundamentals to the inexperienced reader.

Chapters 5–9 review preliminary and predominantly primary treatment units that can be combined with wetland systems. Chapters 10–15 summarize predominantly secondary but also tertiary treatment technologies that can be used in combination with wetland technologies or as alternatives in cases where land availability is restricted due to costs. Usually nonessential traditional technologies are briefly presented in Chapters 16 and 17 for the reason of completeness.

Microbiological and disinfection issues relevant for treatment wetlands are covered in Chapters 18 and 19. Chapter 20 introduces wetland science and biological treatment processes based on microbial biodegradation. Furthermore, examples of different wetland types have been presented for readers new to the subject matter. Chapter 21 highlights sludge treatment and disposal options that should be considered for sludges obtained from wetland systems.

Chapters 22−38 focus predominantly on a wide variety of timely applied research case studies related to constructed wetlands and associated technologies for runoff and diffuse pollution treatment. Moreover, wetlands such as sustainable flood control basins used for both diffuse pollution and flood control purposes are introduced. These chapters are written for professionals and students interested in design, process, and management details.

Miklas Scholz, Salford, October 1, 2015

Acknowledgments and Dedications

I would like to thank all current and previous members of my research groups at The University of Salford, The University of Edinburgh, and the University of Bradford for their research input, and all institutions that provided funding for my research. I am also grateful for the support received from the publishing team at Elsevier.

I would like to dedicate this book to my wider family and friends, who supported me during my studies and career. Particular thanks go to my partner **Åsa Hedmark**, children **Philippa Scholz**, **Jolena Scholz**, **Felix Hedmark,** and **Jamie Hedmark**, twin-sister **Ricarda Lorey** and mother **Gudrun Spieshöfer**.

Common Acronyms and Abbreviations

A	Coefficient *(unknown function of various variables including rainfall intensity and infiltration rate)*
A	Cross-section of flow area (m^2)
A_l	Cross-sectional area of lysimeter (m^2)
AEAICAD	Aesthetic and educational appreciation and inspiration for culture, art, and design (%)
AFTW	Aesthetic flood treatment wetland
ANN	Artificial neural network
ANOVA	Analysis of variance
AS	Activated sludge
ATV-DVWK	*German abbreviation for* German Association for Water, Wastewater and Waste
Avg.	Average (mean)
B	Maximum experimental depth (mm) within the infiltration basin during an individual storm
BC	Biological control (%)
BMP	Best management practice
BMU	Best-matching unit
BOD	Biochemical oxygen demand (mg/l) (*usually five days at* 20°C)
BP	Back-propagation
BP-MLL	Back-propagation for multilabel learning
BRE	British Research Establishment *(company)*
C	Carbon or combined approach or control or chili
C_e	Outflow concentration *(of contaminant in wetland cell)* (g/m)
C_f	Contaminant concentration in infiltration water (g/m^3)
C_0	Inflow concentration *(of contaminant in wetland cell)* (g/m)
CBR	Case-based reasoning
CE	Community and environment approach
CFU	Colony-forming unit
CIRIA	*(British)* Construction Industry Research and Information Association
COD	Chemical oxygen demand (mg/l)
CSS	Carbon sequestration and storage (%)

CST	Capillary suction time (s)
D	Infiltration basin design depth (mm)
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen (mg/l or %)
DWF	Dry weather flow (m^3/s)
E	Global error
EPMSF	Erosion prevention and maintenance of soil fertility (%)
EQS	Environmental quality standard
ES	Ecosystem service approach
ET	Evapotranspiration rate (m/d)
ETAAS	Electrothermal atomic absorption spectrometer
EU	European Union
F	Food (%) or filter
FW	Freshwater (%)
FWS	Free water surface *(flow wetland)*
GAC	Granular activated carbon
GL	Guidance level
GPS	Global positioning system
H_0	Head of water *(in wetland)* (m)
h_{wf}	Average capillary head at the wetting front (m)
Ham.	Hamming
HFR	High flow rate
HFRB	Hydraulic flood retention basin
HNL	High nutrient load
HS	Habitat for species (%)
HSD	Honestly significant difference
I	Hydraulic gradient or infiltration rate *(in wetland cell)* (m/d)
ICP-OES	Inductively coupled plasma optical emission spectrometer
ICW	Integrated constructed wetland
IFRW	Integrated flood retention wetland
IR	*(Empirical)* infiltration rate (m/s)
K	Hydraulic conductivity (m/d)
K	Number of neighbors
K_M	Total roughness
KNN	k-nearest neighbor
L	Loss
L	Depth of wetting front *(beneath ICW cell)* (m) or label *(also l and λ)*
L_0	*(Contaminant)* inflow loading rate (g/m/d)
LCAR	Local climate and air quality regulation (%)
M	Number of instances in a data set
MAC	Maximum admissible concentration
MASE	Mean absolute scaled error
Max	Maximum

MEE	Moderation of extreme events (%)
MGD	Maintenance of genetic diversity (%)
Min	Minimum
MLKNN	Multilabel *k*-nearest neighbor
MLSS	Mixed liquor suspended solids
MLSVM	Multilabel support vector machine
MLVSS	Mixed liquor volatile suspended solids (mg/l)
MR	Medicinal resources (%)
MRP	Molybdate reactive phosphate (mg/l)
N	Number of entries or nitrogen or north
N	Number of instances that are correctly predicted
NFRW	Natural flood retention wetland
nosZ	Nitrous oxide reductase
NTU	Nephelometric turbidity unit *(similar to FTU)*
P	Significance level *(of a test) (also known as p*, *p-value*, *or P-value)* or precipitation rate (m/d)
P	Phosphorus (mg/l) or pollination (%) or sweet pepper
PCA	Principal component analysis
PCR	Polymerase chain reaction
PRAST	Prevalence Rating Approach for SuDS Techniques
Pre.	Precision
Q	Volume of water per unit time (m^3/d) or size of the set of labels or hydraulic loading rate (m/d)
Q_f	Daily water volume infiltrating beneath a wetland cell (m^3/d)
Q_0	Inlet wastewater volume flow rate *(in wetland cell)* (m^3/d)
QR	Quantization error
R	*(Mean product moment)* correlation coefficient
R^2	Coefficient of determination
Ran.	Ranking
RBC	Rotating biological contactor
RBF	Radial basis function
Re.	Recall
RM	Raw materials (%)
RMPR	Recreation and mental and physical health (%)
rRNA	Ribosomal ribonucleic acid
SD	Standard deviation
SESP	Spiritual experience and sense of place (%)
SFRB	Sustainable flood retention basin
SFRW	Sustainable flood retention wetland
SOM	Self-organizing map
SRT	Storm runoff treatment (%)
SS	*(Total)* suspended solids (mg/l)
SSSI	Site of special scientific interest
SuDS	Sustainable drainage system

SVM	Support vector machine
T (or t)	Infiltration time (s) or temperature (°C)
TAV	Tourism and area value (%)
TE	Topographic error *(usually in %)*
TFRB	Traditional flood retention basin
TOC	Total organic carbon (mg/l)
TS	Total solids (mg/l)
UK	United Kingdom
U-matrix	Unified distance matrix
USA	United States of America
UV	Ultraviolet *(light)*
W	West
WTW	Wissenschaftlich Technische Werkstätten *(company)*
X	Variable *(here, cost unit)*
X	Domain of instances
x_i	An instance i
Y	Set of labels
y_i	Label i
Z_1	Factor *(defined by the BRE method)*
Z_2	Growth factor *(defined by the BRE method)*
Γ	Bias parameter of a feed-forward network
Δ	Symmetric difference of two sets

Chapter 1

Water Quality Standards

1.1 INTRODUCTION AND HISTORICAL ASPECTS

Scientific and public interest in water quality is not new. For example, in the United Kingdom (UK), it probably had its origins in the mid-eighteenth century. In 1828, the editor of Hansard, Mr. John Wright, anonymously published a pamphlet attacking the quality of the drinking water in London. This led to the establishment of a Royal Commission, which established the principle that water for human consumption should at all times be "wholesome." The term "wholesome" has been incorporated into virtually every piece of legislation concerned with drinking water ever since.

The first unequivocal demonstration of water-borne transmission of cholera was by Snow in 1854. This stimulated great advances in water treatment practices, in particular the routine application of slow sand filtration and disinfection of public water supplies.

Although the Royal Commission of 1828 was concerned with water quality, it had difficulty in defining it precisely, because there were virtually no analytical techniques available at the time with which to determine either microbial or chemical contamination. Consequently, since that time, there has been a continuing and often fierce debate on what constitutes a suitable quality for human drinking water. Not surprisingly, in the nineteenth and early part of the twentieth centuries, the evaluation was largely based on subjective, usually sensory perception.

Many authorities (e.g., Sir Edwin Chadwick) believed that an atmospheric "miasma" above the water, rather than the water itself, was responsible for disease transmission. As a consequence, great efforts were made to remove the smell, assuming that this would dispel the disease. In 1856, during the "great stink," sheets drenched in chemicals were hung from the windows of the Houses of Parliament to exclude the smell. This action did at least focus the minds of the politicians on the need to take action to improve the quality of London's water supply.

Even today, taste, smell, and appearance (color and turbidity) are considered useful criteria for judging water quality. However, in addition, there are now objective methods for determining the presence and level of many (but by no means all) of the microbial contaminants likely to be present in drinking water.

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Since the 1960s, the emphasis regarding drinking water quality has shifted from its bacteriological quality to the identification of chemical contaminants. This reflects largely the very considerable success of the water industry in overcoming bacteriological problems, although this victory is not complete (e.g., many viruses and *Cryptosporidium* cause public health concerns).

With the great methodological improvements in analytical chemistry over the past 50 years, it was recognized that water contains trace amounts of several thousand chemicals and that only the limitations of analytical techniques restrict the number of chemicals that can be identified. Many of these chemicals are of natural origin, but pesticides, human and veterinary drugs, industrial and domestic chemicals, and various products arising from the transport and treatment of water are very commonly found, albeit normally at very low concentrations.

In addressing the problem of the contribution of water-borne chemicals to the incidence of human disease, water scientists, whose previous experience has typically been confined to microbiological problems, have tended to focus on acute risks. The absence of detectable short-term adverse effects of drinking water has been taken by many as conclusive evidence that the presence of such chemicals is without risk to humans.

While information on the acute toxicity of a chemical can be very useful in determining the response to an emergency situation such as an accidental spillage or deliberate release of chemicals into a watercourse or even into the water supply, such information is of little use in predicting the effects of daily exposure to a chemical over many years.

However, low levels of chemicals are much more likely to cause chronic (rather than acute) effects to health. Here, direct reliable information is very sparse. Some authorities appear to have accepted the "naïve" assumption that information on the acute effects of a chemical, in either humans or experimental animals, can be used to predict the effects of being exposed over a lifetime. In practice, the chronic effects of a chemical have rarely any resemblance to the acute effects.

An evaluation of health risks associated with drinking water is necessary and timely. If we are to obtain a proper assessment of the health risk that could arise in humans through exposure to chemicals in water over a lifetime, understanding must be developed on the following:

- Identification of the chemicals that are of most concern;
- Data on the effects of long-term exposure in humans and/or animals to each chemical;
- A measure of the extent and form of exposure to each chemical;
- Identification of particularly at-risk groups; and
- The means of establishing how exposure to other chemicals in the water can modify the toxicity.

1.2 WATER QUALITY STANDARDS AND TREATMENT OBJECTIVES

It is commonly agreed that there are three basic objectives of water treatment:

1. Production of water that is safe for human consumption;
2. Production of water that is appealing to the customer; and
3. Production of water treatment facilities that can be constructed and operated at a reasonable cost.

The first of these objectives implies that the water is biologically safe for human consumption. It has already been shown how difficult it is to determine what "safe" actually means in practice. A properly designed plant is not a guarantee of safety, standards will change, and plant management must be flexible to ensure continued compliance.

The second basic objective of water treatment is the production of water that is appealing to the customer. Ideally, appealing water is clear and colorless, pleasant to taste, odorless, and cool. It should be nonstaining, noncorrosive, non-scale-forming, and reasonably soft. The consumer is principally interested in the quality of the water delivered to the tap, not the quality at the treatment plant. Therefore, storage and distribution need to be accomplished without affecting the quality of the water; in other words, distribution systems should be designed and operated to prevent biological growth, corrosion, and contamination.

The third basic objective of water treatment is that it can be accomplished using facilities with reasonable capital and operating costs. Various alternatives in plant design should be evaluated for cost-effectiveness and water quality produced.

The objectives outlined here need to be converted into standards so that proper quality control measures can be used. There are various drinking water standards. The key variables are as follows:

- Organoleptic parameters: color, turbidity, odor, and taste;
- Physical and chemical parameters: temperature, pH, conductivity, dissolved oxygen, dissolved solids, chlorides, sulfate, aluminum, potassium, silica, calcium, magnesium, sodium, alkalinity, hardness, and free carbon dioxide (CO_2);
- Parameters concerning undesirable substances: nitrate, ammonium, total organic carbon (TOC), hydrogen sulfide, phenols, dissolved hydrocarbons, iron, manganese, suspended solids, and chlorinated organic compounds other than pesticides;
- Parameters concerning toxic substances such as arsenic, mercury, lead, and pesticides; and
- Microbiological parameters: total coliforms, fecal coliforms, fecal streptococci, sulfite-reducing clostridium, and total bacterial count.

Standards usually give two values: a guide level (GL) and a maximum admissible concentration (MAC). The GL is the value that is considered satisfactory and constitutes a target value. The MAC is the value that the corresponding concentration in the distributed water must not exceed. Treatment must be provided when the concentration in the raw water exceeds the MAC.

Standards also specify the methods, frequencies, and nature of the analysis. For total hardness and alkalinity, the standards specify minimum values to be respected when water undergoes softening.

Most standards group substances into five categories:

- Microbiological;
- Inorganic with consequences on health;
- Organic with consequences on health;
- Appearance; and
- Radioactive components.

One of the main sources of confusion regarding water standards and their interpretation is the lack of any clear indication as to how the standard was derived. This results in the interpretation of all standards as "health standards" by the public and, subsequently, in the difficulty of assessing what should be done by the water supplier if a threshold is exceeded.

This is particularly true of drinking water quality directives because insufficient explanation of the derivation of the actual numbers is often given. There are even thresholds for variables regarded as toxic that are based on political or other considerations, and they are therefore only loosely based on science (e.g., pesticides). The use of such approaches is acceptable as long as the reasoning behind them is clear to all.

International guidelines are usually intended to enable governments to use them as a basis for standards, taking into account local conditions. They are intended to be protective of public health, and they should be absolutely clear, even down to detailed scientific considerations such as the derivation of uncertainty factors and the rounding of numbers. It is therefore incumbent on the expert groups to justify their thinking and present it openly for all to see. Such a discipline avoids the "fudging" of issues while giving the impression of scientific precision, and it can only be of value in increasing public confidence in the resulting guidelines.

It is clear that, at present, standards for water quality are as follows:

- Loosely based on science (although the situation is improving);
- Not static (the science of monitoring as well as our understanding of the health implications of chronic exposure of many contaminants are improving); and
- Important in the quality control of potable water (for both supplier and consumer).

Concerning the outflow water quality of most wetland systems, standards either are unclear or are currently being developed. The local environment regulator usually sets standards for specific wetland system applications.

1.3 BIOCHEMICAL OXYGEN DEMAND

When wastewater, including urban runoff, is discharged into a watercourse, it exerts a polluting load on that water body. Microorganisms present in the natural water and the wastewater break down (stabilize) the organic matter. In permitting discharges to watercourses, the Environment Agency in the UK, for example, tries to ensure that the conditions are aerobic so that all other life forms in the river (e.g., fish) can continue to survive. The early forms of wastewater treatment developed are aerobic, and so the simplest way of estimating the biodegradability of a wastewater sample is to estimate the amount of oxygen required to stabilize the waste.

To devise an easy and simple method of assessing the oxygen demand, the following constituents of a closed system should be considered:

- Air (in excess);
- A small number of bacteria; and
- A finite amount of substrate (waste representing food).

The following phases of biological growth and decline can be identified in such a system:

- Lag phase: Bacteria are acclimatizing to system conditions, in particular the substrate; very little increase in numbers.
- Log growth: Bacteria are acclimatized; food is not a limiting factor; rapidly increasing population of bacteria.
- Declining growth: Food eventually becomes limiting; declining growth rates.
- Endogenous respiration: As the substrate concentration becomes depleted, competition increases; bacteria start consuming dead bacterial cells and eventually start consuming live cells.

It is a system of this type that is used to assess the oxygen demand of wastes, including organic matter from urban runoff. The test developed from this system is the biochemical oxygen demand (BOD) test.

The BOD test is carried out as follows: a known quantity of a wastewater sample (suitably diluted with prepared water) is placed in a 300-ml BOD bottle. The prepared water is saturated with dissolved oxygen (DO), and nutrients and a buffer are added. The bottles are then sealed airtight. The bottles are subsequently incubated at 20 °C in the dark (Clesceri et al., 1998).

Initially, the bacteria break down the carbon-based molecules. In practice, a second oxygen demand is observed. In the case of raw sewage, this stage usually becomes apparent after approximately 8 days of incubation at 20 °C.

This second stage is due to the oxidation of ammonia present in the waste; this is called nitrification. A large percentage of the nitrogen in the wastewater originates from proteins; the protein molecules are degraded to release ammonia. The oxidation process is described in Eqs. (1.3.1) and (1.3.2):

$$2NH_4^+ + 3O_2 \xrightarrow{Nitrosomonas} 2NO_2^- + 4H^+ + H_2O \tag{1.3.1}$$

$$2NO_2^- + O_2 \xrightarrow{Nitrobacter} 2NO_3^- \tag{1.3.2}$$

Nitrification consumes a significant amount of oxygen so that the total demand for nitrification is often comparable with the carbonaceous demand. Nitrification also generates protons (H^+ ions), which increase the acidity (pH) of the waste.

Traditionally, the BOD test is carried out for 5 days; the resulting oxygen demand is referred to as the BOD_5. The BOD is calculated as follows (Eqs. (1.3.3) and (1.3.4)):

$$\text{BOD (mg/l)} = \frac{\text{Initial DO in bottle} - \text{Final DO in bottle}}{\text{Dilution ratio}} \tag{1.3.3}$$

where:

$$\text{Dilution ratio} = \frac{\text{Volume of wastewater}}{\text{Volume of BOD bottle}} \tag{1.3.4}$$

In practice, the test is often modified slightly in that a quantity of seed microorganisms are added to the BOD bottle to overcome the initial lag period. In this variant, the BOD is calculated from Eq. (1.3.5):

$$\text{BOD} = \frac{(D_1 - D_2) - f(B_1 - B_2)}{DR} \tag{1.3.5}$$

where:

D_1 = dissolved oxygen initially in seed and waste bottle;
D_2 = dissolved oxygen at time T in seed and waste bottle;
B_1 = dissolved oxygen initially in seed-only bottle;
B_2 = dissolved oxygen at time T in seed-only bottle;
f = ratio of seed volume in seeded wastewater to seed volume in the BOD test on seed only; and
DR = dilution ratio.

Additional bottles are incubated. These contain only seed microorganisms and dilution water to get the BOD of the seed, which is then removed from the BOD obtained for waste and seed.

However, the BOD test has two major disadvantages: it takes 5 days to obtain the standard test result, and the results can be affected by the process of nitrification (see above). Therefore, a nitrification inhibitor is often used (Chapter 24).

1.4 CHEMICAL OXYGEN DEMAND

The disadvantages of the BOD test have led to the development of a simpler and quicker test. This test is known as the chemical oxygen demand (COD) methodology. In this test, strong chemical reagents are used to oxidize the waste. Potassium dichromate is used in conjunction with boiling concentrated sulfuric acid and a silver catalyst. The waste is refluxed in this mixture for 2 h. The consumption of the chemical oxidant can be related to a corresponding oxygen demand (Clesceri et al., 1998).

The COD test oxidizes material that microorganisms cannot metabolize in 5 days or that are toxic. If the COD is much greater than the BOD in raw wastewater, then the waste is not readily biodegradable, and it may be toxic to the microorganism. If the COD is similar to the BOD, then the waste is readily biodegradable.

1.5 OTHER VARIABLES USED FOR THE CHARACTERIZATION OF WASTEWATER

Most wastewater treatment processes operate best in pH ranges between 6.8 and 7.4; indeed, $pH > 10$ is likely to kill large numbers of bacteria. Suspended solids (SS) is a measure of the total particulate matter content of wastewater. The nature of the SS is likely to vary considerably depending on the nature of the waste.

The two most important nutrients in wastewater treatment are nitrogen and phosphorus; both are needed for cell growth. Nitrogen (N) is used in protein synthesis (e.g., new cell growth). Phosphorus (P) is used for cell energy storage and is usually present as ortho-phosphate (PO_4).

Organic nitrogen is associated with cell detritus and volatile SS. Free ammoniacal nitrogen (NH_3-N) results from the decay of organic nitrogen. Nitrite−nitrogen (NO_2-N) is formed in the first step in nitrification. Nitrate−nitrogen (NO_3-N) results from the second and final stage in the nitrification process.

For proper microorganism growth, the ratio of C:N:P is important. Carbon (C) is measured by BOD_5. Nitrogen is measured by organic nitrogen and NH_3-N. However, NO_3-N is difficult for microorganisms to use in their growth process. Phosphorus is measured as acid hydrolysable ortho-phosphate (PO_4). To achieve growth, the required minimum values for the C:N:P relationship are 100:5:1.