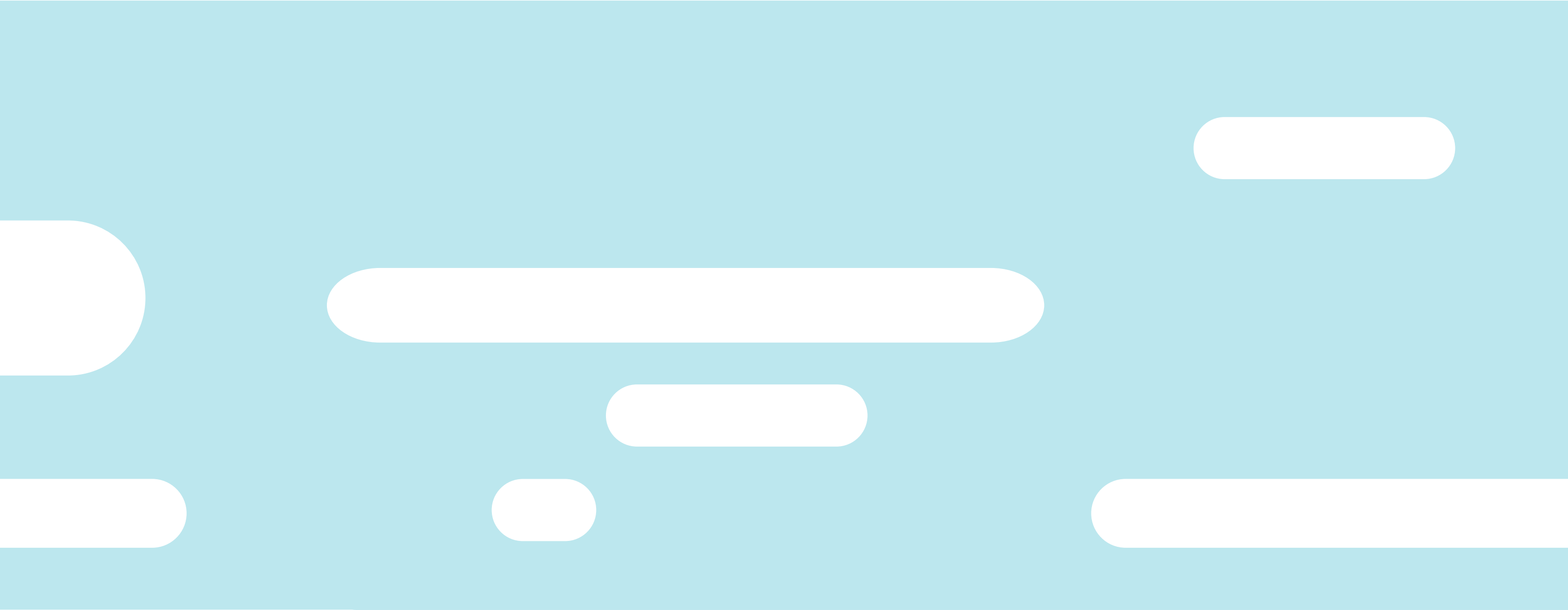
World Health
Organization

PROTECTING SURFACE WATER FOR HEALTH

IDENTIFYING, ASSESSING AND MANAGING DRINKING-WATER QUALITY RISKS IN SURFACE-WATER CATCHMENTS



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FOREWORD

Access to safe drinking-water is fundamental to human development and a basic human right. A lack of access to safe drinking-water sources, coupled with inadequate sanitation and hygiene, remains one of the most critical public health challenges globally.

Despite the significant achievements by the end of the Millennium Development Goal (MDG) era, an estimated 663 million people still lack access to an "improved" source of drinking-water. Many more still lack access to "safe" drinking-water, with at least 1.9 billion people relying on an unimproved source or an improved source that is faecally contaminated. Through the Sustainable Development Goals (SDGs), countries around the world have expressed strong political will to ensure not only that a drinking-water service is extended to unserved populations, but also that this drinking-water is universally safe. This is expressed in Goal 6 of the SDGs, with Target 6.1 stating "By 2030, achieve universal and equitable access to safe and affordable drinking-water for all".

However, as land-use pressures and competition for limited water resources intensify through population growth, it is clear that the entire water cycle needs to be managed as a whole to ensure that limited freshwater resources within are protected. Unless managed effectively, these pressures may affect surface-water quality both directly and indirectly, with adverse effects on public health. Emerging health concerns in this regard, including through climate change, are increasing prevalence of toxic cyanobacterial blooms in addition to on-going threats from pathogens causing cholera, typhoid and other enteric diseases.

> **Protecting surface water for health**
> *embraces the concept put forward by Goal 6 of the SDGs, recognizing that the protection of water quality and water-related ecosystems contributes to public health protection.*

6 CLEAN WATER AND SANITATION

In recognition of this need for a holistic approach to water cycle management, Goal 6 of the SDGs extends beyond human-related targets to capture those concerned with the environment: improving ambient water quality (Target 6.3), integrating water resources management (Target 6.5) and protecting and restoring water-related ecosystems (Target 6.6). *Protecting surface water for health* embraces the concept put forward by Goal 6 of the SDGs, recognizing that the protection of water quality and water-related ecosystems contributes to public health protection.

This book provides a structured approach to understanding surface waters and their catchments to support the identification, assessment and prioritization of the risks, and the development of management strategies for their control, as a basis for providing safe drinking-water. Where source-water quality is maintained, less treatment effort is needed and the provision of safe drinking-water may be achieved with greater reliability. Thus, source-water protection is a key element in a multi-barrier approach to the provision of safe drinking-water. This is particularly true in resource limited settings where there is a lack of effective and reliable water treatment.

This publication is one of a series of supporting documents that provides guidance on implementing the World Health Organization's (WHO) *Guidelines for drinking-water quality* (WHO, In preparation-a) and, in particular, water safety plans (WSPs). WSPs are considered best practice for water supply management with over 90 countries having WSP implementation experience. WHO has produced a number of publications to support water safety planning throughout the drinking-water supply chain, including the complementary publication *Protecting groundwater for health: managing the quality of drinking-water sources* (Schmoll et al., 2006). *Protecting surface water for health* provides guidance and supporting information on the development and application of WSPs in drinking-water catchments to address the assessment and control of surface-water hazards in an effective way. Thus, it is anticipated that this publication, along with the other WHO publications on WSPs, will support the continued uptake and improvement in water safety planning and thereby contribute to the achievement of related SDG water targets.

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INTRODUCTION

Safe drinking-water is essential to sustain life – it is the basis for human health, survival, growth and development. Therefore, access to safe drinking-water is a basic human right. Recognition of this right contributes to the survival of human beings and disease prevention, because water is used not only for drinking, but also for many other purposes such as hygiene, food production, agriculture, cooking and industry.

Unsafe water, in combination with inadequate sanitation and hygiene, still contributes to the deaths of some 842 000 people every year, representing 58% of deaths caused by diarrhoea. About 361 000 of these deaths occur in children aged under 5 years (WHO, 2014a). Safe water supplies are essential not only for health, but also for people's livelihoods, economic growth and development.

One of the targets of the Millennium Development Goals (MDGs) of the United Nations (UN) was to cut by half the proportion of people without sustainable access to drinking-water by 2015 (UN, 2015). This target – measured by the proxy indicator "improved" water supply – was reached ahead of schedule in 2010, with 91% of the world's population using an improved drinking-water source (WHO & UNICEF, 2015). However, important challenges remain, as 663 million people worldwide still lack access to improved water sources, and 159 million of these people rely on untreated surface water, which poses even greater health risks than other water sources. Also, there are significant access disparities both among and within countries. For example, in some countries, less than half of the population has access to improved sources, and access rates are significantly lower in rural areas than in urban areas. Improved sources have, by definition, been designed to be protected from contamination; however, water from improved sources is not always safe to drink (WHO & UNICEF, 2015). Hence, using an improved drinking-water source as an indicator for the use of safe water may overestimate the actual proportion of the global population using safe water (Onda, LoBuglio & Bartram, 2012).

Raw water for drinking-water supplies (also referred to as "source water") includes groundwater, rainwater and various types of surface-water sources, such as rivers, lakes, ponds, creeks, irrigation channels, seawater and constructed reservoirs. The proportion of drinking-water supplies relying on surface-water sources is extremely variable regionally, but globally, surface water is estimated to cover about 50% of drinking-water needs (UNESCO, 2004). As population pressures increase in many parts of the world, it is becoming increasingly apparent that the issues of water quality cannot be managed in isolation. The entire water cycle – including wastewater, recycled water, groundwater and surface water – needs to be managed in a holistic way to efficiently use and protect limited freshwater resources, and to protect human health from waterborne infectious diseases and toxic chemicals.

The UN's Sustainable Development Goals (SDGs) go beyond access to improved water supply (UN, 2016). The SDGs call for achieving universal and equitable access to safe and affordable drinking-water for all. They also call for water quality to be improved by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and at least doubling water recycling and safe reuse globally.

Water quality is often seen as an "end of pipe" issue, to be managed by water treatment before delivery to consumers, or even by treatment in consumers' households. However, a combination of barriers throughout the water-supply system is a fundamental requirement for safe drinking-water. These barriers can include:

- selection and protection of water sources;
- optimization of abstraction and treatment; and
- prevention of deterioration of water quality in the distribution system, including installations in buildings.

A multiple-barrier approach is particularly important when the source water contains a wide range of microbial and chemical hazards, as is often the case with surface water.

Careful selection and protection of water sources can be particularly effective in reducing the risks to raw water for drinking-water supplies, resulting in water that is of high quality (microbially and chemically). Such high-quality water requires less treatment effort. Thus, multiple barriers, particularly barriers to contamination of surface water, are important in the provision of safe drinking-water, especially where treatment is lacking or is only of limited efficacy. Also, using high-quality raw water for drinking-water supplies can lead to cost savings by preventing the need for complex water treatment technology, which is usually cost intensive (in both initial investment and operation). Another benefit is that protection of source waters contributes to safe water use for recreation, crop irrigation and environmental protection.

The ideal situation for high raw-water quality is a "catchment"[1] (also called a "watershed" or "basin") that is dedicated to drinking-water production, and in which potentially contaminating activities are absent or rare. Where all the land in a catchment is under the control of the water-supply entity, the management of raw-water quality can be relatively straightforward. This type of situation can result in water of high quality that varies only in response to natural events (e.g. those that are climate driven). Such scenarios are found in some regions where population densities are sufficiently low, or where protection has been in place historically and is being maintained, usually with the aim of maximizing the health and aesthetic quality of the supplied water, and minimizing treatment costs.

In reality, it is rare that the catchment of a drinking-water source is owned by the water supplier and is used only for this purpose. A much more common scenario is that the protection and provision of water supplies is just one of a number of competing land uses. The process of water-source protection therefore often involves multiple stakeholders with differing interests in land-use planning and in management of potentially polluting activities. Such activities include agriculture, aquaculture, commerce, industry, mining, traffic, recreational uses and operation of wastewater facilities. Hence, stakeholders may have the desire to use the catchment for purposes other than raw-water protection. In doing so, they also have the option to carry out their activities in ways that minimize impacts on the surface waterbody. Thus, water suppliers need to be able to communicate with the relevant stakeholders, to influence land-use activities and planning decisions over which the supplier may well have no direct control. For example, a water supplier may be able to influence stakeholders to carry out their activities in such a way as to minimize impacts on the surface waterbody.

What is the purpose of this book?

Protecting surface water for health aims to provide practical guidance on identifying, assessing and managing risks related to surface water, as a basis for providing safe drinking-water and thus protecting public health. This text is one of a series of supporting documents that provide guidance on implementing the WHO *Guidelines for drinking-water quality* (GDWQ; WHO, In preparation-a). It promotes close collaboration between the health and environmental sector in their endeavours to protect catchments, and is the partner publication to *Protecting groundwater for health: managing the quality of drinking-water sources* (Schmoll et al., 2006).

The information given here will be useful in the development and application of risk-management approaches to protect drinking-water resources. Based on a structured approach to understanding surface waters and their catchments, this book provides practical guidance on:

- analysing hazards to surface-water quality and pollution sources;
- assessing the risks the hazards may cause for a specific water supply;
- setting priorities in addressing the identified risks; and
- developing management strategies for the control of the risks.

As with *Protecting groundwater for health* (Schmoll et al., 2006), this publication advocates the adoption of a water safety plan (WSP). A WSP is a comprehensive preventive risk-management approach that encompasses all steps in a water supply, from catchment to consumer (Bartram et al., 2009), and this document gives specific guidance on how the principles of a

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[1] A catchment is the area drained by a river, lake or reservoir, contributing water to a common discharge point or outlet.

WSP can be applied to assessing and managing surface-water risks. WSPs are part of WHO's *Framework for safe drinking-water*, which is part of the GDWQ (WHO, In preparation-a).

In the context of this publication, surface water includes "groundwater under the direct influence" of surface water; that is, groundwater sources that receive direct surface-water recharge. This book focuses on sources for drinking-water; it does not cover protection of surface waters used for recreational or other purposes (although the approaches in both cases can be similar). Further information on recreational aspects is provided in the WHO *Guidelines for safe recreational water environments* (WHO, 2003a). Also, this document does not specifically provide guidance on the consideration of socioeconomic factors, although these may significantly influence the characteristics of surface-water systems and potentially polluting activities and appropriate management options.

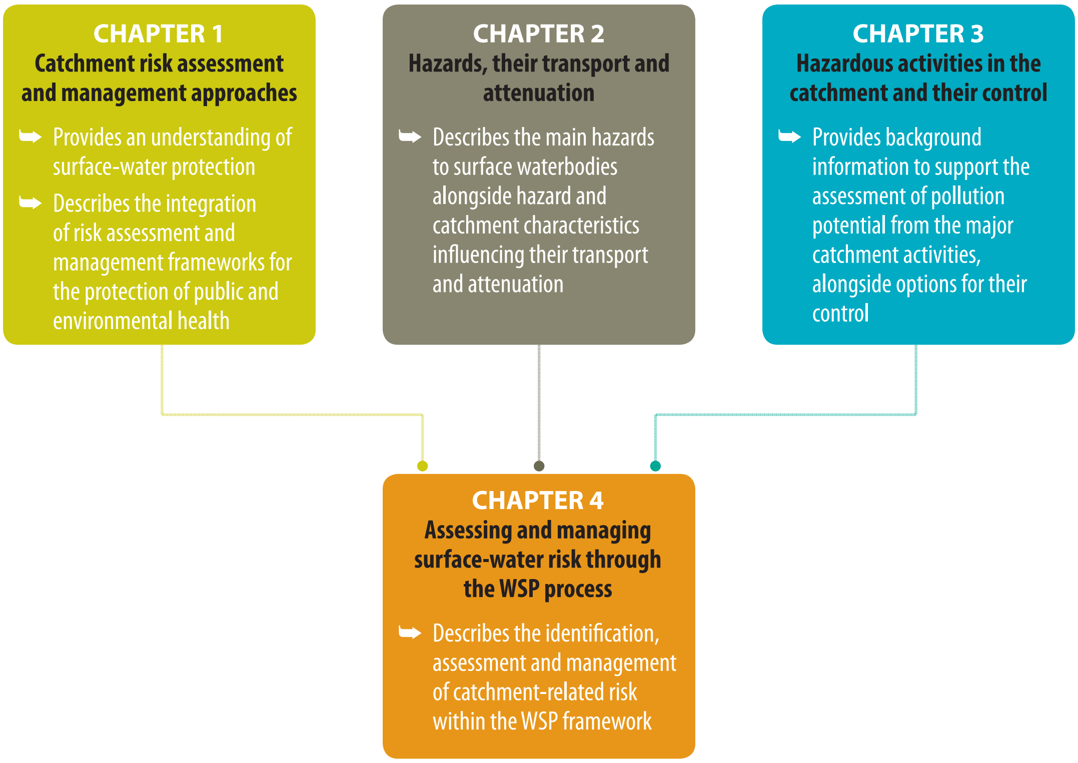
For whom is this book intended?

The target audience of *Protecting surface water for health* is primarily professionals in the health, environmental and water sectors, including government agencies, and it will be a useful resource for assessing catchment-related water-quality risks and safely managing such risks. This book may also assist water suppliers who wish to improve management of their water supplies in collaboration with those responsible for activities in the catchment. It does this by supporting integration of catchment-management and resource-protection aspects in overall water-supply management. Additionally, this publication may be a resource for professionals from other sectors, giving them a point of entry for understanding health aspects of surface-water management.

How is this book structured?

Protecting surface water for health is divided into four chapters (Fig. 1):

Figure 1 Structure of *Protecting surface water for health*



CHAPTER 1
Catchment risk assessment and management approaches

- Provides an understanding of surface-water protection
- Describes the integration of risk assessment and management frameworks for the protection of public and environmental health

CHAPTER 2
Hazards, their transport and attenuation

- Describes the main hazards to surface waterbodies alongside hazard and catchment characteristics influencing their transport and attenuation

CHAPTER 3
Hazardous activities in the catchment and their control

- Provides background information to support the assessment of pollution potential from the major catchment activities, alongside options for their control

CHAPTER 4
Assessing and managing surface-water risk through the WSP process

- Describes the identification, assessment and management of catchment-related risk within the WSP framework

Chapter 1 introduces the concept of developing a catchment-specific risk assessment and management plan for the protection of surface water and public health. It provides information on typical environmental risk assessment and management frameworks that may inform the development of drinking-water quality risk assessment and management plans, and vice versa. Chapter 1 also discusses some of the specific challenges faced by small water supplies.

Chapter 2 provides technical background information on the main hazards relevant to surface-water protection. It includes discussion of catchment and waterbody characteristics and processes that determine pollution pathways, such as:

- factors influencing hazard "transport" (i.e. the movement of a hazard from its source, through the catchment and waterbody, to the offtake point for raw-water abstraction); and
- hazard "attenuation" (i.e. the reduction, removal or retardation of a hazard within a catchment or waterbody).

Chapter 3 provides technical background information to support the assessment of potential pollution from the major human activities in catchments of surface waterbodies: agriculture; aquaculture and fisheries; wastewater and stormwater effluents; commerce, industry, mining and military sites; traffic; and recreational activities. Chapter 3 provides guidance on:

- conducting catchment inspections;
- identifying major polluting activities and events that introduce hazards to, or fail to remove them from, the water supply, which may lead to the presence of hazards in raw water; and
- identifying measures for the control of hazards.

Chapter 4 discusses how the WSP framework may be used to assess and manage catchment-related risks for the protection of surface-water quality and public health. This chapter integrates the general risk assessment and management guidance and technical information from Chapters 1–3 within the WSP process (after Bartram et al., 2009), focusing on the components of a WSP that address the assessment and control of risks in surface-water catchments.

Many different frameworks for catchment-related risk assessment and management are currently in use. The technical information and guidance presented in Chapters 1–3 may be applied under any risk assessment and management framework. However, this book focuses primarily on assessing and managing catchment-related risks under the WSP framework, which WHO considers the optimum water-quality risk assessment and management approach to protecting human health (WHO, In preparation-a).

CHAPTER 1

CATCHMENT RISK ASSESSMENT AND MANAGEMENT APPROACHES

Managing risks to public health that arise from drinking-water is typically seen as the primary duty of the entity responsible for drinking-water supply. However, most catchments are used by various stakeholders, including for purposes that may contaminate the raw water used for drinking-water. In such cases, close collaboration is required between the water suppliers and the stakeholders who can take action.

It is helpful to involve government agencies responsible for public health and the environment as allies in this communication process, because they can initiate the regulation of activities that influence water quality in the catchment. Information and tools required for the protection of raw water for drinking-water supplies are therefore particularly important for:

- water suppliers;
- public health professionals responsible for the surveillance of drinking-water quality; and
- representatives from other sectors active within the catchment (e.g. environmental protection, agricultural and industry).

This chapter introduces the concept of developing a comprehensive risk assessment and management plan for the protection of human health, with a specific focus on surface-water catchment aspects, and it discusses this in relation to environmental management issues. The particularities of risk assessment and management in small water supplies are also considered.

The provision of safe drinking-water at all times requires a preventive approach. Reliance on end-product testing for selected hazards alone is insufficient. In particular, for protection from pathogens, end-product testing is often “too little, too late” because:

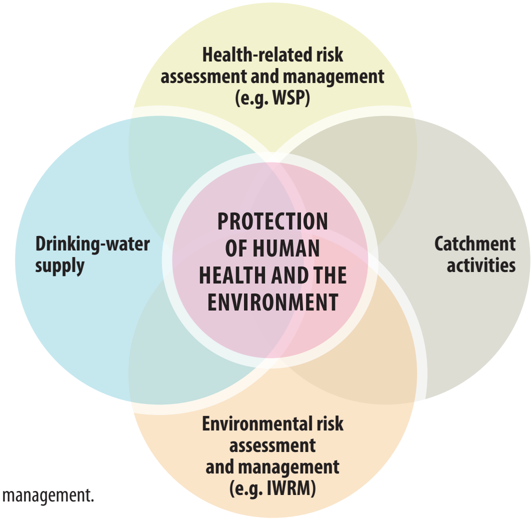
- there are inherent limitations with the use of microbial indicators of faecal contamination;
- water is likely to have been consumed by the time results are available;
- tested volumes are rarely statistically representative; and
- testing may not detect short-term fluctuations in microbiological quality.

These limitations explain why outbreaks have been reported in cases where no indicators of faecal contamination have been detected.

The overarching ideal is to supply drinking-water that is free from risk to public health, but in practice this is not always entirely possible or economically feasible. Therefore, the objective is to minimize the public health risk. A comprehensive, balanced approach to managing risks to achieve the drinking-water quality target requires a thorough understanding of the drinking-water supply system. In particular, it requires an understanding of the hazards that challenge the supply’s safety, the barriers in place and their efficacy, and the options for further measures that could be implemented to minimize the risk of contamination.

Although risk-management approaches to drinking-water quality always focus on protecting human health, they may also lead to environmental improvements (Fig. 2). For example, they may prioritize sanitation improvements, particularly in small systems. In addition, some environmental risk-assessment approaches target both human health and the environment. This chapter discusses frameworks for the assessment and management of drinking-water quality and environmental risks, and describes how these approaches can be integrated in a catchment setting.

Figure 2 Common ground between health and environmental management in drinking-water catchments



IWRM, integrated water resource management.

1.1 Health and environmental risk assessment and management frameworks

1.1.1 Health risk assessment and management frameworks

WSPs are a comprehensive, preventive approach to risk assessment and management (Bartram et al., 2009). They represent a holistic framework that considers the entire water-supply chain (from the source-water catchment through to the point of human consumption) for identifying and prioritizing water-quality risks and further measures required to mitigate risk. To best ensure the safety of drinking-water, WHO, through its GDWQ (WHO, In preparation-a) recommends the application of WSPs as the optimum approach for risk assessment and management of drinking-water quality. WSPs are typically developed by water suppliers with the aim of controlling hazards and the events that introduce such hazards to the system, and of increasing the overall safety of drinking-water. The WSPs provide the basis for system protection and process control to ensure that the numbers of pathogens and concentrations of chemicals and radionuclides do not exceed levels defined to meet the public health targets, and that water is acceptable to consumers. Hence, this publication focuses primarily on catchment risk assessment and risk management under the WSP framework. Detailed guidance on how to develop a WSP for a catchment is given in Chapter 4.

The process of developing a WSP typically builds on documentation and measures already in place (e.g. existing maps of the catchment, information on activities within the catchment and management measures for control of those activities). WSP development involves asking and answering the following questions:

- What are the hazards, hazardous events and resulting risks to public health in my supply system?
- How important are they?
- How do I fix them?
- How do I know they are fixed?

In this context, *hazards* are biological, chemical, physical or radiological agents that can cause harm to public health, and *hazardous* events are events that introduce hazards to the system, or fail to remove them from it. The resulting *risks* are described by a combination of identifying the likelihood that hazardous events will occur, and evaluating the severity of consequences if those events were to occur.

The approach advocates for the implementation of additional *control measures* (i.e. the activities and processes applied to reduce or mitigate risks) if the assessment reveals that the risks are insufficiently controlled. It also requires that management and communication plans be established and implemented, and be periodically revised to result in incremental improvements.

The key actions involved in the WSP process and the relevant chapters of this publication are presented in Fig. 3.

Figure 3 **Summary graphic of catchment-related actions (modules) within the WSP framework (after Bartram et al. 2009) and the corresponding section in this publication**

KEY ACTIONS

(including the relevant WSP module and corresponding section reference within this publication)

ASSEMBLE THE WSP TEAM

(Module 1; Section 4.1)

- Include responsible local authorities, regulators, licensing bodies and stakeholders
- Consider the need for expert input (e.g. hydrologists, limnologists and ecotoxicologists)

DESCRIBE THE CATCHMENT AND WATERBODY

(Module 2)

- *General checklist for characterizing the catchment and waterbody* (Section 3.2)
- *General checklist for activities in the catchment* (Section 3.2)
- *Activity-specific checklists* (Sections 3.3 to 3.8)

HAZARD ANALYSIS, CONTROL MEASURES AND RISK ASSESSMENT

(Modules 3 and 4)

- Identify hazards and hazardous events (Sections 2.1 and 2.2, 3.3 to 3.8, and 4.3.1)
- Assess the "degree of inherent protection" for the raw water (Section 4.3.3)
- Identify and validate control measures (Sections 3.3 to 3.8, and 4.3.4)
- Perform the risk assessment (Section 4.3.5)
- Determine the level of risk for the raw water at the point of abstraction (Section 4.3.6)

DEVELOP, IMPLEMENT AND MAINTAIN AN IMPROVEMENT AND UPGRADE PLAN

(Module 5; Sections 3.3 to 3.8, and 4.4)

- Document timings, responsibilities and resource requirements
- Prioritize based on the risk assessment ranking and available resources

DEFINE MONITORING OF THE CONTROL MEASURES

(Module 6; Section 4.5)

- Consider appropriate parameters, frequency of monitoring and responsibility
- Define appropriate critical limits and corrective actions for deviations

VERIFY THE EFFECTIVENESS OF THE WSP

(Module 7; Section 4.6)

- Consider end-point testing at the point of raw water abstraction
- Perform periodic internal and external audits of the WSP

PREPARE MANAGEMENT PROCEDURES

(Module 8; Section 4.7)

- Develop procedures (and associated corrective actions) for normal conditions and emergency situations

DEVELOP SUPPORTING PROGRAMMES

(Module 9; Section 4.8)

- Consider training, research and education needs (e.g. public, stakeholders)

PLAN AND CARRY OUT PERIODIC WSP REVIEW

(Module 10; Section 4.9)

- Schedule routine review meetings
- Update after changes in catchment (e.g. changes in activity or land use)

REVISE WSP FOLLOWING AN INCIDENT

(Module 11; Section 4.10)

- Revise the WSP following incidents, emergencies or near-miss events

1.1.2 Environmental risk assessment and management frameworks

Numerous risk assessment and management frameworks with an environmental focus are available and in use worldwide (Box 1.1).

Box 1.1 Examples of common environmental risk assessment and management frameworks

Integrated water resource management (IWRM): the process of managing water resources in an environmentally sustainable way across an entire catchment with the involvement of multiple stakeholders (also called "integrated water cycle management"). IWRM represents an iterative, adaptive process that takes a coordinated approach and considers the different uses of the water resource. For further information, refer to the Global Water Partnership (2009).

Environmental impact assessment (EIA): a one-off exercise conducted before the implementation of plans, programmes or projects that may have effects on the environment. It includes public participation, and aims to ensure that the environmental implications of decisions are taken into account before those decisions are finalized. In some countries, it is obligatory to conduct an EIA before major public undertakings.

Environmental risk assessment (ERA): an assessment that evaluates the potential adverse effects that human activities or substances have on the environment. It can be applied in various contexts, and is typically used for ranking alternative choices (e.g. for cleaning up contaminated sites) to balance invested resources – particularly costs – and benefits that can be achieved when dealing with a formulated problem.

ISO 14001: The ISO 14000 series of international standards are used as the basis for a continuous environmental management system tool for existing organizations. The goal is to identify and control the environmental impact of activities, products or services; to continually improve environmental performance; and to apply a systematic approach to setting future objectives and targets.

1.1.3 Comparison of health and environmental risk assessment and management

Differences between the risk-management paradigms for drinking-water quality and the environment can lead to some matters being considered important for public health but not relevant to the environment, and vice versa. For example:

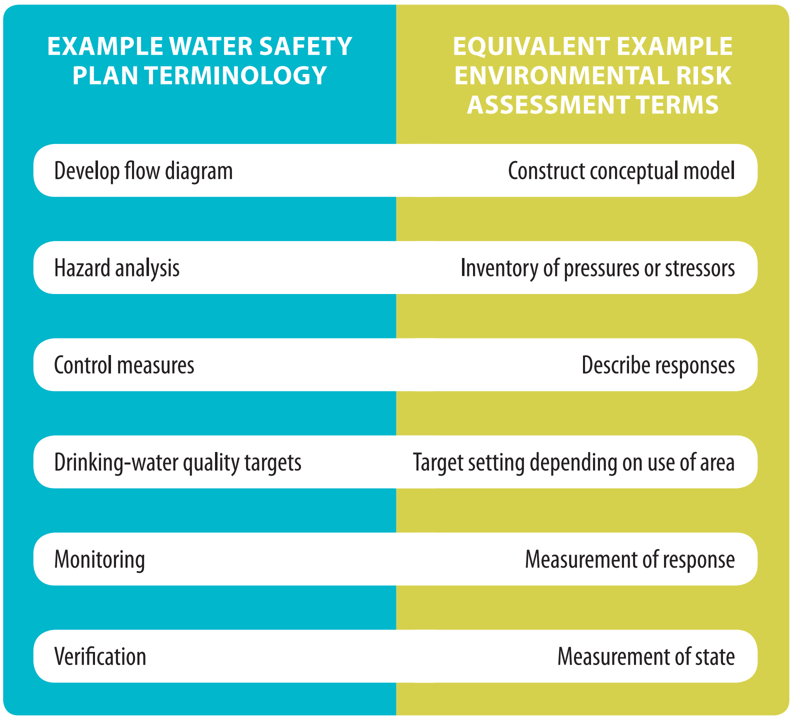
- pathogens causing illness in humans are typically not a threat to aquatic organisms, whereas barriers to fish migration (e.g. weirs and dams) are not significant with respect to human health;
- public health risk profiles tend to be dominated by the influence of short-term fluctuations (Teunis, Davison & Deere, 2003) and events that are rare or extreme, whereas environmental risk profiles tend to be dominated by longer term trends and the overall state of the environment;
- drinking-water quality risk-management systems (e.g. WSPs) take into account both acute and chronic effects to human health, whereas environmental risk assessments are likely to focus on chronic effects on the environment; and
- drinking-water quality risk mitigation frameworks should be applied continuously, whereas environmental risk-assessment frameworks can be one-off activities (e.g. undertaken before implementing significant activities in a catchment) or continuous processes.

These different risk-management paradigms can create conflicts between water supply and environmental risk targets when setting priorities in catchment management. The specific conflicts will depend on the nature of the catchment. If a mechanism has already been established for any of these processes, it can be beneficial to use this for an additional process. For example, if a working group has been established to manage catchments for environmental purposes, that group could add a WSP approach. This approach allows relevant stakeholders to be involved and reduces the work needed, mitigating the perception that yet another plan needs to be developed.

1.1.4 Integrating drinking-water quality and environmental risk assessment and management approaches

Risk assessment and management systems for both drinking-water quality and the environment use specific terms (or "jargon") to describe the principles and steps in their application. These terms originate from the respective health or environmental sector, and are not always familiar to professionals in other sectors; even worse, terms can sometimes mean different things to those in different sectors. This can cause communication difficulties, for example when applying WSPs within catchments. However, in practice, the differences are almost entirely semantic. A simple illustration is given in Fig. 4 to show how some examples of WSP steps match some examples of environmental risk assessment and management steps. When combining the WSP approach with environmental management approaches it may therefore be useful to prepare a table showing the respective terminology of each system.

Figure 4 **Comparison of example terminology from health (i.e. WSP) and environmental risk assessment and management approaches**



EXAMPLE WATER SAFETY PLAN TERMINOLOGY	EQUIVALENT EXAMPLE ENVIRONMENTAL RISK ASSESSMENT TERMS
Develop flow diagram	Construct conceptual model
Hazard analysis	Inventory of pressures or stressors
Control measures	Describe responses
Drinking-water quality targets	Target setting depending on use of area
Monitoring	Measurement of response
Verification	Measurement of state

Fig. 5 shows a possible example framework for managing water-quality issues in a catchment by integrating the WSP philosophy with existing approaches for environmental protection. Such an approach may protect water quality for the benefit of both human health and the environment.

Some experience is available of integrating the risk-management principles for drinking-water quality into the context of environmental risk management, and there are some legal frameworks calling for this (Box 1.2).

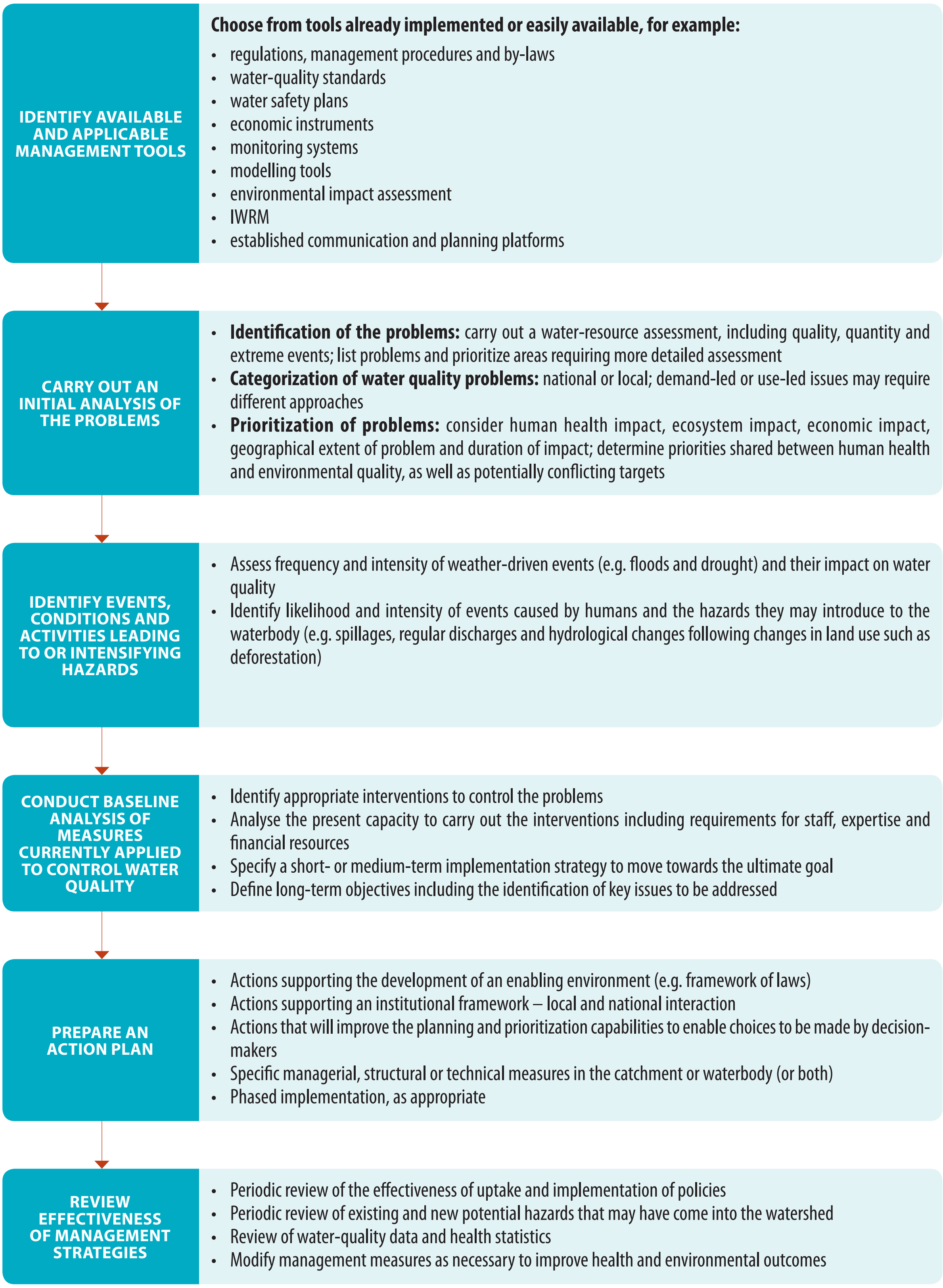
An early example of integrating the risk-management principles of drinking-water quality into the context of IWRM is that of Schneider et al. (2003), who describe integrated water cycle planning (IWCP) in New South Wales, Australia. IWCP is based, among other principles, on hazard analysis and critical control points (HACCP). The HACCP system was developed for the food sector, and is similar to the WSPs used for risk assessment and management of drinking-water quality. IWCP envisions that planning and managing of water supply, sewerage and stormwater are combined, with the demands and effects of each component taken into account. Steps completed as part of this approach include:

- identification of hazards to be addressed under the integrated water cycle plan;
- identification of associated water-management activities; and
- identification of control measures for management.

The approach takes into account balance outcomes planning, which assesses control measures against environmental, economic and societal objectives.

The basic management tool of the Water Framework Directive (EC, 2000) is the development of a river basin management plan, which must include details of significant activities in the catchment and their impacts, together with the measures taken to deal with these impacts. The use of techniques such as EIA and ERA and other environmental risk-assessment frameworks is an integral part of this process. For example, in England and Wales, 10 river basin districts have been identified, and two official bodies – in England, the Environment Agency, and in Wales, Natural Resources Wales – are responsible for implementation. The need for collaboration with numerous bodies, each responsible for different activities in the river basins, has been met through extensive public consultation (EA, 2009).

Figure 5 **Example framework for integration of WSPs with approaches for environmental protection**



IDENTIFY AVAILABLE AND APPLICABLE MANAGEMENT TOOLS

Choose from tools already implemented or easily available, for example:

- regulations, management procedures and by-laws
- water-quality standards
- water safety plans
- economic instruments
- monitoring systems
- modelling tools
- environmental impact assessment
- IWRM
- established communication and planning platforms

CARRY OUT AN INITIAL ANALYSIS OF THE PROBLEMS

- **Identification of the problems:** carry out a water-resource assessment, including quality, quantity and extreme events; list problems and prioritize areas requiring more detailed assessment
- **Categorization of water quality problems:** national or local; demand-led or use-led issues may require different approaches
- **Prioritization of problems:** consider human health impact, ecosystem impact, economic impact, geographical extent of problem and duration of impact; determine priorities shared between human health and environmental quality, as well as potentially conflicting targets

IDENTIFY EVENTS, CONDITIONS AND ACTIVITIES LEADING TO OR INTENSIFYING HAZARDS

- Assess frequency and intensity of weather-driven events (e.g. floods and drought) and their impact on water quality
- Identify likelihood and intensity of events caused by humans and the hazards they may introduce to the waterbody (e.g. spillages, regular discharges and hydrological changes following changes in land use such as deforestation)

CONDUCT BASELINE ANALYSIS OF MEASURES CURRENTLY APPLIED TO CONTROL WATER QUALITY

- Identify appropriate interventions to control the problems
- Analyse the present capacity to carry out the interventions including requirements for staff, expertise and financial resources
- Specify a short- or medium-term implementation strategy to move towards the ultimate goal
- Define long-term objectives including the identification of key issues to be addressed

PREPARE AN ACTION PLAN

- Actions supporting the development of an enabling environment (e.g. framework of laws)
- Actions supporting an institutional framework – local and national interaction
- Actions that will improve the planning and prioritization capabilities to enable choices to be made by decision-makers
- Specific managerial, structural or technical measures in the catchment or waterbody (or both)
- Phased implementation, as appropriate

REVIEW EFFECTIVENESS OF MANAGEMENT STRATEGIES

- Periodic review of the effectiveness of uptake and implementation of policies
- Periodic review of existing and new potential hazards that may have come into the watershed
- Review of water-quality data and health statistics
- Modify management measures as necessary to improve health and environmental outcomes

Box 1.2 Enabling environment to support the protection of raw water for drinking-water supplies

In some national and state contexts, the protection of source water is supported by regional or national policies, programmes, legislation and regulations. Types of support include education and awareness campaigns, assistance from experts in a range of subject matters, tools, funding schemes and regulations.

For example, in **Canada**, Chapter 22 of the province of Ontario's *Clean Water Act* (2006) sets out a framework for the development of source-water protection plans. The framework includes identification of stakeholders' roles and responsibilities; identification of risks; early action on identifying priority risks; and the development, implementation and regular review of source-water protection plans. It also covers the involvement of landowners, business owners, community groups, farmers, industry and the public. Where conservation authorities do not exist, the Act allows for the development of a locally driven, scoped planning process, and suggests that the community should consider participating in such processes.

In the **European Union**, Article 7 of the Water Framework Directive (EC, 2000) is aimed at protecting inland surface waters, transitional waters, coastal waters and groundwater. It states that "Member States shall ensure the necessary protection for the bodies of water identified with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking-water. Member States may establish safeguard zones for those bodies of water" (EC, 2000; EC, 2012).

In the region of **Eastern Europe, the Caucasus** and **Central Asia**, the schemes for integrated use and protection of water resources (UNECE, 2014) have similar features to IWRM. Also, primary legislation is in place in some of the countries to fully incorporate basin management. Horizontal coordination mechanisms are typically defined in the respective national water codes, and intersectoral coordination for water resource use has been established in Armenia, Kyrgyzstan, Tajikistan and Ukraine. For example, the Tajik Water-Energy Council of the Government, which meets twice a year, consists of members of various ministries and state agencies.

In the **United States of America** (USA), the Source Water Collaborative of the United States Environmental Protection Agency (US EPA) is a group of 26 organizations dedicated to protecting sources of drinking-water. The Collaborative includes other federal agencies such as the United States Department of Agriculture, state and utility associations, nongovernmental organizations (NGOs) and other partners. It provides planning resources and technical support for local, state and regional source-water partnerships, with a focus on reducing nutrient pollution.

In the Thames river basin, for example, lakes and rivers surface waters are widely used for producing drinking-water. An extensive number of organizational contacts were identified to ensure that, under the water treatment regime in operation, the potable water produced met the quality standards of the drinking-water directive. To support this, and to avoid deterioration of source-water quality and reduce the level of treatment needed, protection zones – so-called "surface water safeguard zones" – were designated. Action focuses on these zones, through joint initiatives by the regulatory bodies and water companies.

Advantages of integrating health and environmental risk assessment and management

The first barrier to contamination in a drinking-water supply is the catchment of the waterbody. As explained above, although not all hazards to human health are relevant to aquatic ecosystems, there is some overlap between environmental management for environmental protection and for the protection of human health. Where environmental management systems are in place, they may usefully support catchment management for drinking-water supplies, and it may be possible to expand the systems to include drinking-water quality targets, as shown by the example in Box 1.3.

Box 1.3 Combining environmental land protection and drinking-water protection in Cape Town, South Africa

In the **City of Cape Town, South Africa**, 60% of the three major water-source areas are subject to land protection. One of the challenges here was the presence of invasive plants that use large amounts of water, which reduced the amount of water in surface waterbodies. For example, the annual runoff in these areas was reduced by almost one third. The Working for Water programme, under which people remove invasive plants, is funded by the national government and has been active since 1995. The City of Cape Town collaborates with this programme to reduce invasive plants in the area of its main surface-water source for drinking-water, the Wemmershoek Dam. Thus, the programme serves both drinking-water supply and environmental protection purposes, and also creates jobs for the people involved in plant removal.

Source: After The Nature Conservancy (2014).

There are advantages to considering health and environmental risk assessment and management together. One advantage is that information already available from implementation of one approach can be used when implementing the other. For example, chemical hazards may affect both aquatic organisms and humans, and the events causing these hazards to reach a waterbody are the same, whether it is risks to humans or to the environment that are being considered. Another advantage is that important considerations in the overall management of a surface-water resource may include not just human health aspects, but also environmental aspects, risks to aesthetic quality, and recreational, industrial and agricultural uses of water. For example, sanitation safety plans (SSPs) are increasingly being developed (WHO, 2015a). SSPs are sometimes linked to or included in WSPs (i.e. creating water and sanitation safety plans), to pay due attention to the whole water-supply cycle, including wastewater production and discharge. Such approaches consider the influence of sanitation on drinking-water quality and the application of wastewater in agriculture and aquaculture (Box 1.4).

Box 1.4 Sanitation safety plans

Sanitation safety planning (as described in WHO, 2015a) is a risk-based management tool for sanitation systems. It assists in:

- systematically identifying and managing health risks along the sanitation chain – such risks include those from generation of wastes, conveyance of wastes (e.g. in sewerage systems), treatment of wastes, use of sanitation by-products (e.g. in agriculture) and discharge into the environment;
- guiding investment based on actual risks, to promote health benefits and minimize adverse health impacts; and
- providing assurance to authorities and the public on the safety of sanitation-related products and services.

The hazards, hazardous events and associated management plans developed in the SSP process can, and should, inform catchment risks in water safety planning. These can be at a macro catchment scale (with diffuse or point-source releases) or at the level of a small community.

For example, in **Kampala, Uganda**, wastewater treatment plants discharge to a swamp and then to Lake Victoria, which acts as the drinking-water source for Kampala. One of the objectives of the SSP was to protect the Lake Victoria drinking-water catchment. Hence, the SSP included water-quality monitoring along the treatment process and discharge canal, and in Lake Victoria itself.

Another example is that of **Benavente, Portugal**. Here, the SSP process for an inter-town sanitation and drainage system included development of plans for better and more consistent monitoring of watercourses in proximity to the sewerage system, and monitoring of activities in the protection zones for the water sources.

Further information on this topic is given in WHO's manual on sanitation safety planning (WHO, 2015a).

There is likely to be much overlap between the risk paradigms for drinking-water quality and the environment in relation to structural ecosystem elements. Such overlap includes:

- the establishment of vegetation buffers along shorelines to mitigate loads from surface "run-off";[1]
- construction of wetlands not only for wildlife, but also to create retention zones that allow for natural degradation of contaminants (which includes retention time for the inactivation of pathogens);
- the target of reducing "eutrophication"[2] – although in this case, the motivations differ:
  - for the drinking-water supply, it is high algal and cyanobacterial biomass that challenges the treatment process, with cyanobacterial toxins potentially present being a hazard to human health; and
  - for aquatic ecosystems, it is the deterioration of biodiversity that reduces environmental quality.

Thus, both approaches share the target of avoiding chemical risks, but microbial risks are more significant in protection of human health.

1.2 Catchment risk assessment and management considerations in small water supplies

The precise definition of "small water supplies" varies among countries; for example, population size, amount of water supplied or the type of supply are used to define such supplies within regulations and policies. However, it is typically their common challenges that set small water supplies apart from large utilities. Worldwide, small supplies are often those most

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[1] Run-off, also sometimes referred to as "overland flow", is defined as water from precipitation or irrigation that does not evaporate or seep into soil but flows into rivers, streams or lakes, and that may carry eroded sediment (WHO, 2003b).

[2] Eutrophication is the enrichment of a waterbody with nutrients that may lead to excessive biomass production (see Section 2.1.3).

vulnerable to contamination and breakdown. As such, even in developed countries these water supplies pose potential health risks.

Box 1.5 Challenges facing small water supplies

According to WHO and the United Nations Economic Commission for Europe (WHO & UNECE, 2011), challenges that set small water supplies apart include the following:

- different regulations or lack of regulations for small-scale water supplies (including lack of or reduced monitoring of water quality);
- lack of awareness, knowledge, attention and responsibility;
- lack of staff, undertrained staff, limited knowledge on the management of small supplies and larger geographical spread;
- greater vulnerability to contamination and limited water-source protection;
- limited water treatment; and
- larger per-unit cost of materials and construction.

In many settings, no comprehensive information is available at the national level on small-scale water supplies, including data on drinking-water surveillance and quality. However, there is some information suggesting that compliance levels are often lower in small-scale water supplies than in larger systems – as shown, for example, in a survey of the European Commission (EC, 2014).

In rural areas where sanitation facilities are in close proximity to drinking-water supplies, an approach of strongly integrating sanitation aspects into WSP methodology is beneficial because it takes into account the significant effect sanitation may have on small-scale supplies.

As is the case for large utilities, many different stakeholders may need to be involved when developing a WSP for small supplies. Stakeholders include catchment authorities, water-quality regulators (e.g. government health and environment ministries), landowners, business owners, community groups (including representatives of informal settlements), farmers, fishery or fisher folk, general industry and the public (see Section 4.1 for further discussion of stakeholder considerations). Stakeholder considerations can be an important issue in small communities where resource-protection measures limiting commercial activities can threaten the livelihoods of a substantial proportion of the community. Conversely, protecting the raw water may be the most effective intervention, particularly where resources are limited and treatment options are lacking (or their operation is unreliable). For example, in situations where the raw waters come from areas used only for extensive pasture, keeping livestock out of the watercourse may be the most important protection measure, and may be fairly straightforward to achieve through fencing and regular inspection of fence integrity. Where protection of raw water for drinking-water is neglected and this affects others, social controls may be effective in exerting pressure for better practice in small communities.

A community may be intimidated when trying to address a large upstream industry that is discharging effluent into the community's raw water for drinking-water supplies, particularly if that industry is the main employer for the community. The community can seek to initiate and influence indirect interventions; for example, identifying the authority responsible for the activity, and negotiating possible raw-water protection interventions, potentially involving another party such as catchment authorities or NGOs. In situations where water supplies are managed at household level, or where the community is dispersed over a wide geographical area, surface-water protection activities are best supported by country- or state-level programmes that provide education and awareness, technical support and, ideally, funding. If it is difficult for the WSP to cover the entire catchment of a small community water supply, and if a number of communities are served by the same large raw-water source, it may be useful to work together to assess and manage the catchment area. Such collaboration is best initiated by a responsible authority, but where governmental structures are lacking it can also be initiated by local communities or professionals supporting management of small water supplies.

Small communities should also draw on networks of expertise, because the networks will have a greater capacity, experience and possibly authority for raw-water protection than the community members themselves. For further information on setting up an effective team for addressing catchment-related risk under the WSP framework, see Section 4.1.

CHAPTER 2

HAZARDS, THEIR TRANSPORT AND ATTENUATION

This chapter provides technical background information on the main hazards relevant to raw water for drinking-water supplies, how those hazards may reach the waterbody and the processes through which they may be attenuated.

Section 2.1 describes various hazards relevant to surface-water protection for public health: microbial, chemical and eutrophication and, to a lesser extent, physical and radiological. The characteristics of these hazards are discussed with relevance to their transport and attenuation within a catchment, from their source to the point of offtake for drinking-water supplies. Section 2.2 describes the features and processes within a waterbody that influence the transport and attenuation of these hazards within a catchment. This information is key to assessing the risk posed by particular catchment activities and hazards to a given waterbody.

Hazards may be introduced to the catchment or directly into the waterbody through human activities (e.g. urban, industrial or agricultural activities). Some may also originate from natural sources such as wildlife (e.g. some pathogens), bedrock (e.g. fluoride) or atmospheric deposition (e.g. after wildfires or volcanic eruptions). It is important to:

- identify hazards and their sources;
- assess which hazards and sources may be the most relevant in a given setting; and
- assess by which pathways hazards may reach the surface waterbody and the point of offtake for drinking-water supplies.

Understanding the activities in a catchment that may introduce hazards to the waterbody (discussed in Chapter 3) is important to identifying risks. In many cases, some information from chemical and microbiological analyses will be available at the outset of the process, even if there is no comprehensive overview of the activities. Such information may be available from sources such as independent surveillance of drinking-water quality, raw-water analyses, analyses performed by the entity responsible for the water supply or research projects. On its own, such information does not indicate the sources of the hazards, which need to be known in order to develop the most effective control measures. However, it does provide valuable information for assessing the risks to human health from the contaminants that may be present in the drinking-water supply. In particular, such information may trigger the catchment assessment described in Section 3.2, to identify likely sources of contamination. In addition, information on hazards known to occur can be obtained using direct observation of a waterbody (e.g. visual indications, such as turbidity or algal blooms).

The two approaches to identifying catchment-related risks – that is, analytical results and observations, versus assessment of the pollution risks from activities in the catchment – are complementary and may inform each other. On the one hand, results of water-quality analyses can indicate potentially contaminating activities within the catchment (see Box 2.1).

Box 2.1 Role of raw-water analysis – regular monitoring and specific screening programmes

Data from the analysis of raw water are highly valuable to complement inspections of the catchment and inventories of activities therein (see Chapter 3). Hence, such data support hazard analysis and risk assessment. Water-quality monitoring data in the catchment can:

- identify existing hazards;
- provide early warning of source contamination;
- be the basis for developing adequate control measures (e.g. treatment requirements); and
- show whether corrective action for managing catchment-related risks has worked.

The number of samples that can be taken and the range of parameters that can be analysed may also be influenced by available financial and staff resources, and it is rarely possible to analyse for the full range of hazards identified as potentially occurring. A highly useful approach is a screening programme for an extended list of parameters, tailored from information about activities in the catchment that may be emitting specific contaminants. This can start with a one-off exercise that will not capture contaminants occurring irregularly, but nevertheless will provide baseline information on the water quality, including on "geogenic contaminants" (i.e. contaminants derived from underlying country rocks and their sediments; e.g. arsenic and fluoride) potentially present and radioactive substances (e.g. naturally occurring radionuclides). This information may be supplemented by incident-driven or periodic screening (e.g. during certain seasons or weather conditions) of a limited set of parameters (e.g. microbial indicators of faecal contamination). It may also be possible to request and collect monitoring or screening results for the surface-water resource from reliable third parties, such as the monitoring programs of local or national agencies.

For all of these data sources, it is important to evaluate the significance of the monitoring results during the risk assessment and to perform a plausibility check. Ideally, the outcome of such screening programmes will be a limited set of parameters that will be regularly monitored in raw water (e.g. microbial indicators of faecal contamination and selected chemicals).

On the other hand, the identification of potentially contaminating activities can lead to the development of a monitoring programme for the verification of water quality, by showing which parameters to include. A useful practical guide to the design and implementation of freshwater quality studies and monitoring programs is given by Bartram and Ballance (1996).

2.1 What are the main hazards?

Sections 2.1.1 to 2.1.5 focus on the main hazards that are associated with surface water, and that may pose a risk to human health when such water is consumed as drinking-water. The GDWQ (WHO, In preparation-a) should be consulted for further information on hazards, including those not covered in this chapter.

Hazards may be introduced by different activities conducted in the catchment, some of which are described in Chapter 3. The types of hazards are numerous and not limited to the examples given below, and their presence depends both on the human activities and natural conditions in the particular catchment. In some cases, comprehensive monitoring data are available that may indicate the range of hazards that occur in the system. However, such data should not be regarded as the only, or even the main, source of information. They cannot replace catchment assessment; that is, identification of potential pollution sources and the hazards they may introduce.

2.1.1 Microbial hazards

This section describes microbial hazards of significance to surface waterbodies and public health, as well as their characteristics relevant to transport and attenuation processes. The focus is on pathogens for which there is evidence – from studies of outbreaks or from prospective studies in non-outbreak situations – of diseases being caused by ingestion, inhalation of water droplets or dermal contact with water (WHO, In preparation-a). More specific information on the different pathogens that can be present in surface water can be found in the GDWQ (WHO, In preparation-a).

Humans, animals and the environment itself serve as reservoirs and sources of microorganisms that are hazardous to public health, the so-called waterborne pathogens. Human pathogens may be bacteria, viruses or parasites; these microorganisms differ in size, surface charge and other parameters that affect their persistence, and therefore their fate and transport in the aquatic environment. Waterborne pathogens in surface waterbodies are typically of faecal origin, chiefly from humans as well as animals (i.e. "zoonotic" pathogens that originate in animals but may be transferred to humans, where they may cause infection). Microbial hazards can be introduced into the waterbodies from sources such as human faecal material (including from sanitation), agricultural activities, wildlife and boat traffic, and (sometimes) from use of the water for recreational and ritual purposes (see also the relevant activity sections in Chapter 3). Most cases of disease linked to drinking-water consumption are the result of diarrhoeal diseases spread by the faecal–oral route (i.e. originating in faecal material and subsequently ingested by a host). Many outbreaks of waterborne disease have been attributed to surface-water contamination with these pathogens. Waterborne pathogens present the greatest public health risk for all water supplies that use either surface water or groundwater influenced by surface water.

In the USA, outbreak investigations have identified the agents causing disease (e.g. microorganisms and their toxins), and deficiencies in the treatment and distribution of drinking-water (Table 1). Such investigations have exemplified the high risk associated with unfiltered surface-water systems (Craun, 2012).

Table 1 Examples of specific waterborne disease outbreaks in the USA (1971–2008)

Pathogen	No. of outbreaks	No. of cases
Campylobacter spp.	19	5 608
Cryptosporidium parvum	12	421 301
Giardia intestinalis	115	28 161
Noroviruses	38	14 398
Total	**184**	**469 468**

Source: Craun (2012).

It was estimated that, in the USA, exposure to municipal surface-water systems resulted in about twice as many infections (26 million per year) as did exposure to both community and non-community groundwater systems (13 million per year) (Reynolds, Mena & Gerba, 2008).

Table 2 presents information relating to sources and reservoirs of waterborne pathogens, and Fig. 6 shows potential routes of human exposure. For some bacteria, the environment may serve as a reservoir of naturally occurring human pathogens in surface waters. Examples include *Vibrio* and *Legionella* (Table 2). In general, pathogens originating from humans and animals inactivate or "die off", and cannot grow in surface waterbodies, whereas those deriving from the environment can. Waterborne pathogens originating from environmental sources can grow to high levels in surface waters under specific conditions that are determined mainly by temperature and nutrients.

Table 2 Waterborne pathogen sources and reservoirs

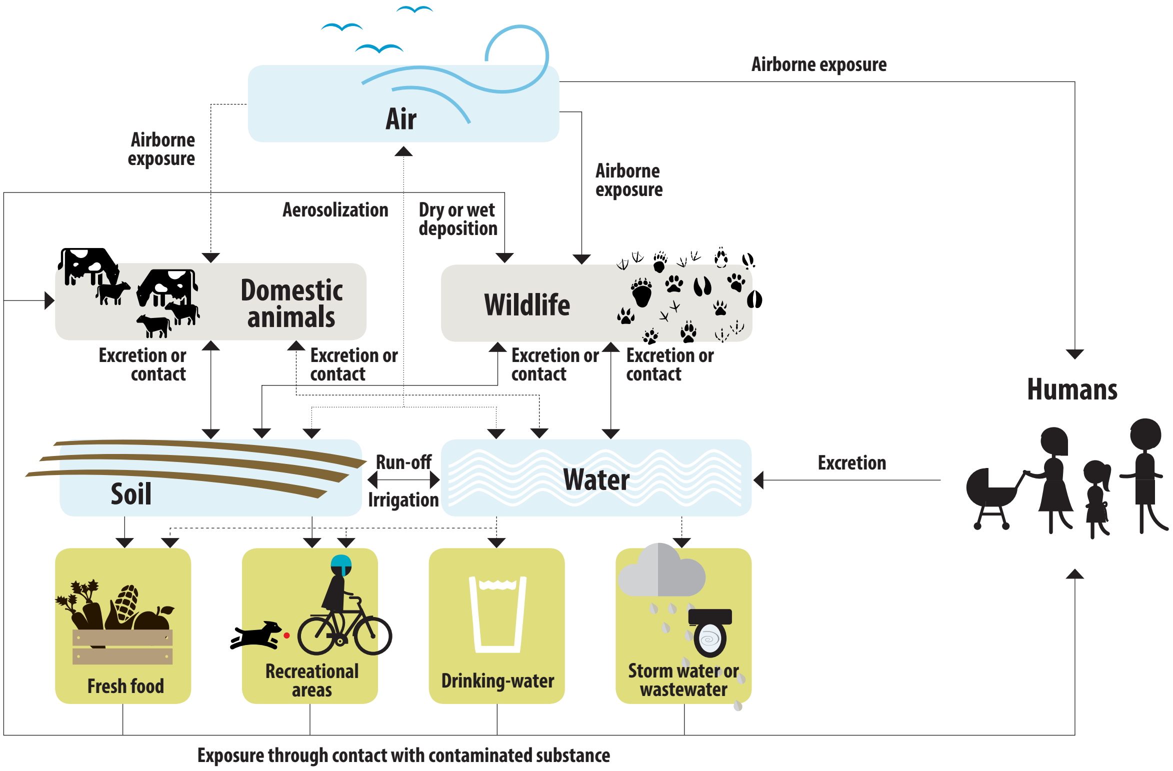
	Source		
Pathogen	**Human**	**Animal**	**Environmental**
Acanthamoeba			●
Adenovirus	●	●	●
Cryptosporidium	●	●	
Escherichia coli 0157	●	●	
Enterovirus	●	●	
Giardia	●	●	
Hepatitis A virus	●		
Legionella			●
Mycobacterium (nontuberculous mycobacteria)			●
Naegleria fowleri			●
Norovirus	●		
Rotavirus	●	●	
Shigella	●	●	
Staphylococcus aureus	●		
Vibrio	●	●	●

Source: Adapted from de Roda Husman and Sketch (2010).

Occasionally, waterborne pathogens from environmental sources have been found to be relevant and to pose some health risk (e.g. *Legionella* in the hot water systems of large buildings). However, most waterborne outbreaks of infectious disease with substantial health risks result from pathogens originating from humans and animals.

It is impractical to analyse a wide range of pathogens from all potential sources, and impossible to analyse for as yet unknown human pathogens. A more effective approach is to monitor the raw-water quality for indicators of pollution sources that introduce pathogens, particularly faecal pollution (referred to as "faecal indicators"; see Box 2.2).

Figure 6 Schematic diagram of environmental compartments, contamination sources, exposure-relevant sites and processes affecting the survival and spread of pathogens



Box 2.2 Microbial testing in source waters

Examples of faecal indicators used for microbial monitoring

E. coli is a common bacterium found in faeces (in excess of 100 million bacteria per gram of faeces is possible). *E. coli* is an effective microbiological indicator of recent faecal contamination of water for the following reasons:

- it is present in high numbers in faeces;
- most types of *E. coli* are harmless;
- it is normally absent in uncontaminated water;
- when shed with faeces it is slowly inactivated and destroyed, but in water it normally survives for at least as long as other waterborne pathogens (e.g. the bacteria that cause typhoid fever, cholera and dysentery); and
- it is relatively easy to detect.

These characteristics support the use of *E. coli* to indicate potential risks of human waterborne disease, and in the GDWQ it is considered the more specific faecal indicator of recent contamination (WHO, In preparation-a). Although there is evidence of *E. coli* growth in some environments – particularly tropical environments (Byappanahalli & Fujioka, 1998) – this growth is atypical and is less common than growth of other environmental thermotolerant coliforms.

The group of thermotolerant coliform bacteria includes, in addition to *E. coli*, other species of enteric bacteria from the genus *Escherichia*, and some species of the genera *Klebsiella, Enterobacter* and *Citrobacter*. The thermotolerant coliform test has fallen into some disfavour for the assessment of human health risk, mainly because of the natural presence of thermotolerant coliforms in the environment in tropical and some temperate countries. Hence, the detection of these bacteria does not necessarily indicate the presence of human and animal wastes in a water sample. Accordingly, *E. coli* should be the first organism of choice in monitoring programmes for verification, including surveillance of drinking-water quality, with thermotolerant coliform bacteria considered a less reliable but acceptable alternative indicator of faecal contamination (WHO, In preparation-a).

Testing for reference pathogens in source waters

Reference pathogens are representative pathogens for three microbial groups: bacteria, parasites and viruses. Testing for reference pathogens in source waters is typically used as a basis for determining performance targets (i.e. the required Log reduction values for specific pathogens). Testing is expensive and is normally restricted to well-resourced water utilities. Alternatively, performance targets may be based on estimates of reference pathogen concentrations, as described in the GDWQ (WHO, In preparation-a).

Human sources

Concentrations of pathogens from human sources in surface water depend on the number of pathogens in faeces from humans, the population density, infections prevalent in the population and the pathways into water. The pathogen concentrations in faeces are higher than those in receiving waters, whether those waters are surface water or wastewater (see examples in Table 3). From human sources, pathogens reach the surface waters from open defaecation sites through overland run-off of rainfall or from wastewater systems by overflows of untreated wastewater and discharges of (partially) treated wastewater. Other routes may be disposal of human waste from boats or houses, directly from humans working in or near surface waters, or from swimmers and other recreational water uses (see Sections 3.5 and 3.8).

Table 3 Occurrence of pathogens in faeces and wastewater (adapted from WHO, In preparation-a)

Pathogen	Number per gram of faeces of humans with infection	Number per litre from untreated wastewater
Campylobacter spp.	10^6	$100–10^6$
Vibrio cholerae[a]	10^6	$100–10^6$
Enteroviruses	10^6	1–1 000
Rotaviruses	10^9	50–5 000
Cryptosporidium	10^7	1–10 000
Giardia intestinalis	10^7	1–10 000

[a] *Vibrio* can grow in the aquatic environment.

Sources: AWWA (1999); Bitton (2005); Feachem (1983); Gerba et al. (1996); Jones, Betaieb and Telford (1990); Koenraad et al. (1994); Lodder and de Roda Husman (2005); Lodder et al. (2010); Maier, Pepper and Gerba (2000); Masini et al. (2007); Metcalf & Eddy Inc (2003); Rutjes et al. (2009); Schijven and de Roda Husman (2006); Stampi et al. (1992); Stelzer et al. (1989).

Animal sources

Animals that may contribute to contamination of surface waters with zoonotic pathogens include wildlife, livestock and companion animals. Livestock may include cattle, poultry, pigs, sheep and goats. Infected animals will excrete pathogens in their faeces. In particular, age is a significant factor with regards to pathogen occurrence in animals; for example, bovine calves are an important reservoir for *Cryptosporidium* (Sanford & Josephson, 1982). The largest contributions of zoonotic pathogens may be expected from run-off of animal manure after its application on land. Different types of husbandry animals produce different types of manure (liquid or solid) in different amounts. Survival of pathogens in liquid and solid manure may be different (Guan & Holley, 2003). Both the intrinsic characteristics of the pathogens and the environmental conditions determine pathogens' survival. For example, pathogens generally survive longer in environmental samples at low temperatures. Pathogens in manure reach surface waters via run-off from agricultural areas fertilized with manure, from grazing pastures and from direct defaecation to stream margins accessed for stock watering and, particularly, from feedlots. The amounts of pathogens depend on the conditions of the area; for example, slope of the terrain, vegetation cover and ploughing practices, and in particular the intensity of rainfall events (see Section 2.2.1 and Section 3.3).

Wild animals that may contribute to contamination of surface waters include pest animals (e.g. rats and other rodents), wild birds, various species of waterfowl, small wild mammals such as marmots, and large ruminants. The faeces of these animals can also be a source of pathogens in surface waterbodies.

Wild animals may be infected with bacteria such as *Campylobacter* and *Leptospira* (associated with leptospirosis or Weil's disease), viruses such as hepatitis E viruses, and parasites such as *Cryptosporidium* and *Giardia*. Wild fowl are an important source of *Campylobacter*. Faeces from wild animals may reach surface waters by direct defaecation into the water or by overland run-off caused by rainfall. Data on faecal production and numbers of pathogens per gram of faeces are scarce. However, for estimates of loads to watercourses, concentrations can be assumed to be similar to those of the more extensively studied husbandry animals of similar species and size. Additional information is given in the WHO publication *Animal waste, water quality and human health* (WHO, 2012a).

Occurrence in surface water

A wide range of variation can be expected for pathogen concentrations in waterbodies, because a range of factors determine their occurrence – in particular, illness currently prevalent in a human or animal population. For example, some enteric viruses (i.e. those associated with the digestive tract; e.g. rotavirus and norovirus) are known for characteristic seasonal patterns, whereas others (e.g. adenovirus) tend to occur year-round. The extent to which farm animals carry and spread pathogens will depend on stocks of farm animals, their access to water and the location of feedlots in relation to watercourses and run-off from erosion. Similarly, the extent to which wild animals carry and spread pathogens will depend on their contact with humans (which influences their rate of infection with human pathogens) and their population density (which influences the amount of faeces containing pathogens that they spread in a catchment). The loads reaching a waterbody from wastewater inflows or surface run-off will vary, as will percentages of wastewater and surface water, and environmental conditions (e.g. Westrell et al., 2006). In theory, the concentrations to be expected can range from zero to those concentrations found in wastewater or the run-off from a farm or feedlot; however, the actual concentrations will depend on attenuation processes and environmental conditions.

Table 4 shows an overview of the concentrations of selected waterborne pathogens in fresh surface water reported from different countries. Their span reflects substantial variations in conditions, such as season or presence and proximity of human and animal faecal sources and probably the stream flow status at the time of the sample acquisition. Higher concentrations occur near wastewater discharges. *Cryptosporidium* and *Giardia* concentrations are higher in agricultural environments, where run-off from land carries these pathogens into watercourses.

Table 4 Reported concentrations (numbers per litre) in river water of enterovirus, *Campylobacter*, *Cryptosporidium* and *Giardia*

Pathogen	Mean (n)	Median (n)	Maximum (n)	Reference
Enterovirus	3×10^{0} $(5 \times 10^{-3} - 4 \times 10^{1})$ [14]	3×10^{-1} $(0–2 \times 10^{0})$ [10]	2×10^{1} $(2 \times 10^{-2}–2 \times 10^{2})$ [15]	(Lodder et al., 2010; Payment et al., 2000; Shieh et al., 2008; Tani et al., 1995)[a]
Campylobacter	4×10^{3} $(10^{0} - 6 \times 10^{4})$ [16]	1×10^{4} $(2 \times 10^{0} - 4 \times 10^{4})$ [3]	2×10^{4} $(1 \times 10^{2}–2 \times 10^{5})$ [8]	(Arvanitidou et al., 1995; Brennhovd, Kapperud & Langeland, 1992; De Boer, 1996; Obiri-Danso & Jones, 1999; Stelzer et al., 1989; Till et al., 2008; Vereen et al., 2007; Wilkes et al., 2009)[b]
Cryptosporidium	10^{0} $(0–10^{1})$ [47]	2×10^{-1} $(0–10^{0})$ [18]	4×10^{1} $(2 \times 10^{-2}–1 \times 10^{3})$ [47]	(Ayebo, Plowman & States, 2006; Denis et al., 2011; Helmi et al., 2011; Hoogenboezem et al., 2000; Hu, 2002; Kistemann et al., 2008; Mons et al., 2009; Montemayor et al., 2005; Payment et al., 2000; Robertson & Gjerde, 2001; Robertson et al., 2008; Robinson et al., 2011; Rose, Gerba & Jakubowski, 1991; Rouquet et al., 2000; Skerrett & Holland, 2000; Solo-Gabriele et al., 1998; Till et al., 2008; Wilkes et al., 2009)[c]
Giardia	3×10^{0} $(0–7 \times 10^{1})$ [38]	6×10^{-1} $(0–4 \times 10^{0})$ [17]	4×10^{1} $(0–6 \times 10^{2})$ [27]	

The values shown are the:

- mean
- (minimum–maximum); between the brackets is the wide span of the reported values included
- [number] of the reported mean, median and maximum values.

Note that some of the studies report mean values, whereas others report median values.

[a] Data are from the following countries: Canada, Japan, the Netherlands and the USA.

[b] Data are from the following countries: Australia, Canada, Germany, Greece, New Zealand, Norway, United Kingdom and the USA.

[c] Data are from the following countries: Belgium, Canada, England, France, Germany, Honduras, Ireland, Luxembourg, New Zealand, Norway, Scotland, Spain, Taiwan and the USA.

For enterovirus, *Cryptosporidium* and *Giardia*, mean concentrations reported span a range of about 4 Log units, and often they are found in the range of 1 pathogen in a 100 L or even a 1000 L sample. *Campylobacter* are more frequently found in higher concentrations, such as ≥10/L, and concentrations reported span an even wider range, of about 5 Log units.

For estimating concentrations at the offtake point for drinking-water supplies, published data are of limited value, providing only an initial estimate of concentration ranges to expect. Better estimates can be obtained by understanding the potential pathogen loads to the local waterbody and the attenuation processes within that waterbody, which will reduce concentrations that reach the drinking-water offtake. As discussed in detail in Sections 2.2.2 and 2.2.3, the most relevant attenuation processes for microbial hazards are dilution through water exchange, sedimentation and "die-off" or inactivation, which may be driven by ultraviolet (UV) light in the water column. Dilution and sedimentation, discussed in Section 2.2.3, are processes that act on all hazards that reach surface waterbodies. In contrast, inactivation is specific to microorganisms, and is therefore discussed in this section.

Inactivation or "die-off"

The time that a pathogen can persist in the environment is called "survival time". For the converse process, the term "inactivation" is more appropriate than "die-off" because some pathogens (e.g. viruses) are not "alive" in a strict sense unless they have infected a host cell. The inactivation rate of microbial pathogens, once discharged into a waterbody, is highly variable. It depends on the quality of the receiving waters – particularly the turbidity, oxygen levels, nutrients and temperature – and on the inherent characteristics of the pathogen.

Nutrients that increase the survival rates of some pathogens normally stem from organic material deposited from nearby terrestrial areas. Their levels are influenced by adjacent vegetation, land-use factors, discharge characteristics and the ratio of rainfall to run-off.

The rate at which pathogens are inactivated on land and in water is highly related to temperature and UV irradiance. Equations for temperature-dependent Log_{10} concentration reductions for enteric viruses in surface water are given by Bertrand et al. (2012), for *Campylobacter* and *Cryptosporidium* by Schijven et al. (2013), and for *E. coli* by Franz et al. (2014). The mathematical equation for calculating temperature-dependent inactivation is as follows (Bertrand et al., 2012):

$$Log_{10}\left(\frac{C_{t,T}}{C_0}\right) = -10^{-(a_0+a_1T)}t \quad \text{(Equation 1)}$$

Where C_0 is the initial concentration (numbers per litre), t is the time (days), T is the temperature (°C), and a_0 (Log_{10} day^{-1}) and a_1 (Log_{10} day^{-1} °C^{-1}) are inactivation rate parameters.

Table 5 provides values for parameters a_0 and a_1 for a number of waterborne pathogens, and the time to reach 1 Log_{10} reduction in concentration (i.e. 10 times reduction). When using these data for predictive purposes, it is recommended that uncertainties be taken into account.

Table 5 Temperature-dependent inactivation of waterborne pathogens in surface water

			Time to 1 Log_{10} reduction (days)		
Pathogen	**a_0**	**a_1**	**10 °C**	**20 °C**	**Reference**
Enterovirus	1.8	–0.035	28	13	Bertrand et al. (2012)
Adenovirus	2.1	–0.036	55	24	Bertrand et al. (2012)
Norovirus	2.3	–0.036	87	38	Bertrand et al. (2012)
Campylobacter	0.53	–0.017	2.3	1.5	Schijven et al. (2013)
E. coli	1.04	–0.017	17	11	Franz et al. (2014)
Cryptosporidium	3.1	–0.078	210	35	Schijven et al. (2013)
Giardia	2.2	–0.07	31	6.3	Derived from data in DeRegnier et al. (1989)

See Equation 1 for the meaning of a_0 and a_1.

Pathogen survival is short in tropical climates, measured in the order of days, and can extend to months in winter in cold climates (as shown in Table 5, with the time to 1 Log_{10} reduction at 10 °C and 20 °C for a number of pathogens). Pathogens can persist for some considerable time in faeces, particularly in cold climates, where they can persist throughout the winter, to be released from land along with snowmelt or during storms (Kistemann et al., 2002; Tiedemann et al., 1987). Other factors, such as sunlight, can help reduce pathogen concentrations, but temperature appears to be the major driver affecting the rate of inactivation in most surface-water systems. In general, vegetative bacterial pathogens are the least persistent (surviving for days). Viruses have wide-ranging and typically intermediate persistence (surviving for days to weeks), based on special characteristics such as their small size, stability over a wide range of temperature and pH, resistance to various chemical agents such as oxidants and proteolytic enzymes, and propensity to aggregate and adsorb to surfaces of particles (see "Sedimentation and sorption" in Section 2.2.3). For virus inactivation, equations for including this uncertainty are given in Bertrand et al. (2012). Encysted protozoa have the greatest persistence (surviving for weeks to months) in most surface-water catchment environments. Oocysts and cysts of *Cryptosporidium*, *Giardia* and *Cyclospora* can survive for months in surface waters (IWA, 2001), with protozoan cysts survival times of up to 176 days reported.

Equation 1 assumes that inactivation proceeds as a first-order reaction; that is, the Log_{10} of the concentration decreases linearly over time. However, over longer time periods, the inactivation rate may slow down (de Roda Husman et al., 2009). Also, considerable uncertainty is involved in the predicted concentration reductions, which may span several orders of magnitude. For viruses (Bertrand et al., 2012) and for *E. coli* (Franz et al., 2014), the time to 1 Log_{10} reduction (T_{90}) may be higher or lower by a factor of about 10.

Combining Equation 1 with dilution estimates, it is possible to estimate pathogen concentrations in the river water at a point of interest – for example, an offtake point for drinking-water production or a bathing area – within about an order of magnitude. Using the example of *Cryptosporidium*, Schijven et al. (2015) gives a further model for this purpose. However, as mentioned above, there may be considerable uncertainty involved in the predicted concentration reductions.

Infectivity of human pathogens

Infection is defined as colonization, multiplication and possibly invasion of the gastrointestinal tract by the pathogen. It may be confirmed by microbiological examination of stool specimens and, in some cases, by determining an immune response. Often, infection will lead to symptoms of illness (Teunis et al., 1996), and when infection does occur without symptoms, the host still carries and transmits pathogens.

The probability of infection can be described by a dose–response relationship, and there are several models for such relationships. The simplest model is the exponential dose–response model, with a constant fraction of a pathogen giving infection. However, infectivity of pathogens often varies widely between the types or strains and conditions of a pathogen; it also depends on host susceptibility (i.e. the immune response). For some pathogens, only one or a few organisms can cause infection; examples include rotavirus, *C. jejuni* and *C. hominis*. For other pathogens, high numbers need to be ingested before infection occurs; examples include echovirus and *V. cholerae*. More complicated dose–response models may therefore be needed to reflect this range of infectivity.

Dose–response relations have generally been derived from studies in which a specific strain of the specified pathogen was given to human volunteers (Teunis, Chappell & Okhuysen, 2002a; Teunis, Chappell & Okhuysen, 2002b; Teunis et al., 1996). Details on dose–response models and data can be found in the following publications: Teunis et al. (2005); Teunis et al. (2002a); Teunis et al. (2002b); Teunis et al. (2010); Teunis, Ogden and Strachan (2008a); Teunis et al. (1996); Thebault et al. (2013); WHO (2016). For information on the use of dose–response relationship data for risk assessment, see "Risk-assessment considerations for pathogens" in Section 4.3.5.

2.1.2 Chemical hazards

Human health risks from chemicals in water are different from the risks caused by pathogens. The latter are of concern because they cause acute illness (possibly exponentially exacerbated through person-to-person contact), whereas only a few chemicals occur in drinking-water at concentrations that can result in acute health effects (WHO, In preparation-a). The vast majority of chemicals found in drinking-water are at low concentrations – in most cases, below a threshold of concern. Where concentrations are higher, they are usually of concern only after many years of exposure. Such concerns may relate to a wide range of health effects, including cancer, depending on the chemical involved.

A vast range of different chemicals can occur in surface waters. However, in each surface waterbody, only a fraction of these chemicals is likely to be present. Some chemicals can be of natural origin; for example, arsenic, fluoride and chromium (VI). However, human activity in the catchment can increase the concentrations of such natural chemicals to a waterbody; for example, by augmenting erosion. Many other chemicals originate from anthropogenic sources (i.e. human production and use of substances), and some can originate from both natural and anthropogenic sources. Only a small fraction of these chemicals have been shown to cause widespread health effects through drinking-water exposure when present at high concentrations (see "Inorganic chemicals" section). A few substances degrade to products more toxic than the parent chemical, and this may even happen through processes in drinking-water treatment such as oxidation; one example is dimethylsulfamide, which is produced by ozonation of the fungicide tolylfluanid as it degrades.

Where chemicals reach drinking-water from the environment (rather than from drinking-water treatment or distribution), drinking-water may well not be the only or even the major route of exposure. For example, where drinking-water is contaminated with pesticides used in agriculture, the major exposure pathways may be food and direct contact (e.g. by farm workers). Nevertheless, assessments of the risk to public health from such chemicals need to take all pathways into account.

Some chemicals also affect surface-water quality indirectly; for example, by causing oxygen depletion, or massive growth of planktonic algae or cyanobacteria, which may be of potential health concern and may render the water unacceptable for drinking due to taste and odour. Other chemicals, although not directly harmful to health, may impair the aesthetic or acceptability of the drinking-water by affecting turbidity, colour, taste and odour (see Section 2.1.4).

WHO establishes guideline values (or health-based values[1]) in the GDWQ when:

- there is credible evidence that they occur in drinking-water; and
- there is evidence of actual or potential toxicity.

Guideline values may also be established when the chemical is of significant international concern. Guideline values are generally set at levels intended for safe lifetime consumption; for more information, see the GDWQ (WHO, In preparation-a).

Only a small number of chemicals are likely to be found in a given drinking-water source at concentrations of significant health concern: in most cases, chemicals occur in drinking-water at very low or trace amounts. Although little is currently known about interaction of chemicals, or the risk and effects of mixtures, the potential for interaction and possible toxicity of the various chemical mixtures is limited if they occur in very low concentrations. Measures to control the occurrence of chemicals are therefore most effective for the protection of public health when they focus on the chemicals that are most likely to be present in a given waterbody, and to reach the raw-water offtake for drinking-water supplies at concentrations of potential health concern. Assessing which chemicals these may be in a given setting requires an understanding of the potential sources of these chemicals (for examples, see the activities described in Chapter 3) and the principles that govern their occurrence. Section 2.1.2 briefly describes the types of chemicals that may be found in drinking-water sources and the processes determining their transport and attenuation in catchments and waterbodies. Furthermore, the GDWQ (WHO, In preparation-a) provide a brief discussion of potential sources for each of the chemicals for which a guideline value or health-based value has been developed in those guidelines, in Chapters 8 and 12. A more extensive description for each

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[1] Guideline values and health-based values normally represent the concentration of a constituent that does not result in any significant risk to health over a lifetime of consumption. For some chemicals, no formal guideline values are established when occurrence is likely to be well below a level that would be of concern for health. Establishing a formal guideline value for such substances may encourage Member States to incorporate a value into their national standards when this may be unnecessary. When a formal guideline value is not established, a health-based value may be determined, to provide guidance to Member States when there is reason for local concern. This reference value provides both a means of judging the margin of safety in the absence of a specific guideline value and a level of interest for establishing analytical methods (for further information see Section 8.2 in the GDWQ (WHO, In preparation-a)). For simplicity, this publication references guideline values, although the GDWQ may have derived guideline values or health-based values.

chemical can be found in the background documents on the WHO website.[2] The WHO publication *Chemical safety of drinking-water* (WHO, 2007) provides guidance on which chemicals in a particular situation should be given priority in developing strategies for risk management and chemical monitoring in drinking-water.

Inorganic chemicals

Inorganic chemicals reaching surface water may arise from both natural and anthropogenic sources. The chemicals that have been shown to have widespread public health significance through drinking-water include arsenic, fluoride and, sometimes, nitrate (Table 6).

Table 6 Guideline values for selected chemicals that are of public health significance in drinking-water (after WHO, In preparation-a)

Chemical	Guideline value (mg/L)	Remarks
Arsenic	0.01	The guideline value is designated as provisional on the basis of treatment performance and analytical achievability
Fluoride	1.5	—
Nitrate	50	50 mg/L as nitrate ion (or 11 mg/L as nitrate-nitrogen) When nitrate is found with nitrite, the sum of the ratios of the concentrations of each to its guideline value should not exceed 1

Major ions

Ions potentially relevant for drinking-water quality include the cations sodium, potassium, calcium and magnesium, and the anions chloride, nitrate, sulfate and bicarbonate. Some of these ions affect water quality because, at high concentrations, they affect drinking-water acceptability by causing turbidity or unacceptable tastes and odours.

Major ions predominantly comprise the total dissolved solids (TDS) present naturally in waters; they are largely derived through water contact with soil, sediment or rock material. Elevated concentrations of major ions (>1000 mg/L TDS) may occur naturally through prolonged contact with soluble minerals, as may occur, for example, with groundwater before it flows into a waterbody. Major ions may also originate from direct anthropogenic inputs; for example, elevated levels of sodium or chloride in run-off containing de-icing salts (Meriano, Eyles & Howard, 2009), and discharges of wastewater that has been insufficiently treated or arise from contaminated urban or industrially used land. Nearby irrigation activities may also be a significant source of ions, where evaporative losses are high and groundwater with an elevated mineral content is used for irrigation. Elevated major ion concentrations of sulfate, for example, may arise from both natural sources (e.g. gypsum or anhydrite rock dissolution) and anthropogenic sources (e.g. urban sulfur oxides [SO_x], atmospheric sulfur emission and subsequent deposition, and use of agriculture fertilizers) (Kopacek et al., 2014).

The fate of major ions depends on the prevailing conditions and the ions' biogeochemical reactivity. In thermally stratified waters (i.e. waters with distinct layers arising from different temperature gradients; see "Shape, size and stratification of lakes and reservoirs" in Section 2.2.2), inorganic ions may accumulate in the deeper water layer. Calcium and magnesium, although not biodegradable, can undergo precipitation reactions with carbonate, sulfate and organic matter. Under the strongly reducing conditions found in high organic carbon environments (e.g. lake sediments), sulfate can be reduced to hydrogen sulfide (H_2S), which may in turn react with iron, manganese or some trace metals present and precipitate as largely insoluble sulfides. In lake or reservoir sediments, sulfate may increase the release of phosphorus (P), thus impairing water quality indirectly. In aerobic, mildly reducing conditions at concentrations below gypsum saturation (c. <1400 mg/L), sulfate will normally be conservative (i.e. display low chemical reactivity) and therefore transport without reaction, precipitation or sorption (i.e. the process by which substances attach, or sorb, to a solid or colloidal matrix; see "Sedimentation and sorption" in Section 2.2.3). Cations can behave conservatively; however, divalent magnesium and calcium (and ammonium), in particular, may be effectively sorbed by ion-exchange reactions onto clay mineral sediments or particulates, with accompanying release of monovalent sodium or potassium.

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[2] http://www.who.int/water_sanitation_health/water-quality/guidelines/chemicals/en/

Nitrogen

Nitrogen (N) occurs in surface water as nitrate (NO_3^-) and ammonium (NH_4^+), and as traces of nitrite (NO_2^-). Microorganisms can convert ammonium to nitrite and nitrate in a process known as "nitrification"; and under anoxic conditions (i.e. low oxygen), they can denitrify nitrate to atmospheric nitrogen (N_2) in a process known as "denitrification". Durand et al. (2011) give a comprehensive overview of nitrogen processes in aquatic systems.

Food is generally the main source of human exposure to nitrate. Nitrate is toxic to human infants through causing methemoglobinemia ("blue baby syndrome") by oxidizing haemoglobin (Hb) to methaemoglobin (metHb), which leads to infants being unable to transport oxygen to the tissues until they are about 6 months old. The WHO guideline value for nitrate in drinking-water is set at 50 mg/L as nitrate ion (which equals 11 mg/L as nitrate-nitrogen, NO_3-N) and 3 mg/L as nitrite ion (which equals 0.9 mg/L as nitrite-nitrogen, NO_2-N), which is protective of bottle-fed infants, the most sensitive subpopulation (see Table 6). Because of the possibility of the simultaneous occurrence of nitrate and nitrite in drinking-water, the sum of the ratios of the concentrations of each to its guideline values should not exceed 1. Nitrite in the presence of amines and low pH supports formation of carcinogenic nitrosamines in mammalian metabolism.

The weight of evidence from numerous epidemiological studies does not support an association between cancer and exposure to nitrate or nitrite per se. The International Association for Research on Cancer (IARC) has concluded that there is inadequate evidence in humans to determine the carcinogenicity of nitrate per se from exposure in food or in drinking-water, and that there is limited evidence in humans for the carcinogenicity of nitrite in food, although nitrite in food was associated with an increased incidence of stomach cancer (IARC, 2010). Overall, IARC (2010) has concluded that ingested nitrate or nitrite, under conditions that result in internal endogenous nitrosation (formation of N-nitroso compounds, which are recognized carcinogens), is probably carcinogenic to humans (Group 2A).

Although nitrogen occurs naturally in surface waters, concentrations in many parts of the world have become elevated where waters have been affected by diffuse sources of inorganic fertilizer, manure, soil drainage or sewage. Replacing pit latrines with flush toilets and sewerage protects groundwater from nitrate (and other hazards); however, it increases loads to surface waterbodies if wastewater treatment is lacking or is insufficient. In some countries, the introduction of denitrification in sewage treatment has reduced N-loads from such point sources, but loading from diffuse agricultural sources is generally more difficult to manage and reduce. Also, especially in countries where crop fertilization is widely practised, nitrogen may reach surface waters with biomass (i.e. organisms and decaying material).

Natural levels of ammonium in surface waters are generally below 0.2 mg N/L; elevated concentrations are an indicator of possible pollution with bacteria, sewage or animal waste, or perhaps industrial or landfill sources leaching to the waterbody. Since the presence of ammonia is usually transitory (because microbes will oxidize it to nitrate if oxygen is available), it may be indicative of ongoing or recent pollution.

Nitrite does not typically occur in natural waters at significant levels, except under highly (sulfate-) reducing conditions. Nitrite concentrations in treated effluents or wastewater seldom exceed 1 mg N/L and in surface waters they are usually <0.1 mg N/L.

Concentrations of nitrate in unpolluted surface waters are in the range 0.2–2.0 mg NO_3-N/L (equivalent to about 1–10 mg/L nitrate), whereas in wastewater effluents they may reach 20 mg NO_3-N/L (equivalent to about 90 mg/L nitrate). In catchments with extensive agricultural use, and in surface waters affected by sewage effluents, the nitrate concentration in receiving surface waters can exceed the drinking-water guideline value of 50 mg/L (as nitrate ion). Nitrate, nitrite and ammonia are very soluble in water, and they reach waterbodies through a combination of rapid surface run-off and much slower inflow from groundwater-based pathways. Where nitrate application with mineral fertilizer or manure has exceeded the demand and uptake by crops, nitrate may continue leaching to groundwater, and nitrate-contaminated "baseflow" (i.e. the portion of river flow derived from groundwater) may continue to reach surface water for many years or even decades after the original application to crops (Rivett et al., 2007; Sutton et al., 2011).

Significant denitrification occurs primarily in riparian buffer zones and in zones beneath and alongside stream beds where shallow groundwater and surface water mixes (Pinay et al., 2009; Rivett et al., 2008). The denitrification potential of gravel riverbeds is low if conditions are "oxic" (i.e. oxygen is present), but denitrification does occur in their sediments if these are anoxic and rich in organic matter.

Arsenic

The metalloid arsenic (As) is one of the few substances shown to cause cancer in humans through exposure via drinking-water. Epidemiological studies have shown a strong relationship between arsenic in drinking-water and several types of cancer, particularly skin, bladder and lung (WHO, 2004). IARC has classified arsenic as a Group 1 human carcinogen ("defined as carcinogenic to humans"), primarily on the basis of skin cancer (arsenicosis). The WHO guideline value for arsenic in drinking-water is 0.01 mg/L (Table 6).

Two dominant species of arsenic occur in the environment, depending on pH and oxidizing conditions. Arsenate, As(V), is negatively charged as $H_2AsO_4^-$ or $HAsO_4^{2-}$ at the typical pH range of surface waters. Arsenite, As(III), occurs mainly in its neutral form (H_3AsO_3) in surface waters, and is more soluble and mobile than arsenate. Arsenate can form adsorbates with a variety of organic and inorganic compounds such as ferric hydroxides, mineral surfaces and humic substances.

The sources, occurrence and behaviour of arsenic in natural waters have been reviewed by Smedley and Kinniburgh (2002). The study found that natural baseline concentrations of arsenic in river waters are normally low (usually 0.1–0.8 µg/L, and up to 2 µg/L). Most environmental arsenic issues are associated with release of this metalloid into groundwater from arsenic-rich bedrocks or sediments under natural conditions (Ravenscroft et al., 2005). High arsenic concentrations have frequently been encountered in moderately shallow alluvial aquifer systems; for example, the widespread occurrence in tube wells in the Bengal Basin, Bangladesh (Ravenscroft et al., 2005), and in the Mekong, Red River (Berg et al., 2007) and Yellow River basins (Guo & Guo, 2013).

Anthropogenic impacts may also be locally significant through some of the following activities:

- mining;
- smelter operations;
- fossil fuel combustion;
- the use of arsenical pesticides or herbicides and phosphate fertilizers;
- the use of arsenic in wood preservation; and
- the use of arsenic as an additive to livestock (poultry) feed.

The impact of arsenic on surface waters is principally via geothermal sources, baseflow of groundwater contaminated by arsenic-rich bedrock or sediment, or surface run-off and erosion of contaminated sediments, exacerbated by storm events. In such cases, arsenic levels in river water can reach several hundred micrograms per litre. Anthropogenic impacts to rivers have been observed from various sources (Smedley & Kinniburgh, 2002), particularly from urban and industrial sources. The use of arsenical products has decreased significantly in recent decades; however, impacts from former use may persist. Mine wastes and mill tailings may also be significant sources. Although arsenic may effectively accumulate in riverbed sediments due to sorption or surface reactions that form precipitates, it nevertheless has the potential to be released under certain biogeochemical-hydrological conditions, and gradual increases in concentration along some streams have been reported (Frau et al., 2013). Frau et al. (2013) discuss the ongoing challenges of remediating such mine-impacted river sediments.

Concentrations of arsenic in lake waters are typically lower than those found in river water, but elevated concentrations are generally ascribed to similar sources (e.g. mining activity and geothermal water). These lower values are ascribed to arsenic removal from solution by adsorption onto iron oxides under the neutral to mildly acidic conditions often encountered in lakes.

In stratified waterbodies (i.e. those with distinct layers caused by different densities of the water due to temperature or chemical gradients; see "Shape, size and stratification of lakes and reservoirs" in Section 2.2.2), arsenic concentrations may also show stratification, with a higher ratio of As(III) to As(V) in deeper water layers. Arsenite is usually very stable and mobile in surface waters.

The most important natural attenuation processes known for arsenic are adsorption onto or co-precipitation into insoluble minerals. In anaerobic environments, arsenic can be immobilized by precipitation of arsenopyrite whereas, in aerobic settings, adsorption onto iron oxyhydroxides can significantly reduce dissolved arsenic levels (Zheng et al., 2004).

Metals

The presence of metals depends strongly on the prevailing biogeochemical conditions. Metals may be present:

- as free ions;
- as dissolved inorganic and organic chemical compounds or complexes;
- as insoluble chemical compounds, complexes or precipitates; and
- adsorbed on suspended solids or sediments.

Hence, site-specific conditions need to be established on a case-by-case basis. Data on metals may usefully be evaluated with geochemical modelling tools, to predict fate and sensitivity to varying conditions. For example, PHREEQC (an acronym of pH-redox-equilibrium-C[3]) is a widely used and freely available modelling tool produced by the United States Geological Survey for simulating chemical reactions and transport processes in natural or polluted water.

Metals of interest for water quality include two groups:

- "trace metals", which are typically encountered at low, but potentially health-relevant concentrations (e.g. aluminium, barium, boron, cadmium, chromium, copper, lead, mercury, nickel, selenium and uranium); and
- metals typically encountered at more elevated concentrations, some of which may not be directly health relevant (e.g. iron and manganese; see Section 2.1.4).

Although the presence of metals in water may give cause for concern, a low level of intake of some metals (e.g. chromium, copper, iron, nickel, selenium and zinc) is a nutritional requirement, but some of these metals can become toxic or carcinogenic at high doses. In addition, metals present in drinking-water at elevated concentrations may lead to quality problems with taste and odour (e.g. zinc and iron), colour (e.g. iron), turbidity (e.g. aluminium), or staining of laundry and sanitary ware (e.g. copper, manganese and iron).

Metals often originate from a variety of sources; for example, aluminium occurs naturally (constituting about 8% of the earth's crust), is in almost all foods and is a component of food additives and personal-care products. Also, aluminium salts are commonly used in drinking-water treatment. It is not clear whether the presence of aluminium in drinking-water is of relevance to human health. Metals enter surface waters from natural weathering and volcanic activity, as well as anthropogenic sources (e.g. industrial and mining discharges, sewage effluents and landfill leachates). Atmospheric emissions from activities such as smelting, refining, power generation and waste incineration may be large, with subsequent dry or wet deposition.

Metals in waters not affected by human activity are generally present at background concentrations of less than 1 μg/L to a few μg/L. Comparison with the WHO guideline values for drinking-water indicates that, in general, metals do not often contaminate surface water in health-relevant concentrations; that is, exceedance of guideline values is occasional rather than widespread. However, concentrations may be locally higher where there are major inputs (e.g. from mine drainage or particularly polluting urban–industrial activities), or where acidification and de-oxygenation enhance metal desorption from sediment particles and solubility. In some regions, acid rain and disturbance of acid sulfate soils have led to soil and water acidification, and thus to increased metal concentrations in water. If copper, lead or nickel are found in tap water, materials used in the distribution pipework are a likely source to check before attributing these to the waterbody, as discussed in the WHO publication *Water safety in distribution systems* (2014c).

The greatest metal mobility is typically associated with low pH and dissolved-phase speciation. On discharge to surface waters, pH may return to near neutral and oxic conditions that may favour metal partitioning to suspended and riverbed sediments. Metal re-solubilization from sediments may occur when contrasting oxic and anoxic conditions develop due to organic matter deposition, or when there is variable mixing of surface water and groundwater. Metals within surface

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[3] "C" refers to C and C++ computer programming codes.

waters may accumulate in bed sediments downstream of urban or industrial source areas (Wildi et al., 2004), possibly over timeframes of decades and even centuries, due to significant partitioning to the solid phases. The potential remains for later mobilization via natural flood events, dredging activity or changes in biogeochemical conditions.

Anthropogenic organic chemicals

Many synthetic organic chemicals have been identified in surface waters. Some of these organic chemicals are only detected by highly specific non-routine analytical methods; others are picked up by routine monitoring. As methods are becoming increasingly sensitive, lower detection limits are resulting in more findings of trace-level contaminants, often in the nanogram per litre range. The focus of this section is on chemicals for which WHO has established drinking-water guideline values; thus, it focuses on chemicals evaluated as possibly relevant for health if they occur at elevated levels in drinking-water. In consequence of the large diversity of organic compound structure and properties, their transport and attenuation also varies widely, both as they travel through a catchment and within waterbodies.

Pesticides

The term “pesticide” is generic; it refers to all chemicals (and formulations) that are designed and used to kill or control pests, and covers hundreds of predominantly organic chemicals. The intended biocidal action of pesticides may also inadvertently affect humans (and wildlife, domestic animals and aquatic ecosystems), making them of particular interest for surface-water quality. Pesticides include herbicides, fungicides, insecticides, nematocides, rodenticides and slimicides. They have been widely and extensively used for many decades.

The main source of surface-water contamination from pesticides is from their use in agriculture, for crop protection. Other uses of pesticides that may be relevant include:

- vector control to protect public health (e.g. reduction of disease-transmitting insects such as mosquitoes);
- protection of municipal infrastructure (e.g. control of weeds on and around hard surfaces);
- use in industry and transportation (e.g. control of weeds on railway tracks, treatment of wood);
- use in the home and garden (including urban lawns and golf courses); and
- use on a larger scale in some regions in forestry (i.e. in silviculture).

In consequence of their application on surfaces, pesticides usually reach surface waterbodies as diffuse pollution. However, point-source discharges (e.g. from farmyard outflows after cleaning of equipment) should also be considered as relevant entries into waterbodies.

Some of the most effective pesticides developed and applied in the middle of the last century – for example, chlorinated organics such as dichloro-diphenyl-trichloroethane (DDT) – have since been shown to pose significant problems in terms of environmental persistence, and environmental effects (often subtle effects), which have led to their being banned in some countries. In general, these problems are less likely to occur with new pesticides because modern pesticide registrations require the production of thorough toxicology dossiers, and the majority of human exposure is assumed to be via residues in food rather than drinking-water. Moreover, whether or not pesticides or their metabolites reach surface waterbodies depends on a range of factors (FAO, 1996):

- conditions of application (e.g. spraying) and proximity of application to surface water;
- weather conditions (e.g. heavy rainfall after application that causes run-off, or high temperatures that favour volatilization);
- the physico-chemical properties (e.g. water solubility and volatility) of the active ingredient(s) in the pesticide formulation;
- contaminants that are present as impurities in the active ingredient(s);
- additives that are mixed with the active ingredient(s), such as wetting agents, diluents or solvents, extenders, adhesives, buffers, preservatives and emulsifiers; and
- products that are formed during degradation of the active ingredient(s), either chemical (e.g. during drinking-water disinfection), microbial or photochemical.

Furthermore, pesticides differ in their persistence. Those reaching surface water via baseflow discharge of groundwater may often include persistent substances such as atrazine, because of the long timeframes involved. Like nitrate, they may arise from use in previous decades, and this may account for detections of pesticides no longer in use. Modern pesticides designed to be less persistent can nonetheless reach surface waterbodies when run-off is rapid. This has been observed, for example, in the United Kingdom with metaldehyde used to protect crops from slugs (Kay & Grayson, 2014), or when substance properties (e.g. a low solid-water partition coefficient K_{oc}) increase the leaching potential or distribution in the environment (see "Sedimentation and sorption" in Section 2.2.3).

In general, only the insecticides (including organophosphates, carbamates and pyrethroids) have mechanisms of action in target pests that are directly relevant to mammals and humans; namely, nervous system toxicity. The molecular mechanisms of action of herbicides and fungicides tend to be specific to the biochemistry of the target species, and often this does not occur in humans. With regard to health effects in humans (and animals), irreversible toxic effects (neurotoxicity, mutagenicity, carcinogenicity and teratogenicity) have in the past been of most concern in relation to pesticides. More recently, there have been concerns about potential longer term effects on developing immune and endocrine systems. For some substances (e.g. the traditional organochlorine pesticides), the main concern is not acute toxicity but rather environmental persistence, and the ability to build up in tissues and be transferred via the food chain.

WHO has evaluated toxicity data, and calculated tolerable daily intakes (TDIs) and drinking-water guideline values, for 32 pesticides (WHO, In preparation-a). More detail on individual compounds, their toxicology and health effects is found in the chemicals background documents for the GDWQ (WHO, In preparation-a) and Tomlin (2000).

Worldwide, at least 800 pesticide compounds are in use (Tomlin, 2000), but there are distinct regional and national differences in the types of compounds registered and used. The use of pesticides in terms of frequency and amount, particularly for agricultural uses, tends to follow the pattern: Herbicides > fungicides > insecticides > other types.

Volatile organic compounds

Volatile organic compounds (VOCs) are small, often relatively polar, molecules that are sparingly to very soluble in water, with solubilities spanning 100–20 000 mg/L. The boundary between VOCs and semi-volatile organic compounds (SVOCs) is not precise, since the analytical methods for either may pick up neighbouring members of the other group. VOCs include the single-ring aromatic hydrocarbons such as benzene, a proven carcinogen in humans. Volatile halogenated hydrocarbons include well-known chlorinated solvents such as trichloroethene (TCE) and perchloroethene (PCE) and their degradation products cis-dichloroethene (cDCE) and vinyl chloride (VC).

The aromatic hydrocarbons benzene, toluene, ethylbenzene and xylenes (BTEX) are associated with point-source releases of fuels and oils originating from petroleum production, refining, and wholesale or retail distribution. They are also used as solvents and raw materials in chemical production. Halogenated solvents have been widely used to degrease metals, circuit boards, textiles (in dry-cleaning) and leather, and are used in chemical and pesticide manufacturing.

Environmental transport of chemical hazards may be greatly increased by conditions that mobilize otherwise recalcitrant or poorly water-soluble chemicals. For example, hydrocarbon fuels may mobilize other organic chemical residues in soil.

VOCs may enter surface waters in the dissolved phase; for example, via point-source industrial effluent discharge pipes, contaminated groundwater baseflow, urban run-off or stormwater discharges. Effluent discharges can be significant if VOCs are not regulated. VOC concentrations in groundwaters may also be extremely high, and some dissolved plumes may travel long distances (kilometres) to finally discharge to surface water. A survey of 191 chlorinated solvent-contaminated sites across North America and Europe indicated that at least 15% had groundwater plumes discharging to surface waters (McGuire et al., 2004).

VOCs can also enter surface waters by the direct discharge of non-aqueous phase liquids (NAPLs). Because they do not dissolve readily in water, VOCs may form either light NAPLs (LNAPLs) if substances have a lower density than water, leading to oil phases, or dense NAPLs (DNAPLs) if substances have a higher density than water. LNAPLs with moderately soluble components cause elevated dissolved-phase concentrations. Typical NAPL releases entering river systems primarily relate to LNAPL fuel or oil spillages that may migrate along an underlying water table, and may reach waterbodies as bankside seepages from spills on adjoining contaminated land (CL:AIR, 2014); poorly operated interceptor systems that fail to remove oil phases from pipe end discharges to a river; and releases from boating traffic. Although these may generate significant contamination, they are generally visible; hence, appropriate interception measures can be promptly implemented. Also, as LNAPLs tend to form surface layers, their impact on deeper water supply offtakes can be minor if the waterbody is stratified. However, control of LNAPL seepages from contaminated land spills to the subsurface that contain substantial accumulations of fuels or oils on the adjoining water table can be challenging. They may lead to long-term impacts to river quality downstream, because they require expensive measures that need to be operated in the long term, and may not be affordable in the desired timeframes.

WHO gives drinking-water guideline values for many VOCs, as exemplified in Table 7. VOCs have a vapour pressure of >0.01 kPa (at 20 °C), with boiling points of <200 °C. Their solubility in water depends on temperature and is described by the Henry's law constant (Table 7). Solubilities of VOCs can be several orders of magnitude greater than WHO drinking-water guideline values. Hence, to meet guideline values, substantial dilution and attenuation of concentrations are required in the water environment during the transport of dissolved-phase plumes from any source areas or discharges that might contain halogenated hydrocarbon DNAPLs and aromatic hydrocarbon LNAPLs that may dissolve to solubility limits.

VOCs are poorly sorbed to solids (see low values of Log K_{ow}, a hydrophobicity measure, in Table 7) and are primarily attenuated in surface waters by simple "volatilization" (i.e. converting a chemical substance from a liquid or solid state to a gaseous or vapour state; see "Volatization" in Section 2.2.3) to the atmosphere. This significantly reduces VOC risks to supply offtakes. Volatilization from surface water to the air is controlled by the Henry's law constant (Table 7), with greater values leading to greater loss, and by the flow regime characteristics (Aisopou et al., 2015). VOCs that enter the riverbed (or "hyporheic zone") may undergo significant attenuation due to biodegradation; for example, through "reductive dechlorination" of chlorinated VOCs (i.e. microbially mediated degradation of chlorinated compounds involving the sequential removal of chlorine). Degradation may mitigate impacts of groundwater plumes discharging to surface waters (Freitas et al., 2015).

Table 7 Physico-chemical properties for selected volatile organic compounds

Chemical	Solubility (mg/L)	Log K_{ow}	Henry's law constant (Pa m^3 mol^{-1})	WHO guideline value (mg/L)
Volatile aromatic hydrocarbons				
Benzene	1 780	2.13	557	0.01 (a)
Toluene	530	2.73	660	0.7 (C)
Ethylbenzene	160	3.15	843	0.3 (C)
Xylenes (o, m, p-isomers)	160–210	3.12–3.20	550–730	0.5 (C)
Styrene	320	3.05	286	0.02 (C)
Epichlorohydrin	~65 000	0.3	3.08	0.000 4 (P)
Volatile chlorinated hydrocarbons				
Vinyl chloride	2 700	1.38	2 680	0.000 3 (a)
1,2-dichloroethane	8 600	1.48	112	0.03 (a)
1,2-dichloroethene (trans- and cis-isomers)	4 500 (trans) – 6 400 (cis)	1.86 (cis) – 1.93 (trans)	460 (cis) – 960 (trans)	0.05
1,2-dichloropropane	2 420	2.24	280	0.04 (P)
Trichloroethene	1 280	2.53	1 030	0.02 (P)
Chloroform	8 700	2.0	372	0.3
Carbon tetrachloride	1 200	2.64	2 990	0.004
Tetrachloroethene	210	2.88	1 730	0.04

Data mainly abstracted from Lawrence (2006) and supplemented from Nikunen et al. (2000); WHO guideline values are from WHO, In preparation-a.

P – provisional guideline value because of uncertainties in the health database.
a – indicates that value is derived for the target of an excess lifetime cancer risk of not more than 10^{-5}.
C – indicates that concentration at or below this value may affect appearance, taste or odour of the water.

Semi-volatile organic compounds

SVOCs have been variously defined as organic compounds that have boiling points higher than water (or even higher; e.g. 200 °C). Analytical practice tends to define the upper limit of molecule sizes and boiling points; thus, for example, the widely used gas chromatography-mass spectrometry (GC-MS) methods may include compounds of very high molecular weight that are essentially non-volatile and have boiling points of up to 500 °C, such as the 5-ring polycyclic aromatic hydrocarbons (PAHs). The most widely used SVOC analytical methods are those developed by the US EPA. These methods tend to screen a wide range of SVOCs and include a diversity of compound types such as PAHs, chloro- and nitro-phenols, anilines, phthalates, halogenated benzenes and ethers. Some laboratory SVOC listings include, for example, polychlorinated biphenyls (PCBs) and pesticides; however, with more targeted analytical methods being adopted, PCBs and pesticides are increasingly being reported as distinct groups. In this discussion, PCBs are included as a higher end class of the SVOC group. Physico-chemical properties for selected SVOCs included in the WHO GDWQ (WHO, In preparation-a) are indicated in Table 8.

Table 8 Physico-chemical properties for selected semi-volatile organic compounds

Chemical	Solubility[a]	Log K_{ow}	Henry's law constant (Pa m^3 mol^{-1})	Degradation rate (abiotic-biotic $T_{1/2}$ in river water)	WHO guideline value (mg/L)
Monochlorobenzene	Sparingly soluble 0.086 g/L 7.6E-4 mol/L	2.8	382	<30 days	Taste and odour
1,4-dichlorobenzene	Sparingly soluble 0.018 g/L 1.2E-4 mol/L	3.4	240	<14 days	0.3 (C)[b]
1,2-dichlorobenzene	Sparingly soluble 0.018 g/L 1.2E-4 mol/L	3.4	193	<14 days	1 (C)
Trichlorobenzenes (total)	Sparingly soluble 3.6E-3 g/L 2.0E-5 mol/L	4.2	360	Persistent	Taste and odour
Hexachlorobutadiene	Sparingly soluble 2.9E-3 g/L 1.1E-5 mol/L	4.8	110	<7 days	0.000 6
Di(2-ethylhexyl)phthalate	Sparingly soluble 1.1E-4 g/L 2.9E-7 mol/L	5	0.99	<40 days	0.008
Benzo[a]pyrene	Sparingly soluble 1.9E-6 g/L 7.4E-9 mol/L	6.35	0.113[c]	Persistent	0.000 7 (a)[e]
Acrylamide	Soluble 36 g/L 50 mol/L	–0.8	0.001[d]	—	0.000 5 (a)

All data abstracted from Nikunen et al. (2000), except where indicated; WHO guideline values are from WHO, In preparation-a.

[a] Based on SciFinder/ CAS Database. The solubilities are predicted values, which are calculated using Advanced Chemistry Development (ACD/Labs) Software V11.02 (© 1994–2015 ACD/Lab).

[b] "(C)" indicates that concentration at or below this value may affect appearance, taste or odour of the water.

[c] www.epa.gov/superfund/resources/soil/part_5.pdf

[d] www.epa.gov/opptintr/rsei/docs/tech_app_b.pdf

[e] "(a)" indicates that value is derived for the target of an excess lifetime cancer risk of not more than 10^{-5}.

Widespread use has contributed to widespread, low-level accumulation of SVOCs (e.g. PAHs and phthalate plasticisers) in sediments across catchments, particularly those that are more urbanized.

As a generalization, with increasing molecular weight (size), SVOCs are likely to be less volatile, have lower aqueous solubility, be increasingly hydrophobic (higher Log K_{ow}) and prone to greater sorption to sediments. They will also be less bioavailable for biodegradation, and undergo greater partitioning to biota and to "bioaccumulation" (i.e. the accumulation of a compound in the tissue of an organism over time). An approximate trigger value of Log K_{ow} >3 is used to identify compounds that may bioaccumulate or significantly sorb to sediments. In Table 8, K_{ow} spans several orders of magnitude and indicates a diversity of behaviour for the various SVOCs. Abiotic chemical reactivity is typically low; however, biodegradability may be significant for some SVOCs. Biodegradability tends to decrease with increased molecular mass, numbers of polycyclic aromatic rings and greater chlorination. Some SVOCs (e.g. some PCBs and PAHs) may be classified as "persistent organic pollutants" (POPs); that is, compounds that are resistant to environmental degradation, and pose a risk to human and environmental health.

Although sorption mechanisms differ, hydrophobic SVOCs show parallels with trace metals, in that transport to a surface water may perhaps be sediment-particulate associated in run-off, or may be retarded by sorption to the geological subsurface. Dissolved-phase hydrophobic SVOC plumes in groundwater are much less likely to reach surface waters and discharge as baseflow than the more mobile, less hydrophobic VOC plumes. However, the marginally denser-than-water coal tar creosotes' DNAPLs (rich in PAHs and phenols) may migrate laterally in the subsurface. They then accumulate in DNAPL pools in riverbed depressions or in sediments, which may be dispersed further downstream by flood events, potentially leading to contamination along kilometre stretches of a river. Former gasworks or coal coking works (manufactured gas plants) abound around the world (the United Kingdom alone has about 1000 sites) and inevitably have experienced spills, some of which have significantly affected adjacent rivers, leading to expensive remediation of contaminated riverbed sediments (Zapf-Gilje, Patrick & McLenehan, 2001). Out-of-sight subsurface or riverbed NAPLs may persist decades after spillage, and pose a long-term hazard. Environmental mobility may also be influenced by "cosolvency", wherein one substance acts as a solvent for another substance that is otherwise of limited water solubility and mobility. Other SVOC DNAPLs that may accumulate in riverbeds include dense PCB oils that may likewise occur as dispersed DNAPL within the riverbed or as PCBs sorbed to sediments. Although PCB has been banned in several countries for many years (e.g. in the USA in the late 1970s), a significant legacy may remain in urban river or lake sediment environments, as illustrated by the Hudson River PCB Superfund site in New York State that is over 300 km long and has recently undergone targeted dredging of a 60 km sub-reach.[4]

Sorption is the most important process in the transport and fate of SVOCs within surface waters. Thus, the fate of SVOCs within the surface water is influenced by sediment, with greater SVOC hydrophobicity leading to increased scavenging by the river sediment load; hence, the greater the hydrophobicity of a SVOC, the greater its deposition and accumulation in bed sediments, and the lower its fraction in the dissolved phase. Main transport downstream is via flood-event mobilization of sediments, which may spread SVOC over many kilometres when source inputs are major or long term; this process is sometimes sustained by DNAPL droplets entrained in sediments.

Dissolved-phase SVOC concentrations in surface waters are generally not expected to be high (i.e. in the high nanograms per litre to the low micrograms per litre range), particularly for low-solubility hydrophobic SVOCs, but drinking-water guideline values are also very low (Table 8). Hence, where contaminated sediments are suspected, screening may be important to ensure that drinking-water offtakes do not draw in SVOC contamination associated with suspended particulate or colloidal material.

Natural organic substances

Most natural organic matter (NOM) is not hazardous to health per se; however, at elevated concentrations, NOM may impair water quality and acceptability in a number of ways. The main way in which this occurs is through degradation of large amounts of NOM – this process consumes oxygen, which in turn may result in fish kills and create foul, unacceptable water. This phenomenon is typical where untreated wastewater carrying high amounts of faecal or other organic material reaches a waterbody. A widely used measure for water-quality degradation through oxygen depletion is the "saprobic index". This index uses the prevalent species of aquatic invertebrate fauna as a time-integrating indicator of the oxygen conditions; thus, if animals sensitive to oxygen depletion are missing, this is taken as an indication that oxygen deficiency occurs at least periodically. Waterbodies with a high saprobic index are very poor sources for drinking-water.

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[4] http://www.epa.gov/hudson/, accessed 04 December 2015.

Further impacts of high levels of NOM on water quality include the following:

- Biodegradable dissolved organic carbon (BDOC) supports bacterial growth in drinking-water systems, and in distribution networks in particular this may impair quality.
- NOM may include compounds that cause objectionable tastes and odours even at very low concentrations; for example, humic substances impart an undesirable brown or yellow colour to water, and compete with compounds to be eliminated by treatment.
- NOM substantially affects water treatment processes, first because some of these substances are not amenable to coagulation and may therefore be difficult to remove, and second because hydrophilic NOMs foul membranes. Hence, high levels of NOM may cause major direct challenges to drinking-water treatment.
- Organic matter may react with chlorine to form disinfection by-products (DBP) such as trihalomethanes (THMs) and haloacetic acids, some of which may be carcinogenic.
- NOM affects transport of chemicals and microbes, which may "stick" to NOM or to particulate organic matter (POM), forming colloids.
- NOM may act as an electron donor in "biodegradation" reactions (i.e. the biological breakdown of substances; see "Degradation of chemical hazards" in Section 2.2.3) and thus serve to enhance the degradation of chemicals.
- Some natural organic compounds may have a direct effect on human health or on drinking-water acceptability; for example, some cyanobacteria can produce toxins; and some algae, cyanobacteria and fungi can produce offensive tastes and odours (e.g. geosmin or 2-methylisoborneol [MIB]).

All surface waters contain some NOM, dissolved organic matter (DOM) and POM. The concentrations of NOM are usually quantified in terms of the amount of carbon within the molecules of organic matter. Values are reported as total organic carbon (TOC). Although there is substantial variability between waterbodies, 70–85% of organic matter in natural waters exists as dissolved organic carbon (DOC). One source of NOM is surface run-off that carries POM and DOM (e.g. plant debris and humic substances from terrestrial vegetation such as forests and wetlands) to a waterbody. Another source are organisms that grow within the waterbody, such as dead and decaying phytoplankton and zooplankton, faeces excreted by fish, and disrupted and degrading plant material. As POM decays, it is degraded to DOM, leaving poorly degradable dissolved humic material that typically contributes about 50% to >90% of the DOC in most natural waters (Malcolm, 1985). Decaying vegetation may release dissolved glucosides such as tannin, leading to brown-coloured or sweet-smelling water.

NOM concentrations are subjected to seasonal differences. For example, spring or monsoon run-off events can introduce high organic carbon loadings due to increased surface-water run-off and soil erosion; similarly, plankton growth shows pronounced seasonal patterns in many waterbodies. The amount of NOM forming in a waterbody depends on the concentration of nutrients, particularly phosphorus but also nitrogen. This is because high nutrient levels can lead to high growth of plankton biomass, which then constitutes a larger fraction of the POM in the waterbody. POM renders the water turbid and directly challenges treatment, because particles need to be removed for disinfection to be effective. In addition, the degradation of POM increases the amount of NOM, again challenging drinking-water treatment and disinfection.

Emerging issues in relation to chemical hazards in surface-water catchments

The increasing availability of far more sensitive methods for chemical analyses has led to an increase in traces of many chemicals being found in surface waters. In many countries, public concern has developed around groups of such substances. Among the substances that may cause concern are pharmaceuticals, personal-care products and their metabolites. Such chemicals may enter surface waters from sewage effluents, but also from pharmaceuticals widely used in animal husbandry, such as antibiotics and growth hormones. This problem occurs predominantly in industrialized countries with high rates of both per capita consumption of these chemicals and per capita connection to sewerage systems. The rationale behind the concern is that these substances are designed to have an effect on humans – albeit at doses several orders of magnitude higher than the levels found in drinking-water sources. The other issue of public concern is the occurrence of endocrine-disrupting compounds. This concern first arose in the context of the observation of sex shifts towards a higher share of females in some species of aquatic wildlife, particularly in surface waters near sewage outfalls. These effects are thought to be caused by low concentrations of some anthropogenic endocrine-disrupting compounds. Although such observations indicate an issue that requires attention, their use for assessment of risks to human health is limited. This is because:

- substances causing such effects are diluted and degraded between sewage outfalls and drinking-water offtakes (also, drinking-water treatment removes many of these substances and reduces the concentrations of others); and

- aquatic animals are substantially more exposed than humans – their uptake is not only through the gastrointestinal pathway but also continuously, 24 hours a day 7 days a week, through large body surfaces (i.e. skin and, in particular, gills).

Discussions on both pharmaceuticals and endocrine-disrupting compounds are linked because some pharmaceuticals that reach surface waters with sewage have an endocrine action (e.g. steroid estrogens from human contraceptive pills). These organic micropollutants are commonly subsumed within the term "emerging issues", but are more accurately termed "issues of emerging concern".

Pharmaceutically active compounds

Pharmaceutically active compounds (PhACs) comprise human medicines – both prescription and "over-the-counter" products – and veterinary preparations. Human and veterinary pharmaceuticals are administered in relatively low absolute dose levels because of their potency; for example, the oestrogen in the contraceptive pill has a typical dose of 35 µg per patient per day. However, for drugs such as oestrogens or analgesics, the patient population base is large, and this is coupled with frequent use of varying doses. Whether or not pharmaceuticals reach surface water depends on various factors:

- their metabolism in the humans or animals that consume them;
- their physico-chemical properties, such as solubility or degradability in wastewater treatment and in the environment; and
- the extent to which they are subject to other attenuation mechanisms.

Only a fraction of the wide range of PhACs used worldwide is found in surface waters. These include the widely used anti-inflammatory agents (e.g. diclofenac and naproxen), antibiotics (e.g. sulfamethoxazole), antiepileptics (e.g. carbamazepine, gabapentin and primidone), beta-blockers (e.g. sotalol, metoprolol, propranolol) and the antidiabetic drug metformin (see, for example, Kasprzyk-Hordern, Dinsdale & Guwy, 2008; Roig, 2010; Sacher et al., 2008; Scheurer et al., 2012).

Antibiotics may be used in veterinary medicine: prophylactically, in high-intensity livestock operations, and as growth promoters. Veterinary pharmaceuticals reach surface waters from the spreading of manure and slurry from treated animals on pasture and fallow land, and from excretion by grazing animals after treatment. Direct inputs to surface waters can occur from veterinary pharmaceutical use in, for example, fish farms, where antibiotics are administered in pre-dosed food.

With few exceptions (e.g. spills or point-source discharges from manufacturing) the levels of pharmaceuticals found in surface waters are many orders of magnitude below those set as therapeutic dose levels in humans and animals. They are also considerably below the dose levels used in testing with experimental animals before a pharmaceutical is released to the market. Short-term exposure to such low levels of pharmaceuticals as generally occurs in surface waters is therefore highly unlikely to be of concern for human health (WHO, 2012b). Some uncertainty remains as to whether any effects can occur in humans from longer term exposure to very low levels (WHO, 2012b). Because concentrations of pharmaceuticals likely to be found in drinking-water are far below the levels that would have a pharmacological effect, guideline values for pharmaceuticals in drinking-water have not been established in the GDWQ, and little benefit would be expected from routine monitoring for pharmaceuticals in drinking-water (WHO, 2012b).

Information campaigns can reduce disposal of unused pharmaceutical products through the sewerage system, but excretion from proper use of these compounds is inevitable. Public health concerns arising from uncertainties about long-term effects of very low concentrations of pharmaceuticals in drinking-water compete with the benefits of having those pharmaceuticals available for therapy. Designing their active ingredients for better degradability remains a long-term challenge.

The presence of antibiotic-resistant bacteria and residues in the environment gives rise to emerging concerns about the role of environmental reservoirs, including surface water, in the spread of antimicrobial resistance. The public health risks associated with gene transfer from resistant to non-resistant strains in sewage collection and treatment, and in the aquatic environment, are being intensively researched (e.g. Stoll et al., 2012; Zhang et al., 2015). For further information, see also *Antimicrobial resistance: an emerging water, sanitation and hygiene issue* (WHO, 2014b).

Endocrine-disrupting compounds

Some substances mimic estrogenic, androgenic, thyroidal or other endocrine functions. Harrison (2001) defines an endocrine disrupter as "an exogenous substance that causes adverse health effects in an intact organism, or its progeny, subsequent to changes in endocrine function". This definition clearly includes – but also extends beyond – oestrogenic and reproductive endpoints, and links adverse health effects to dysfunction in any part of the endocrine system. Chemicals currently implicated in endocrine-disrupting activity include some industrial chemicals, pesticides and medicines, but also naturally occurring substances. As the range of chemical classes that are currently considered to have the potential for effects on some aspect of the endocrine system is extremely broad, their sources are many and varied. They enter surface waters both from point sources and from diffuse sources, including a number of large industrial sectors, large-scale agriculture, and human and animal health provision. There is currently no conclusive evidence for actual adverse human health effects occurring as a direct result of exposure to endocrine disrupters in the environment, including in drinking-water, although data are limited; this situation is discussed in Meeker (2012) and Villanueva et al. (2014).

The variety of anthropogenic chemicals, together with the increasing sensitivity of the analytical methods for their detection, poses a challenge for assessment of the risk to human health. However, this can be addressed by comparing the – usually very low – concentrations found to those deemed likely to have an impact on human health on the basis of experience with other substances (Box 2.3). It is important to realise and to communicate that exposure to these substances, as with most chemicals, is rarely only through drinking-water, and is rarely mainly from that source. Major exposure routes include food, air (including contaminants adhering to dust particles and VOCs from furniture, carpets or paints in indoor air) and textiles.

For most trace contaminants, their concentration in surface water is likely to be a minor exposure pathway, and their concentrations are likely to be too low to be a public health priority (Box 2.3). On this basis, routine monitoring of such substances is generally not recommended.

Box 2.3 Addressing concerns about trace chemicals for which there are no regulatory limits or drinking-water guideline values

Highly sensitive blanket analytical methods (e.g. modern non-target screening) are increasingly being performed by various institutions in the context of research programmes. Such methods can detect a huge number of chemicals in a given surface-water sample. In most situations, the concentrations of the chemicals are at or below a few nanograms per litre. WHO guideline values or national drinking-water standards are available for only a small fraction of these chemicals; in addition, toxicological data are often lacking or are too fragmentary to be used in calculating appropriate limits. Nonetheless, public health authorities responsible for drinking-water quality may be faced with public concerns about such findings. Hence, assessing the public-health impact of trace chemicals is a challenge for risk assessment.

Public health risks from chemicals found at concentrations of a few nanograms per litre are negligible in the large majority of cases, as demonstrated by Dieter's (2014) comprehensive study of evaluations for relevant substances detected in drinking-water. The study found the following:

- The limits set by six large public health authorities for the concentrations of 113 non-genotoxic substances in drinking-water were never below 0.3 µg/L (300 ng/L). The data examined covered almost 200 evaluations, because some substances were evaluated by more than one authority.
- The same authorities published limits for 14 "non-threshold" substances, 13 of which showed a structural alert for genotoxicity (a total of 23 evaluations). These authorities set limits to meet the health-based target of "not more than one additional cancer case in a population of one million" (with 2 L of drinking-water consumed per day for a lifetime). Except in one (disputable) case, these limits were not below 0.1 µg/L (100 ng/L).

To address concerns related to substances found in drinking-water during investigative surveys, the German Federal Environment Agency used this information to set a level of 0.1 µg/L as the default concentration below which the water is considered safe, unless the substance shows a structural alert for genotoxicity. If it shows an alert for genotoxicity, the default concentration is 0.01 µg/L; however, if genotoxicity can be excluded, the agency uses a default concentration of 0.3 µg/L. If concentrations detected exceed these health-alert values, the finding triggers further actions, such as assessment of existing prevention and mitigation options, implementation of additional controls, or commissioning of toxicological evaluations to reduce data gaps. Such a finding also triggers the implementation of measures to reduce the concentration of the substance. Whether the water is deemed unsafe for potable purposes until such measures are effective is decided on a case-by-case basis, and depends on the concentrations to which people are exposed and the nature of the substance.

Another approach to address trace concentrations of pharmaceuticals is to compare the levels of occurrence of these substances to the minimum therapeutic dose (MTD) or acceptable daily intake (ADI), as discussed in *Pharmaceuticals in drinking-water* (WHO, 2012b). A judgement of safety might be based on the magnitude of this margin of exposure (MOE) for the particular pharmaceutical. If the margin of safety is substantial, particularly when comparing the MTD to the concentrations found in drinking-water, the risk to human health is probably negligible.

Routine monitoring of concentrations of chemicals is generally not an effective use of limited resources; hence, concerns about trace chemicals should be considered within the overall priority of hazards to human health. However, where specific circumstances (e.g. data from a catchment survey) indicate that concentrations of pharmaceuticals and other non-regulated chemicals in the surface-water source may be of concern, it may be useful to conduct targeted investigative studies.

Risk perception and source-water protection in relation to chemical hazards

As discussed at the beginning of Section 2.1.2, chemical hazards – in contrast to microbial ones – are rarely acute; rather, chemical hazards are potentially harmful only through long-term exposure to higher levels. However, public perception and concern tend to focus on chemical hazards, probably because such hazards are often poorly understood. Humankind is inventing and producing an increasing number of chemicals, and these are being detected at an ever greater frequency, owing to improved analytical methods with lower detection limits. At the same time, little is known of the impact of such hazards on human health, especially the effects of long-term exposure to very low or trace levels found in drinking-water.

Where there is pronounced public concern about trace concentrations of emerging contaminants, it is important to educate consumers on relative public health risks, while also encouraging people's engagement in keeping their water unpolluted at its source through better catchment protection. Indeed, many measures can be taken to ensure effective containment of hazardous chemicals without restricting the basis for the livelihood of parts of the population working in the catchment, and such measures are usually affordable (see Chapter 3).

2.1.3 Hazards from eutrophication

Eutrophication of waterbodies is the process of increased production and biomass of autotrophic organisms. These include planktonic algae and cyanobacteria (together termed "phytoplankton") and, in shallow water, partially or totally submerged plants ("macrophytes"). The increased production of these organisms is caused by elevated loads of plant nutrients (mainly phosphorus, but sometimes also nitrogen) that fertilize the growth of the autotrophic organisms. Waterbodies are differentiated according to their nutrient status, and the amount of autotrophic organisms that these nutrients can support. The scale ranges from oligotrophic (low levels of nutrients), through mesotrophic (moderate levels of nutrients), to eutrophic and hypertrophic (high levels of nutrients). Some nutrient loading from the catchment is a natural process, as is the subsequent increase of the biomass of autotrophic organisms and organic sediments that may reduce the depth of a waterbody (especially in the case of a shallow lake) and eventually transform it into a wetland or even into a terrestrial system. As a natural process, this takes hundreds of years, but where human activity strongly increases nutrient loading, an originally oligotrophic lake may become eutrophic within a few years. In rivers, the trophic state naturally increases from the upper reaches towards the lower part, which receives more nutrients from the larger catchment area.

Eutrophication through human activities can be traced back to early human-induced land-use changes in catchments, such as clearing of forests and development of agriculture. The process of eutrophication was amplified in the past, and continues to be amplified today, by increasing populations along the shores of lakes and rivers, urban developments releasing insufficiently treated human excreta and sewage, and industrialized agriculture using high amounts of fertilizers and manure. Research into the causes of eutrophication and possible remediation started in the first half of the 20th century. Thus, eutrophication and its reversal are now well understood for temperate regions, whereas more knowledge is needed from the tropics.

The elevated production of biomass in a waterbody leads to a higher concentration of decomposable NOM, with the potential consequences discussed above in Section 2.1.2. Such consequences include periodic oxygen deficiency with foul offensive non-potable water and fish kills, enhanced bacterial growth, impairment of treatment processes and the formation of chlorination by-products. A high biomass of phytoplankton also has direct effects on water quality owing to substances with offensive tastes and odours, or the toxins that are produced by certain species. Moreover, eutrophication shifts the composition of phytoplankton species, with some nuisance species typically becoming more dominant. In particular, cyanobacteria often become dominant and prevail for weeks to months on end. Also, in well-mixed waterbodies, diatoms may achieve massive cell densities that clog filters in drinking-water treatment.

The amount of phytoplankton biomass that can occur in a given waterbody is limited by the resources it needs to grow; that is, light and nutrients. In consequence, the key to reducing or largely avoiding nuisance phytoplankton species and elevated phytoplankton biomass is a sufficient reduction of nutrient loads reaching the waterbody. If phytoplankton is growing without nutrient limitation, the atomic ratio of carbon to nitrogen to phosphorus (C:N:P) – known as the "Redfield ratio"

(Reynolds, 1997) – is fairly stable at 106:16:1, which corresponds to a ratio by weight of 42:7:1. This means that reducing the concentration of only one of the nutrients effectively limits the concentration that the biomass can reach in a given waterbody. If the ratio of nitrogen (as nitrate or as ammonia) to phosphorus is less than 16:1 as atomic ratio or less than 7:1 by weight, nitrogen may be limiting the biomass of algae or cyanobacteria. Nitrogen limitation is known to occur in particular in some tropical settings, and during late summer in some shallow lakes. If additional nitrogen reaches the waterbody in such situations, this can allow algal and cyanobacterial cells to multiply. However, in most situations other factors (particularly phosphorus and, in some situations, light) limit the amount of biomass that these organisms may attain; where this is the case, nitrogen concentrations have no impact on their growth. Experience shows that eutrophication management focusing on reducing phosphorus loads is usually the most effective approach. Empirical equations for data from temperate climates link the import of phosphorus from the catchment to the phosphorus concentration in the waterbody and, in a second step, link phytoplankton biomass to phosphorus concentrations in the waterbody (Vollenweider & Kerekes, 1982).

Box 2.4 Exploring the relationship between total phosphorus (TP) concentration and the likelihood of a cyanobacterial bloom

Data from 3231 samples collected from 210 waterbodies throughout **Europe** (Chorus & Niesel, 2011) showed a clear threshold for the TP concentration at which cyanobacteria develop a significant biomass (i.e. to become a potential health concern). The following summarizes the data reported by Chorus and Niesel, presented under headings that indicate the "potential for high cyanobacterial biomass", which closely align with the WHO technical brief on *Management of cyanobacteria in drinking-water supplies* (WHO, 2015b).

Low potential for high biomass of cyanobacteria:

- At TP concentrations of <10 µg/L, cyanobacterial cells were rarely recorded, and then only in low numbers (other phytoplankton dominated).

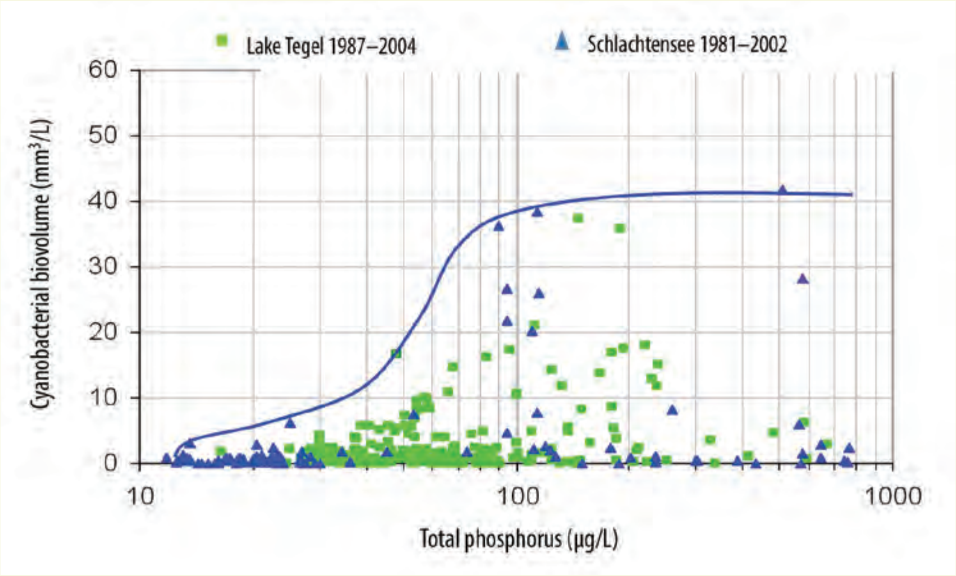
Potential for high biomass of cyanobacteria:

- At TP concentrations of <10–25 µg/L some cyanobacterial taxa were as common as other phytoplankton species, but elevated biomass (biovolume >0.5 mm^3/L, roughly corresponding to >0.5 mg/L) was a rare exception.
- At TP concentrations of >25 to 50 µg/L, a high level of biomass was common.
- At TP concentrations of >50–90 µg/L, some cyanobacterial taxa were twice as likely as other phytoplankton to reach a high level of biomass.

High potential for high biomass of cyanobacteria:

- At TP concentrations of >90 µg/L, five of the six cyanobacterial taxa investigated were four to five times more likely to reach high levels of biomass.

Data from two lakes in **Germany** that cover a wide range of TP concentrations (reduced over time through reducing the TP loads entering the waterbodies) demonstrate how TP concentration limits the maximum biomass that can form in a given lake, as shown in the graphic below (Chorus & Niesel, 2011).



Phosphorus occurs in three forms in water:

- *soluble phosphate* – formerly termed “orthophosphate”, occurring as H_3PO_4, $H_2PO_4^-$ and PO_4^{3-});
- *polyphosphates* – which may undergo hydrolysis in aqueous solutions and transform into soluble phosphate; and
- *organically bound phosphorus* – in organisms or in decaying organic material in surface waters.

The maximum amount of cyanobacteria and algae that can occur in a waterbody is determined by the sum of all three components; that is, by “total phosphorus” (or TP). In assessing a waterbody’s potential to sustain algae and cyanobacteria, it is therefore important to analyse TP as well as soluble phosphorus. Experience shows that focusing on reducing phosphorus loads is usually the most effective way to manage eutrophication. Phosphorus may reach waterbodies from agricultural activities and from wastewater discharges. Wastewater contains high concentrations of phosphorus from human excreta and from detergents (in countries that have not banned its use as a detergent component).

Taste and odour

Substances causing offensive taste and odour in drinking-water can have two sources, both of which are often related to eutrophication:

- Such substances can be directly formed by algae, cyanobacteria and other microorganisms (e.g. actinomycetes) inhabiting surface waters. Eutrophication tends to increase the biomass and duration of occurrence of these organisms, particularly in the case of cyanobacteria, some of which produce the most common odorous compounds: geosmin and MIB. Many people can perceive the earthy and musty odours of geosmin and MIB at concentrations of only about 5–10 ng/L. Other odours associated with cyanobacteria include the tobacco-like or grassy smelling ß-cyclocitral, and the sulfurous di-methyl di- or tri-sulfides.
- Some green and golden-brown algae (chrysophytes) can cause unpleasant odours. Thus, 2,4-heptadienal and decadienal found in, for example, *Uroglena* lead to a fishy or rancid odour, whereas trans,cis-2,6-nonadienal from *Synura* and *Dinobryon* may cause a cucumber flavour. These algae are rarely observed in eutrophic waterbodies, but higher amounts are sometimes seen under mesotrophic conditions. Taste and odour episodes caused by these organisms are reported less frequently, and they tend to be of rather short duration (i.e. days rather than weeks).

Other taste and odour substances form during treatment, storage or distribution (Suffet, Schweitzer & Khiari, 2004), particularly through reactions between organic matter and disinfectants. As concentrations of organic matter are typically higher in eutrophic waterbodies, eutrophication increases the likelihood that they will occur. For further information on this topic, see the review by Suffet, Schweitzer & Khiari (2004).

Cyanobacteria and their toxins

Cyanobacteria, commonly termed “blue-green algae” (in scientific terms, they are bacteria rather than algae), can form mass developments because they are scarcely subject to processes that reduce their biomass; that is, they do not sink to the sediment and are poorly eaten by zooplankton. Furthermore, some species can be buoyant, causing cells and colonies to float to the surface, where they may form scums or so-called “algal blooms”.

Chorus and Bartram (1999) provide a comprehensive overview and guidance on cyanobacteria. The information given here is taken from this monograph unless noted otherwise. Cyanobacteria can produce a range of metabolites that are potentially toxic to humans and are referred to as “cyanotoxins”. The cyanotoxins most intensively studied to date are peptides, alkaloids and organophosphates that can damage the liver and other organs, or are potent neurotoxins (Table 9). Some cyanobacteria can produce a variety of other metabolites, causing effects that are poorly understood. Cyanotoxin concentrations are typically highest where blooms accumulate; that is, along shorelines and in downwind bays.

Table 9 Cyanobacterial toxins, the species or genera producing them, and their health impacts

Toxin	Substance class	Genus or species	Potential health impact
Microcystin	Peptide	*Microcystis, Planktothrix, Anabaena, Nostoc*	Liver toxin Tumour promoter
Nodularin	Peptide	*Nodularia*	Liver toxin Tumour promoter
Cylindrospermopsin	Alkaloid	*Cylindrospermopsis raciborskii, Aphanizomenon ovalisporum, A. flos-aquae, Umezakia natans, Rhaphidiopsis curvata*	Liver toxin
Anatoxin-a	Alkaloid	*Anabaena, Aphanizomenon, Oscillatoria, Planktothrix*	Neurotoxin
Anatoxin-a(s)	Organophosphate	*Anabaena*	Neurotoxin
Paralytic shellfish poisons (saxitoxins)	Carbamate alkaloid	*Aphanizomenon, Anabaena, Cylindrospermopsis, Lyngbya*	Neurotoxin

An important difference between these cyanotoxin groups is the extent to which they remain within the cell or are dissolved in the water. Microcystins are largely cell bound, and are only minimally released from the cells into the water unless the cells die and lyse, in which case the microcystins are usually degraded relatively rapidly (within days to weeks). In contrast, cylindrospermopsin and anatoxin-a are often released into the water, even by healthy cells. Further, whereas rapid biodegradation of dissolved microcystins and anatoxin-a occurs under many circumstances, biodegradation of cylindrospermopsin can be substantially slower.

Not all cyanobacterial blooms contain toxins, and the amount of toxin per unit biomass varies widely. However, when cyanotoxins are present, their levels are generally highest where cells containing them concentrate at the surface, forming dense scums or "blooms". Although acute intoxication can occur, as shown by animal deaths after scum ingestion and by dose calculations, an acutely lethal dose to a human is unlikely, because it would require the uptake of rather large volumes of water containing both scum and toxin. Human deaths clearly attributed to cyanotoxins are known only from incidents in dialysis clinics, but such exposure is not relevant to exposure through drinking-water or recreation.

WHO has established a provisional guideline value of 1 μg/L in drinking-water for a frequently occurring cyanotoxin, microcystin-LR, which has also been classified as "possibly carcinogenic to humans" (IARC Group 2B) by IARC (2010).

Cyanobacterial blooms are becoming one of the most frequently encountered events in surface waters, due to widespread eutrophication in many waterbodies. In drinking-water offtake, the cell-bound fractions of cyanotoxins can be avoided by siting the offtake point outside the depth or bay in which blooms tend to accumulate. This is particularly effective for the largely cell-bound microcystins. Processes influencing the reduction of cyanobacterial toxins within a waterbody are discussed in Box 2.14 (Section 2.2.3).

Further information on the management of cyanobacteria and their metabolites is given in the WHO technical brief *Management of cyanobacteria in drinking-water supplies* (WHO, 2015b) and in Chorus and Bartram (1999).

2.1.4 Physical hazards and acceptability issues

In general, physical hazards represent water-quality parameters that may affect the acceptability of drinking-water but do not necessarily pose a direct hazard to public health. Accordingly, physical hazards are not discussed in detail in this document.

Aesthetic issues are impairments in taste, odour and appearance that can lead consumers to search for alternative, and potentially less safe, water sources. Some substances have aesthetic effects at concentrations or levels lower than their health-based value. This needs to be recognized in developing standards and deciding on actions.

Turbidity and high levels of suspended solids may affect the acceptability of water from the consumer perspective. Although not harmful to health per se, suspended particles in water may carry large numbers of pathogens, and may have high concentrations of heavy metals, pesticides and other substances adsorbing to them. Where water is consumed without prior filtration, such contaminants may be ingested. This mechanism is discussed in the context of sorption in "Sedimentation and sorption" in Section 2.2.3. In addition, suspended solids may carry large amounts of phosphorus into water storages, which in some circumstances can trigger blooms of algae and cyanobacteria, challenging treatment with a high content of organic matter (i.e. POM), tastes and odours, or cyanobacterial toxins (see Section 2.1.3). Furthermore, high suspended solid levels interfere with downstream treatment barriers, such as coagulation and flocculation, clarification, filtration and disinfection. Substantial changes in source-water turbidity can be an indication of pollution events in surface-water catchments (e.g. triggered by storms, thaws, fires and spills). Turbidity changes over time can provide indications of changes in the catchment that require attention.

Iron and manganese are typically considered physical hazards that are of relevance to drinking-water quality. Iron and manganese primarily affect aesthetic water quality through off-colours at elevated concentrations (e.g. red/brown and black, respectively). Blooms of a range of planktonic algae (particularly cyanobacteria) in waterbodies may also produce offensive taste and odour compounds (see Section 2.1.3). These may impair acceptance of affected drinking-water or may require specialized water treatment processes for effective removal.

The human right to water stipulates that water should be safe, acceptable, physically accessible, affordable and available in sufficient quantity. Especially in catchments with competing water uses, providing water in sufficient quantity throughout all seasons may be a major challenge. This can lead to compromised hygiene and can affect public health if drinking-water is not made a priority over other uses. Hazards specific to water quantity are not discussed here in detail, although issues of quantity may impact the quality of surface waterbodies. For instance, when water quantity is limited, water in a reservoir may be drawn from near the bottom strata, where the water is likely to be of poorer quality because of the accumulation of suspended matter and chemicals released from the sediments under anaerobic conditions. Similarly, when river flow is increased by large amounts of stormwater, this can lead to high levels of suspended solids.

2.1.5 Radiological hazards

In drinking-water, radiological hazards typically pose a relatively small risk to human health compared to microbial and chemical hazards. They result from radionuclides that may occur naturally in drinking-water, such as those of the thorium and uranium series. However, the chemical toxicity of uranium is of concern at much lower concentrations than is its radio-toxicity; hence, it is the chemical toxicity that is the basis of the health-based value. Source waters that are under the influence of groundwater from aquifers containing granite ores could contain naturally occurring radionuclides.

Industrial activities such as mining and use of some fertilizers may generate radiological contamination, as may facilities using radioactivity such as medical and nuclear energy facilities. These industries should typically have regulations associated with them for the management of radiological contamination. However, such situations require a comprehensive assessment of the health risk from all the different exposure pathways in question, including drinking-water. Concentrations of radionuclides in drinking-water may occur at levels that are of potential concern for health risks after prolonged exposure, due to the linear relationship assumed between exposure and cancer risk. WHO establishes screening levels and guidance levels based on the individual radiation dose criterion of 0.1 mSv per year; this represents a very low level of risk that is not expected to give rise to any detectable adverse health effect. Further information on this topic is given in Chapter 9 of the GDWQ (WHO, In preparation-a). The GDWQ briefly discusses potential sources, screening levels and guidance values for radionuclides that are most likely to be found in drinking-water, and a methodology for their application in determining potential health risks. For the purpose of assessing the risk of radionuclides reaching a drinking-water offtake, the principles discussed in Section 4.3 can be applied.

2.2 Which features and processes determine pollution pathways?

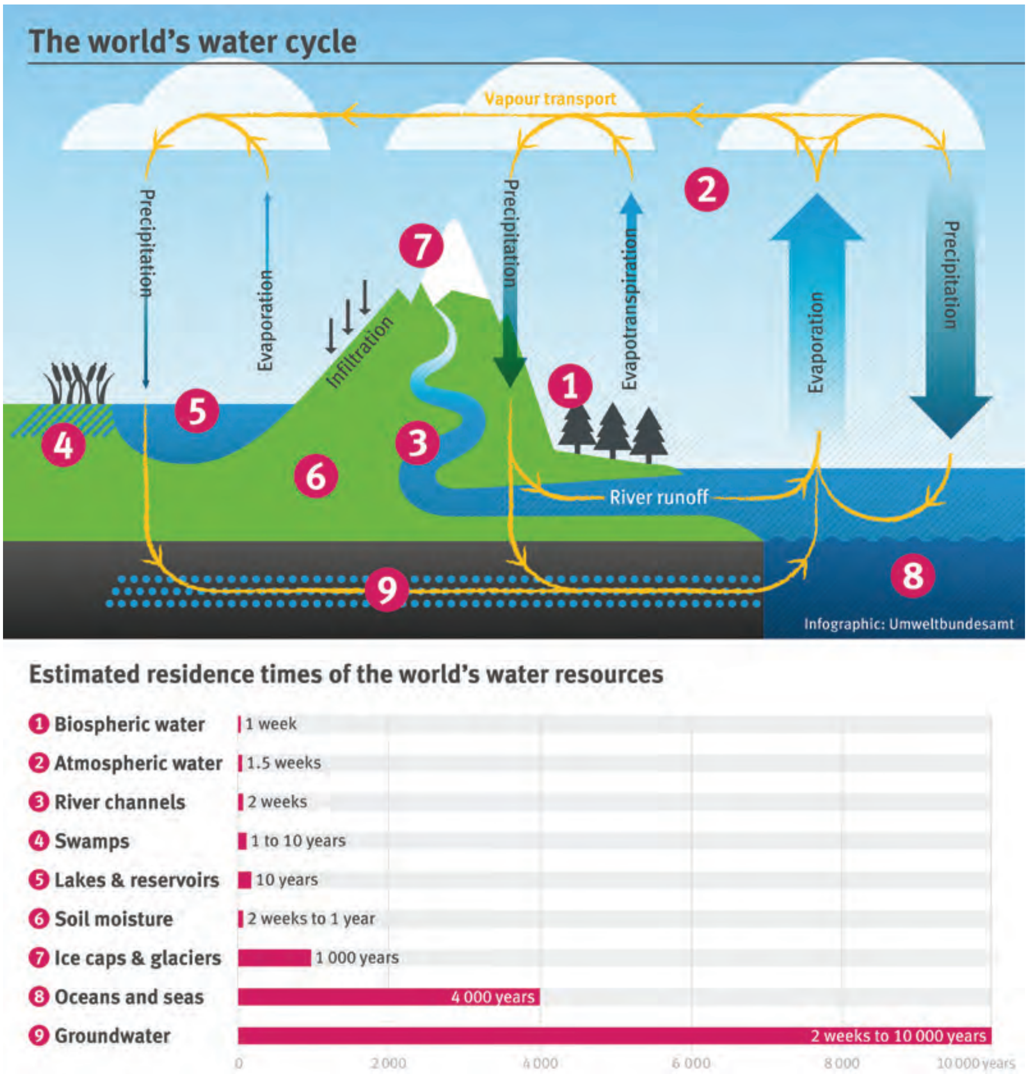
This section provides an overview of the catchment characteristics relevant for assessing the extent to which hazards released in the catchment are likely to reach a surface waterbody.

When assessing the risk from particular contaminants and pathogens, it is important to focus not just on the individual hazards, but also on the hazardous events and conditions responsible for the transport and attenuation of hazards from their source through to the point of offtake. The transport and attenuation of hazards depends on the:

- geomorphological conditions and characteristics within a catchment (i.e. the connection of waterbodies, geology, type of landscape, topography and degree of vegetation cover or of impermeable hard surfaces);
- conditions within the waterbody; and
- characteristics of the particular hazard.

The constant movement of water around the planet is described by the hydrological cycle, which is a conceptual model that indicates how water circulates between the oceans, the atmosphere and the continents of the world (Fig. 7). The time that water remains in any "compartment" in the cycle is highly variable. During its circulation from ocean to atmosphere to land and back to the ocean, water is temporarily stored in streams, lakes or groundwater, ice and snow.

Figure 7 The world's hydrological cycle and the magnitude of water movements and residence times within each compartment of the cycle



Source: based on Igor A. Shiklomanov, State Hydrological Institute (St. Petersburg) and UNESCO, Paris, 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze and Cherry (1979).

Hazards in the catchment do not necessarily pose a risk, unless they reach the drinking-water resource. As development in a catchment progressively increases, so does the number and spatial extent of pollution sources. If these are not effectively controlled, downstream water quality generally deteriorates over a large area. An increase in the number and type of potential pollution sources often coincides with changes in the physical structure of the catchment, such as deforestation, surface sealing (e.g. anthropogenic soil compaction or paved areas), introduction of drainage channels, and reshaping of the riverbed or damming of the river. Such changes significantly alter pathways for hazards. In catchments with intensive land use or high population densities (or both), entire river systems may be affected by contamination.

Some models attempt to quantify the spatial and temporal dynamics of transport and attenuation of hazards that arise from the complex distribution of sources scattered across a catchment, to accurately predict their concentrations at a given surface-water offtake. Alternatively, it is possible to develop an understanding of whether a particular hazard is likely to reach a raw-water offtake at health-relevant levels based on data on potential hazard sources (see also Chapter 4).

In determining the likelihood of a hazard reaching a surface waterbody or drinking-water offtake it is critical to determine:

- the principal transport pathways, including direct emissions, precipitation run-off, sediment transport and input from groundwater systems; and
- the degree to which the reduction of the concentration of a hazard occurs along those pathways due to attenuating processes, including pathogen inactivation, sedimentation, biodegradation, sorption, chemical reaction, volatilization and dilution.

2.2.1 Catchment conditions and transport processes influencing pollution pathways

This section describes catchment conditions and processes that are relevant when assessing the transport and attenuation of hazards. Pathways for hazards reaching a surface waterbody may be subdivided into the following categories:

- direct precipitation, spillage or discharge to surface water;
- overland surface or near-surface transport, including components of surface run-off (stormwater), overland flow and erosion driven by rainfall; and
- baseflow or subsurface transport, including shallow interflow through the unsaturated zone, and deeper groundwater flow in aquifers that naturally discharge to surface waters.

The relative importance of these different pathways or combinations of them varies. For example, overland or near-surface pathways may be particularly important in upland, steep topographic catchments, urbanized hard-surfaced environments or localities underlain by less permeable stratigraphical layers (i.e. layering of rocks). Similarly, subsurface groundwater flow pathways are generally more important in lowland, shallow-gradient or rural catchments underlain by permeable stratigraphical layers (e.g. limestone, chalk, sandstones, sands and gravels), or where surface-water headwaters are predominantly spring fed.

In relation to overland surface processes, transport processes include erosional run-off from contaminated land, run-off with a high content of colloidal or suspended solids (to which many hazards may adhere), and removal of sediment during a flood event (i.e. sediment scouring) and re-deposition of contaminated riverbed or lakebed sediments.

Selected catchment conditions and processes influencing pollution transport are detailed in the sections below. Details on hydrogeological conditions and their influence on groundwater flow are given in Chapter 2 of *Protecting groundwater for health* (Schmoll et al., 2006).

Run-off and slope

The distribution of run-off in a region is strongly influenced by its topographic setting, which both limits the area of land contributing to run-off and determines the distribution of run-off within that land area. The topographic setting also determines the extent to which run-off flows into lakes or discharges through river channels to the coast or inland waterways or, alternatively, infiltrates to the subsurface and to groundwater.

How factors interact in any given setting determines how much run-off occurs (i.e. how much water flows across the land surface). Run-off usually involves the following sequence of events:

- the intensity of rainfall exceeds the rate at which water can evaporate and infiltrate into soil;
- a thin water layer forms that begins to move down-slope under the influence of gravity;
- flowing water accumulates in depressions;
- depressions overflow and form small "rills" (i.e. shallow channels in the ground resulting from erosion from water flow);
- rills merge to form larger streams and rivers; and
- streams and rivers then flow into lakes or oceans.

Erosion

Erosion is an important process for surface-water quality, because it determines the load of suspended particles that impair water quality directly by causing turbidity. Further information on turbidity is given in Section 2.1.4.

The extent to which soil erosion takes place in any given region depends on the interplay of a number of factors:

- *climatic factors* – erosion rates are often high when there is a high rainfall intensity in individual storms and a high average annual rainfall;
- *topography* – erosion rates tend to be high on either very steep or very long moderate slopes;
- *extent of vegetation cover* – erosion rates are lower where there is a dense vegetation cover, because the vegetation reduces the impact of rain splash on soil, and because the plant roots bind soil particles together;
- *soil properties* – the grain size and degree of sorting of minerals in soil, together with their chemical properties can influence erosion rates; thus:
  - very fine grained and very coarse grained soils tend to be more resistant to erosion than soils with more moderate mineral grain sizes;
  - shallow soils and those with low hydraulic conductivity support erosion;
  - chemical precipitates of calcium carbonate, iron oxyhydroxides or silica in the upper part of some soil horizons can bind soil particles together, as can the growth of cyanobacterial mats in some soils;
- *land-use practices* – the way in which activities such as forestry, agriculture or urban development are practised has a major bearing on the degree to which erosion occurs; and
- *water and soil management practices* – excessive irrigation of crops can lead to soils becoming more "sodic" (i.e. having excess salts, including a high proportion of sodium present as sodium chloride) and dispersive, reducing their infiltration capacity and increasing the extent to which they can be eroded by heavy rainfall events (with control possible through practices such as periodically adding gypsum to the soil).

Under natural conditions, catchments generally change their characteristics gradually over long time periods due to stream erosion. However, the rate of that erosion may be accelerated by natural factors such as forest fires or seismic activity and by land-use factors such as those listed above. The land-use factors accelerate the rate of change in the catchment because land

Box 2.5 Effects of soil erosion and sediment

Although increased soil erosion is not a direct health concern, increasing the suspended solid load and the turbidity of run-off increases the risk of higher numbers of pathogens in water. Also, it may reduce the effectiveness of filtration, chlorination or other treatment methods to remove or inactivate pathogens. In agricultural areas, contamination of drinking-water sources by pathogens introduced through erosion is especially problematic when large amounts of manure are transported by overland flow into water sources. This is especially the case for the protozoa *Giardia* and *Cryptosporidium*, which are particularly resistant to chlorination.

The increased sediment load can cause waterbodies to rapidly fill with silt, thus reducing storage volume or leading to the need for dredging. Also, fine sediment particles (generally <65 µm) transport adsorbed phosphorus into surface-water supplies, where it may be released and become available to trigger blooms of toxic cyanobacteria that pose health concerns in drinking-water. Furthermore, these sediment particles can carry persistent pesticides such as DDT and metals into waterbodies. Hence, management of soil erosion and the discharge of sediment into waterbodies is critical to avoid contamination of surface water for drinking-water supplies.

clearing and the introduction of paved surfaces increase both the rapidity at which run-off occurs in response to a rainfall event and the magnitude of the run-off. This in turn increases the erosive power of water flowing across the land surface, particularly where there is little or no vegetation cover to hold soil in place. The introduction of urban development into previously undeveloped catchments can increase the degree to which sediment is eroded and transported by a factor of at least 10 (Novotny, 2003). Erosion may have several effects on surface-water quality (Box 2.5).

To reduce erosion, several measures may be taken; for example, establishing a protective vegetative cover or maintaining the surface soil in a condition that allows it to absorb water. Buffer strips may be established to keep erosion from reaching the drinking-water resource. Measures may also aim at preventing excessive surface run-off or channelling the surface run-off. Accompanying mechanical methods (e.g. furrows, trenches, vegetation strips, pitting and basins) may reduce surface run-off and soil loss by retaining water on-site. For example, these methods may reduce the length of the slope and its inclination, which in turn reduces the volume and velocity of surface run-off (Ffolliott et al., 2013). Examples of control measures to reduce erosion in different settings are given in Box 2.6.

Box 2.6 Case studies on erosion control

After experiencing problems with pollution and siltation in other catchments, the Paddy Land-to-Dry Land programme was introduced after 1997 near **Beijing, China**, to protect the Miyun reservoir, which is the main surface-water source for 20 million people. Farmers in this area were compensated for changing their crops from rice to corn, thus affecting not only the drinking-water supply, but also people's livelihoods. Rice farming may introduce chemicals and other substances (e.g. fertilizers and sediment) to surface waterbodies, because the rice paddies are constantly flooded and are typically on steep terrain. The benefits gained, of US$ 2020 per hectare of farmland (through increased water yield and improved water quality), exceed the costs of about US$ 1330 per hectare.

Riparian areas have been reforested to protect the reservoirs used as drinking-water sources for the approximately 15 million inhabitants of metropolitan **Manila** in the **Philippines**. Previously, only 40% of the area of the Ipo watershed – one of the three watersheds used as raw-water sources – was still forested. Various stakeholders, including Manila Water; the Metropolitan Waterworks and Sewerage System; the concessionaire Maynilad; and academic, private and public organizations, were involved in the activities. For example, volunteers helped replant hillsides as part of an Adopt-a-Watershed programme.

Reforestation was also undertaken in **São Paulo** in **Brazil** as part of the Water Producer Program. Sedimentation from eroding areas had led to reduced capacity of the reservoirs supplying the municipality of Extrema and the water-supply system of São Paulo. A scheme to pay for ecosystem services was established in 2005, through which a federal watershed committee collects fees from water users. This revenue is used to compensate farmers and ranchers for reforesting or terracing their fields to reduce erosion and improve water quality.

Storm events

Storm events with heavy rainfall substantially increase the amount of water drained by ditches, rivulets and channels from the land into larger rivers, lakes and reservoirs. This can temporarily cause a strong increase in turbidity and contaminant loading (e.g. by washing agrochemicals from fields or poorly discarded wastes into the waterbody). However, as water volumes are large during storm events, such increased loads are also diluted, and therefore do not result in equally increased concentrations. Even if concentrations increase, for most chemicals, storm events are unlikely to lead to concentrations in drinking-water that would be hazardous for short-term exposure.

In contrast to the situation with chemicals, when storm events lead to increased exposure of consumers to pathogens, outbreaks of illness are likely. A number of studies have shown the possibility of substantially increased transport of pathogens into surface waters in the wake of storm events (Atherholt et al., 1998; Hunter, 2003; Kistemann et al., 2002). Pathogens are readily transported with bulk flow across land and into water, and may rapidly reach drinking-water offtakes. Examples of enhanced contaminant loads following storm events are given in Box 2.7 (for toxoplasmosis) and in Box 2.12 (for *Cryptosporidium* and *Giardia*; see "Water exchange in lakes and reservoirs" in Section 2.2.2). Enhanced drainage of stormwater can help to prevent exposure of consumers to pathogens due to storm events.

Box 2.7 Toxoplasmosis outbreak associated with heavy rainfall, British Columbia, Canada

In March 1995, an increase in cases of acute toxoplasmosis (a potentially fatal parasitic disease) was noted in the Greater Victoria area of **British Columbia, Canada**. Both geographical mapping of cases and case-control studies of symptomatic cases were performed in response. One-hundred individuals aged between 6 and 83 years met the definition of an acute, outbreak-related case. Investigators hypothesised that faecal material from either domestic cats (*Felis catus*) or cougars (*F. concolor*) may have contaminated a surface-water reservoir with *Toxoplasma gondii* oocysts. Both the mapping and the case-control studies found significant associations between acute infection and residence in the distribution system of one reservoir that supplies water to Greater Victoria. The epidemic curve was bimodal, with peaks in December 1994 and March 1995. The peaks were preceded by increased rainfall and turbidity in the implicated reservoir. A municipal water system that was using unfiltered surface water (disinfected with chloramine) was the likely source of this large community-wide outbreak of toxoplasmosis.

Source: Aramini et al. (1999); Bowie et al. (1997).

Where climate change increases the magnitude and intensity of storm events, this is likely to have an impact on surface-water quality. Examples of surface-water risks associated with climate change are presented in Box 2.8.

Box 2.8 Examples of surface-water risks associated with climate change

Among other impacts, climate change is expected to alter the frequency and severity of extreme weather events (e.g. flooding and droughts). These events are likely to lead to changes in the variability and availability of surface-water sources, although the effects of climate change will probably vary significantly among different regions.

Altered precipitation patterns may strongly influence surface-water quality. For example, intense rainfall events may mobilize contaminants otherwise bound in soils and thus increase the amount of these contaminants reaching a waterbody. The increased contamination may have short-term effects on water quality, such as increased concentrations of pathogens and suspended sediments. In contrast, periods of drought may concentrate contaminants through lower flows and reduced water levels, but may also reduce pathogen concentrations because there is more time for inactivation.

Warmer temperatures and reduced inflow can result in depleted oxygen in stratified reservoirs and lakes, which in turn may trigger the release of hazards from sediments (e.g. phosphorus, iron and manganese). Phosphorus release, coupled with lower inflows and turnover, may promote excessive phytoplanktonic growth. However, warmer temperatures may also increase inactivation of enteric waterborne pathogens. Water unavailability (i.e. water quantity issues) may lead to the need to use alternative water sources that are unsafe for human consumption.

Climate change could also indirectly affect surface-water quality through increased frequency and intensity of bush and forest fires within heavily vegetated catchments. In addition, climate change is expected to affect land use; for example, by increasing population, urbanization and industrial and agricultural activities, increasing stress on water sources used for several purposes (e.g. industry and drinking-water).

The expected impact of climate change (including increased climate variability) on surface-water resources is therefore likely to affect water security and safety; for example, by causing people to use alternative drinking-water sources that are less safe. In light of these risks, water-supply services must consider their resilience to climate variability and current and future change, taking into account the climate-related projections that could increase the likelihood and severity of the consequences arising from catchment-related hazards in the future.

Source: adapted from WHO (In preparation-b).

2.2.2 Waterbody conditions influencing hazard transport and attenuation

This section describes the characteristics of a waterbody that influence the transport and attenuation of contaminants within a catchment system. These characteristics are stream flow; water exchange in lakes and reservoirs; and shape, size and stratification of lakes and reservoirs.

Stream flow

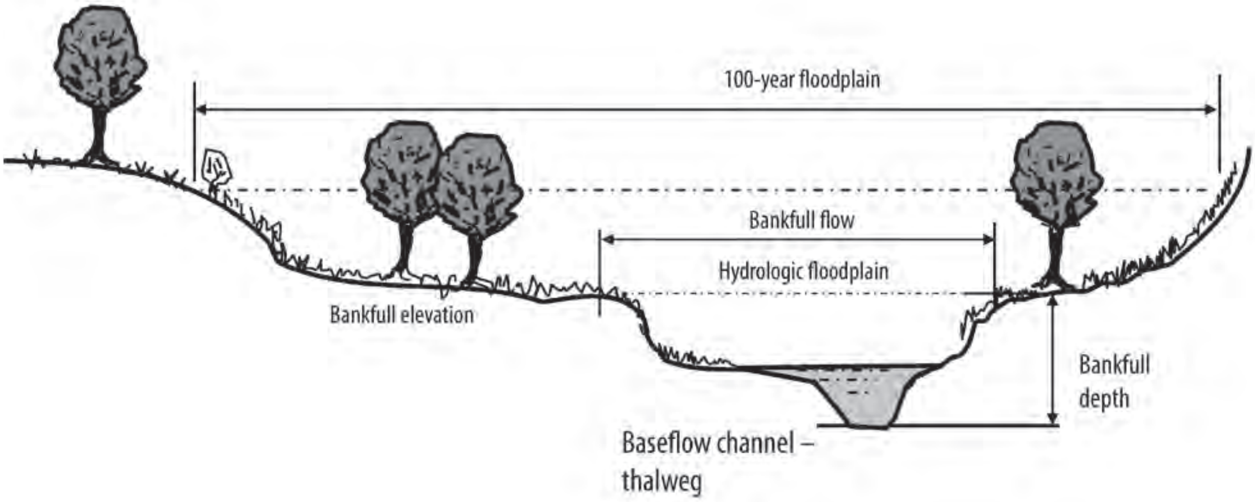
Stream flow can have a profound impact on water quality by influencing the transport and distribution of hazards within surface waterbodies. Within a catchment, stream flow takes place within one or more channels that vary in width and depth. This process depends on factors such as:

- the magnitude of peak and average stream-flows;
- topography;

- geology (particularly the ease with which the bedrock can be eroded);
- climatic factors; and
- the extent to which groundwater discharge provides baseflow, or riverside water abstraction reduces it, potentially causing stream loss rather than gain.

Typically, perennial streams have a baseflow channel that carries groundwater baseflow all of the time. The "thalweg" (i.e. the line defining the lowest points along the length of a riverbed, defining its deepest channel; Fig. 8) is incised within a larger main channel (the floodway), which may fill with water when there is increased run-off during rainfall events. The main channel is often lined by levee banks that have either formed naturally or been constructed, and that may be several metres higher than land adjacent to the river. In rural streams with stable banks, the main channel may occasionally fill or over-fill with water (e.g. annually or once in a few years), but this is likely to happen more frequently if urban development or other land use introduced into the catchment alters run-off patterns. These are known as "bankfull" flows (Fig. 8).

Figure 8 Graphic illustration of stream flow channels



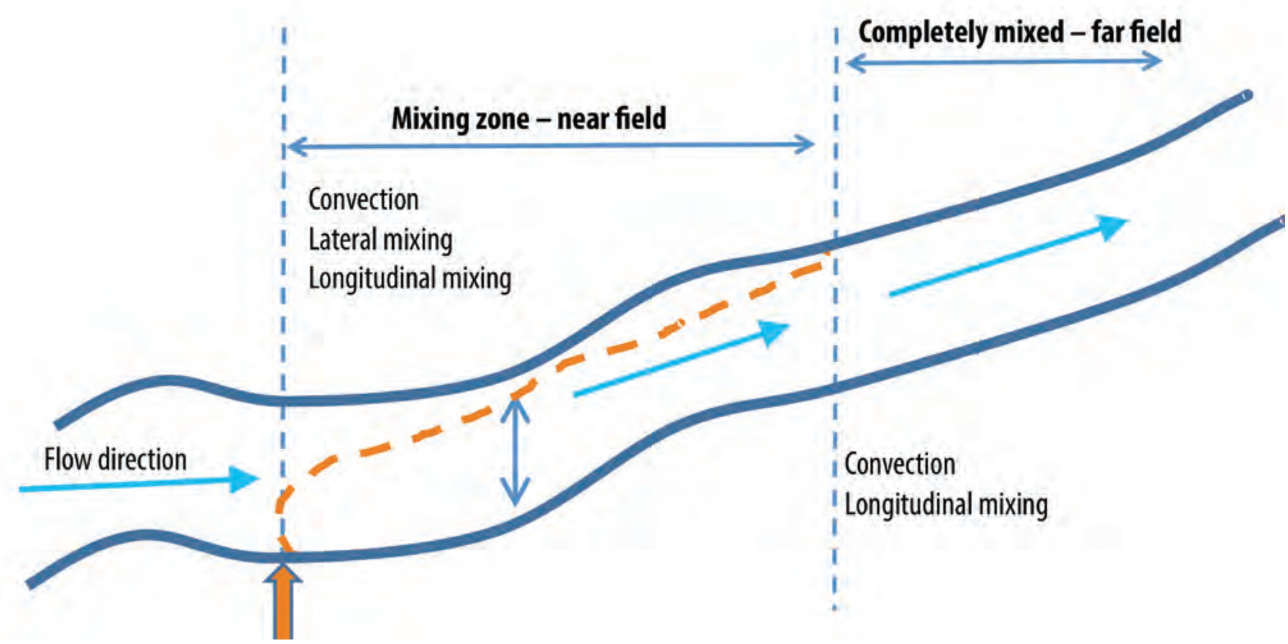
Source: Novotny (2003).

During flood events, the main channel and the adjacent part of the floodplain typically carry most of the water flow. Thus, they may erode substantial amounts of sediments that are commonly redeposited near the margins of the floodplain (where, in some situations, they contribute valuable soil enrichment used for agriculture along such margins).

Many rivers, streams and creeks are characterized by typical flow velocities of about 0.1 to 1 m/s. The factors listed above that influence stream flow (or flow velocity) can cause strong currents and a high average turbulence, leading to thorough vertical mixing of the water masses. When an effluent or a tributary is discharged into a river, it spreads out laterally until the concentrations reach the opposite bank, where the flow becomes completely mixed (Fig. 9). This mixing zone is termed "near field", and here, concentrations are affected by convective flows and by lateral and longitudinal dispersion. Lateral mixing is primarily affected by the channel's depth, velocity and bottom roughness, and to a lesser extent by the channel's banks and winding (or "sinuosity"). Flow rates also affect organism transportation and existence, and structure of habitats within the riverbed, surface exchange of gases and the amount and type of sediment carried.

Chemical contaminants adsorbed to solids may sink to the bottom of the stream and remain in the sediments during lower flows. However, they may be resuspended at times of stronger, more turbulent flow.

Figure 9 **Mixing within streams**



Box 2.9 The relationship between a river and subsurface groundwater

The relationship between a river and subsurface groundwater may be complex and may vary along the river. Hence, assessing variations in flow may require substantial monitoring effort. For example, streams and rivers may receive groundwater discharge for part of their length, and may discharge water to groundwater in other areas. Variability (e.g. seasonal variability) may arise from temporary alterations in groundwater discharge to surface water, such as in the aftermath of a major precipitation event. In some arid areas (where annual evaporation exceeds annual precipitation), only the river headwaters in mountains show permanent run-off because they receive water from melting snow or from springs that arise from groundwater discharge points, often at interfaces between permeable and non-permeable geology. Further downstream, a stream may be losing water as it flows over permeable geologies through which water infiltrates to the underlying aquifer (i.e. groundwater under the direct influence of surface water). Yet further downstream in catchment lowlands, groundwater tables may be high compared to the river level, causing groundwater baseflow to discharge into a river. The river may nonetheless lose water in times of drought or if groundwater abstraction is excessive.

In catchments above permeable limestone or chalk, most of the river flow is probably sustained from groundwater baseflow or spring flow. In more arid parts of the world, where evaporation often exceeds rainfall, run-off typically shows large seasonal variations. In such areas, rivers may be seasonally dry, with short duration of flows (termed "ephemeral") following rainfall or snowmelt. Ephemeral systems typically lose water downstream.

Given this complexity, it may be useful to include groundwater when assessing surface-water flow.

Velocity differences in various parts of the stream's cross-section profile affect the distribution of hazards downstream of their source (Box 2.10).

Box 2.10 The impact of stream velocity on downstream hazard distribution

Consider the simplest possible case, in which a volume of contaminated water is instantaneously released at a point into a stream (e.g. from an accidental spill) upstream of a water-supply intake from the stream. The time of travel from a point of discharge, A, to a downstream offtake for a drinking-water supply, B (see figure below) is simply calculated as:

$T = L/V$

Where **T** = time of travel
L = distance between A and B
V = mean velocity of water in the stream.

However, because the velocity of water is not uniform across a stream, the time of travel calculated above is an average value with some particles of the hazard arriving at point B earlier than others. From the viewpoint of an observer measuring the concentration of the hazard over a period of time at point B, there will be a probability distribution of contamination around this mean value (see figure below). This distribution becomes broader and the peak concentration decreases as the distance between points A and B increases. These effects result from increased mixing and dilution of the hazard.

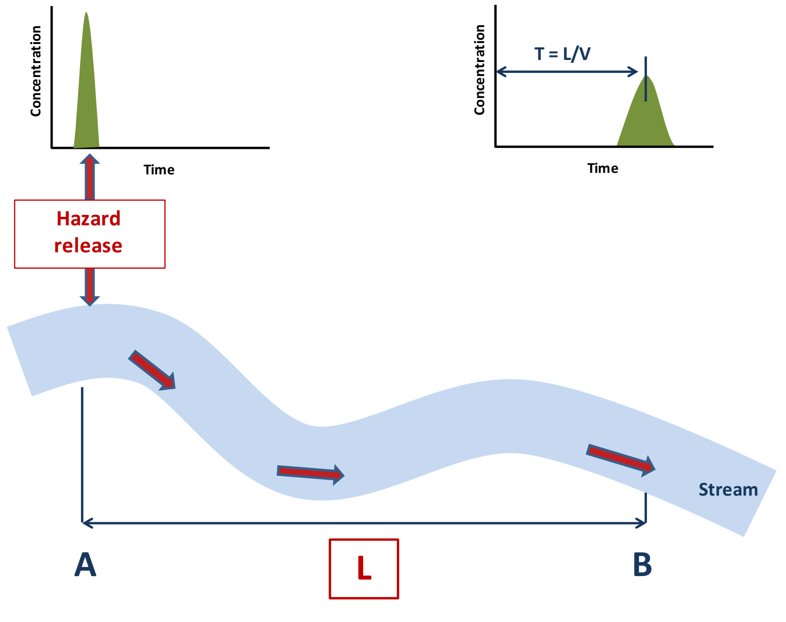


Illustration of probable time of travel of a release of contaminated water between a pollution source (A) and a point of water withdrawal (B).

The example presented in Box 2.11 illustrates how monitoring measures and estimates are used in early-warning protection schemes for drinking-water. They may be applied for river sections upstream of a drinking-water offtake point for drinking-water supply, or for general pollution control. Similar systems are applied along many major rivers in Europe, such as the river Rhine. After large amounts of contaminated firefighting water from the premises of the Sandoz chemical works reached the river in 1986, the International Commission for the Protection of the Rhine was founded, and commissioned the development of an alarm model in case of incidents. Similar models have been adopted for a number of other river catchments, including international agreements for transboundary rivers. The early-warning systems allow for the interruption of drinking-water abstraction while a contaminant flows past the point of offtake.

Box 2.11 Response to a chemical spill in the Ohio River upstream of the Cincinnati City water intake

A network of water-quality monitoring stations along the Ohio River in the **USA** was established by the Ohio River Valley Water Sanitation Commission (ORSANCO) to provide an early warning of chemical spills from industrial facilities along the river.

In 1993, more than 6000 L of the toxic compound ethylene dibromide (EDB) was accidentally released into the river upstream of the water intake for **Cincinnati**. Preliminary modelling indicated that peak concentrations of EDB in the river in the vicinity of Cincinnati could be about 270 µg/L, much higher than the US drinking-water standard of 0.05 µg/L.

The Cincinnati waterworks was notified, and monitoring about 60 km upstream of the Cincinnati water intake started detecting EDB on 13 June 1993. The early-warning system allowed sufficient time to plan a response to the pollution. It was decided to treat the raw water with activated carbon to remove the EDB, and to close the water intake from the river for the period when the EDB concentration exceeded 2 µg/L in the river near the intake. The strategy was effective, and water consumers were not exposed to a health risk.

Water exchange in lakes and reservoirs

Lakes and reservoirs are open bodies of water. The water balance in lakes and reservoirs is affected by inflows and outflows. They behave as storage buffers that delay the discharge of water from a catchment.

The sum of all inflows or all outflows in relation to the water volume of the lake or reservoir determines its “water exchange rate” (or the inverse, its “water residence time”). Outflow may be from flows into rivers or streams, evaporation, groundwater recharge and constructed water offtakes. Outflow into a river can occur through surface drainage outlets or – in the case of reservoirs and some lakes – through deeper outlets that remove water from layers with another quality than the surface layer. Outflow or discharge may also be directly into groundwater flow systems. Inflow may be from discharges from streams, rivers, wastewater or groundwater, and from direct run-off from slopes around the waterbody. Water is also added by precipitation directly onto the surface of rivers, lakes and reservoirs.

An understanding of the water balance of lakes and reservoirs is fundamental for estimating the impact of contamination. Thus, where a waterbody is located in the lowest point of a catchment, it may act as a sink for all water, and hence also the hazards contained in that water, and there may be no water outflow other than evaporation. In such situations, reduction of hazards within the waterbody may occur through UV inactivation, predation, biodegradation and sedimentation (see Box 2.12), particularly if there are long water residence times (months to years). However, where water residence times are long, the waterbody is more likely to accumulate nutrients, particularly phosphorus. This may lead to eutrophication, and problems with algal blooms can occur each season, or within a few weeks in response to large nutrient inputs with water inflow. On the other hand, longer water residence times may cause a greater retention of nutrients (both phosphorus and nitrogen) in the sediment, hence decreasing the rate of biomass generation (or “productivity”) of the system, and thus decreasing the “trophic status”. This is especially relevant in deep stratified waterbodies, where sedimentation and biotransformation are important nutrient attenuation processes.

Box 2.12 *Cryptosporidium* and *Giardia* event, Sydney, Australia

Between July and September 1998, elevated levels of the protozoan pathogens *Cryptosporidium* and *Giardia* were detected in the metropolitan water supply in **Sydney, Australia**. This prompted the issuing of several “boil-water advisory notices” as a public health protection measure, affecting about 3 million residents. Sydney’s catchment had experienced a moderate rainfall event in July 1998, and a subsequent severe rainfall event in August 1998. This led to an unprecedented filling of the Warragamba dam, which rose from 60% capacity to 100% capacity (spill level) in just 10 days.

It is thought that the rainfall events resulted in pulses of poorer quality raw water entering the dam from the catchment, and also altered flow patterns and thus retention times. Under normal flow conditions, the dam was estimated to have a retention time of about 3 years. However, the intense rainfall led to a density current of the poorer quality water passing through the dam at greater velocity. In turn, this reduced retention times within the dam, possibly making the times too short for the natural pathogen attenuation processes that would normally occur within the dam. Such processes include sedimentation, UV inactivation, predation (i.e. the preying of one organism on another) and starvation. Hence, pulses of poorer quality raw water entered the water treatment plant, and may have overloaded the filtration systems. This combination of events may, in part, have contributed to the detection of the increased levels of the protozoan pathogens observed within the water-supply system at that time. The event highlights the importance of surface-water protection as a component of a multiple-barrier approach to ensuring the provision of safe drinking-water for the protection of public health.

Where water exchange rates are high, contaminants can be diluted and thus effectively carried out of the waterbody. This also applies to contaminants stored in sediments. If these contaminants, which include nutrients, are released into the water and the water exchange rate is high, the contaminants will be diluted and eventually carried out of the lake or reservoir at a rate that depends on the amount stored in the sediment, its release rate and the water exchange rate.

The construction of dams on rivers creates a reservoir or impoundment upstream of the dam wall, and water resides longer in these waterbodies than in the river. Impoundment tends to have substantial impacts on water quality. For example, quite different communities of organisms (e.g. cyanobacteria) can establish themselves in the stagnant water of a reservoir as compared to the flowing water of a river. Decisions on impoundments are often based solely on criteria for the management of the amounts of water rather than on its quality. However, in making decisions about the management of impoundments (e.g. in the context of WSP development), it is useful to include quality criteria for human health. This approach can help to avoid unexpected changes in water quality once the reservoir has filled, and the ensuing treatment costs.

Shape, size and stratification of lakes and reservoirs

Water quality within lakes and reservoirs is influenced by the separation and exchange of water masses within these waterbodies, which in turn depend on their geometry and the climate of the region.

Some of the influence of shape and size of a lake or reservoir is self-evident. Water quality in a small (<0.5 hectares) or shallow (<2 m deep) lake or reservoir will be affected more quickly and directly by influences from the immediate surroundings.

Shallow lakes or water storages are especially vulnerable to eutrophication and microbial contamination from access by livestock, birds or other wildlife. In seasonally dry areas, such waterbodies may also become brackish or saline due to evaporation. Deeper waterbodies tend to develop layers with different water-related characteristics; that is, they become stratified. Lakes and reservoirs tend to undergo stratification if (World Bank, 2003):

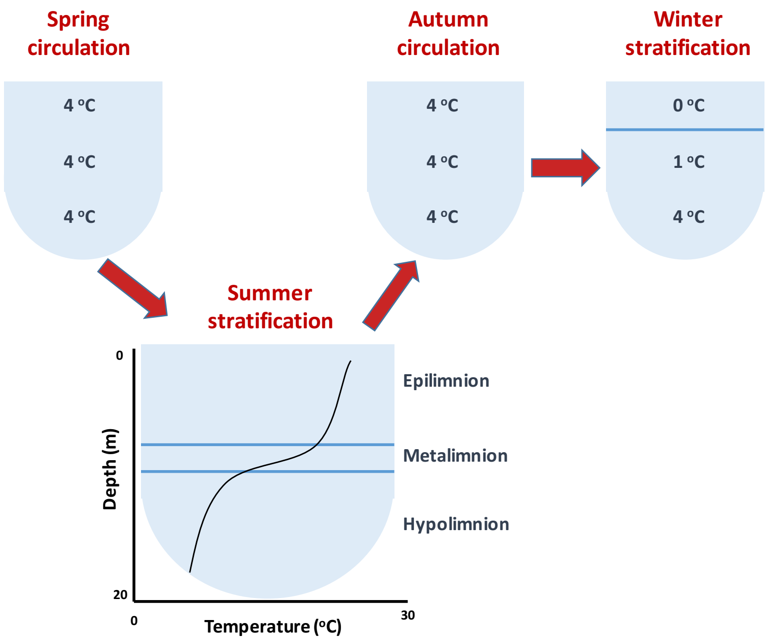
- the water depth is more than 10 m and the surface width is less than 30 times the depth;
- the ratio of inflow to storage volume is small; and
- the reservoir depth is greater than the light penetration.

Stratification leads to differences in water quality between the upper and lower layers. In temperate climates, stable thermal stratification develops in spring, when solar radiation heats up the surface layers while the input of wind energy is not strong enough to mix the waterbody all the way to the bottom. The result is a warm, lighter upper water layer (termed “epilimnion”) and a cool, denser lower water layer (termed “hypolimnion”), separated by a transition layer with steep temperature gradients (termed “metalimnion” or “thermocline”) between the upper and lower layers (Fig. 10). Once temperature differences become pronounced (i.e. >5 °C), there is little water exchange between these layers until the autumn, when the surface layer cools again and reaches a density close to that of the bottom layer.

Strong winds that typically occur in autumn can trigger total waterbody mixing (“autumn overturn”) even before the upper layer has cooled all the way down to the temperature of the lower layer. However, if the hypolimnion has accumulated high concentrations of chemicals (typically salts and dissolved minerals), it becomes denser; this is termed “chemical stratification”, in contrast to the “thermal stratification” discussed above. In such situations, the wind energy may not be strong enough to mix the upper and lower layers, even if their temperatures have become identical. If no mixing occurs all winter long, the chemical gradient will continue to increase, and this chemical stratification will stabilize during the next summer. Such situations occur in lakes that are very deep in relation to their surface areas; for example, volcanic crater lakes. They also occur in catchments affected by the salt used for de-icing and snow removal on roads.

In tropical climates (and in temperate ones during warm sunny days with little wind), thermal stratification may show diurnal patterns, whereby the temperature of the surface layer increases by several degrees during the daytime, but cools sufficiently during the night for renewed mixing. In contrast to seasonal thermal or continuous chemical stratification, this diurnal pattern has little impact on water quality.

Figure 10 Seasonal stratification of a reservoir in a temperate climate



The curve drawn into the summer graphic shows temperature (horizontal axis) over depth (vertical axis).

Seasonal thermal or continuous chemical waterbody stratification has substantial consequences for water quality. Positive effects include the sedimentation of suspended particles, including pathogens and hydrophobic chemicals adsorbed to particles. In a river, the particles remain suspended if flow is usually turbulent (or become resuspended during more turbulent episodes), but in a lake or reservoir, they settle to the bottom. Hence, reservoir water may be clearer than that of the river feeding the reservoir, and poorly water-soluble chemicals adsorbed to particles may be "buried" in the sediment.

If a reservoir or lake has a water residence time greater than about 1 month, a significant proportion of suspended sediment present in the inflow will be deposited in the water storage structure through the process of settling or sedimentation. The downside of this mechanism is that, where erosion rates are high, water storage structures may be filled with sediment within a matter of years. A lack of oxygen in the deeper layer leads to negative effects on water quality. Stratification greatly reduces the exchange of water and dissolved constituents between the epilimnion and hypolimnion; thus, surface sources of oxygen may scarcely reach the hypolimnion. Additionally, light is increasingly limited as water gets deeper, and algae that settle into the hypolimnion take up more oxygen than they produce through photosynthesis, thus imposing a demand on dissolved oxygen in the hypolimnion. This factor, coupled with the oxygen demand caused by bacterial decay of organic matter at the bottom of the lake or reservoir, may lead the hypolimnion to become devoid of oxygen (i.e. to become anoxic).

Anoxic conditions near the bottom of lakes and reservoirs cause conversion of some chemical compounds from their more oxidized states into their more soluble reduced states. For example, this occurs with iron and manganese, with subsequent release of any hazardous compounds that may be adsorbed to iron and manganese coatings on such sediments. Further, anoxic conditions often release large amounts of phosphorus from the sediment into the hypolimnion. Depending on how much water is exchanged between the hypolimnion and epilimnion, this phosphorus may trigger the growth of planktonic algae and lead to blooms of cyanobacteria. In turn, this may result in a higher content of organic material in the warm epilimnion through the growth of plankton, sometimes including cyanobacterial scums (with some cyanobacteria, particularly *Planktothrix rubescens*, sometimes forming dense layers just under the epilimnion; see Section 2.1.3).

In optimizing drinking-water offtake depths, it is essential to understand the stratification of a reservoir in order to identify the depth with the best water quality. The challenge for determining the optimal depth for a drinking-water offtake is discussed in "Lakes and reservoirs" in Section 2.2.4.

Horizontal variations in water quality can be pronounced, particularly in larger lakes and reservoirs with bays, each of which may be influenced by its own tributary and subcatchment. Such differences are sometimes readily visible as water colour or turbidity zones. Also, cyanobacteria may not pose a problem at one shore of the waterbody but accumulate as thick scum at downwind shorelines and bays. As with stratification, understanding such patterns is important for optimizing the siting of drinking-water offtakes.

Another important factor is the impact of other hydrophysical conditions on the water quality of a lake or reservoir. For example, water volume in relation to inflow determines the rate at which constituents from the inflow reach the water reservoir. In particular, variations of inflow volume may strongly affect the transport and attenuation of both particle-bound and dissolved substances within the reservoir. One example would be a severe rainfall event resulting in reduced retention times due to higher inflows and altered flow patterns (i.e. "density currents", created as water from the inflow travels in the layer that has the same density). If management relies on attenuation of hazards in the reservoir and does not adapt treatment to such situations, disease outbreaks may occur (see the case study on the Sydney *Cryptosporidium* and *Giardia* incident in Box 2.12).

2.2.3 Transport and attenuation processes influencing pollution

This section describes the processes that transport and attenuate hazards, both on their pathway through the catchment and within the surface waterbody itself. In addition to large-scale geomorphological catchment conditions, a range of processes may slow the transport of a contaminant to the surface waterbody, or reduce its concentration within that waterbody. Also, a contaminant may be transformed or degraded into another substance or, in the case of microbial contamination, be inactivated (i.e. die off) before reaching the waterbody. Some of these processes (e.g. dilution and dispersion) are relevant for both microbial and chemical contamination; others are specific to microorganisms (e.g. inactivation) or chemicals (e.g. volatilization and degradation). More information – in particular, for estimating the quantitative impact of these specific processes – is in Section 2.1.1 (for microbial hazards) and Section 2.1.2 (for chemical hazards).

"Attenuation" is a catch-all term that is widely used to describe a range of predominantly natural processes that reduce the concentrations of chemicals and pathogens while they are transported to a surface waterbody and while they are within that waterbody (although it has a different meaning in microbiology, where it is used for the reduction of infectivity). The main attenuation processes are listed in Table 10 and discussed below. Their importance depends on the physico-chemical properties of the chemicals or microorganisms, and the environmental conditions.

Table 10 Attenuation processes for chemicals and pathogens in the water environment

Process	Relevant for pathogens	Relevant for chemical hazards	Relevant for physical hazards
Abiotic processes			
Dispersion and dilution	●	●	●
Volatilization		●	
Sedimentation	●	●	●
Sedimentation after sorption to solids or colloids	●	●	●
Chemical reaction (transformation)		●	●
Biotic processes			
"Die-off" (or inactivation)	●		
Aerobic/anaerobic biodegradation		●	
Metabolism by higher organisms		●	

Several processes may occur simultaneously, and act in combination to reduce concentrations of contaminants. A more detailed discussion of attenuation in the subsurface groundwater pathway leading to baseflow discharges to surface waterbodies is given in Chapter 4 of *Protecting groundwater for health* (Schmoll et al., 2006). The different processes that may be relevant for attenuating microbial hazards are described in Boxes 2.13 and 2.14.

Box 2.13 Processes influencing the presence of pathogens in waterbodies

Once a pathogen is present in a waterbody, its persistence in that waterbody is governed by a number of factors, including the following:

- *Survival of the organism in the waterbody* – survival is affected by factors such as temperature, intensity of sunlight, oxygenation, pH and the presence of competing flora or predator species.
- *Removal from the waterbody* – either by sedimentation or by transport away from the sampling point (e.g. throughflow downstream or dilution by other water sources.
- *The distribution of the organism* – most pathogens, especially *Cryptosporidium* and *Cyclospora* oocysts, and *Giardia* cysts, are not homogenously distributed in surface waters; rather, they are usually present in clusters, possibly related to faecal deposits. Hence, sampling for pathogens can miss the presence of such organisms.

Microbiological detection systems that examine water samples typically test only small volumes of water (e.g. 100 mL). Also, samples are taken at discrete intervals and often at low frequency. The absence of pathogen detection in such monitoring programmes can therefore provide a false negative impression of pathogen presence and persistence. In turn, this can lead to potentially misleading assumptions about the microbial safety of the water. This underlines the importance of assessing the risk of pathogen occurrence rather than relying on testing.

Box 2.14 Processes influencing the concentration of dissolved cyanobacterial toxins

In circumstances in which toxic cyanobacterial blooms develop, a number of processes in a surface waterbody influence the concentration of the cyanotoxins.

The toxins are attenuated in a waterbody through "die-off" of the cyanobacterial cells, biodegradation and sedimentation. Microcystins are usually cell bound, but may be released as cells die and decay (lysis). However, only a small proportion of healthy cells lyse, and microcystin biodegradation is usually faster than its release from the cells. Thus, extracellular concentrations of microcystins are usually low, even during mass developments of cyanobacteria. In contrast, a sudden "die-off" of a population – induced by rapid changes in environmental conditions or the application of algicides such as copper sulfate – may increase the extracellular microcystin concentrations for a short time. Therefore, if algicides are to be applied, this should be done while cell numbers are still low, to avoid the release of significant concentrations of intracellular toxins, and compounds that cause tastes and odours (WHO, 2015b).

For dissolved cyanotoxins, including those that are frequently extracellular (e.g. cylindrospermopsin and neurotoxins), the most important attenuation processes are biodegradation by bacteria and dilution. The amounts of extracellular anatoxin-a and of microcystins are often diminished within hours or days, whereas cylindrospermopsin can be quite persistent, particularly when temperatures decrease in autumn. Little is known about the attenuation rates for anatoxin-a(s) and the toxins that cause paralytic shellfish poisoning (PSP).

Sedimentation and sorption

Sedimentation is an important attenuation process for pathogens and suspended solids or particles. It plays a role in rivers, where pathogens and suspended solids settle to some extent in the riverbed. However, it is particularly effective in deep reservoirs that stratify thermally, although the waterbody can be mixed at times (e.g. through storms; low water levels; or, in temperate climates, regular "seasonal overturn" in spring and autumn). Resuspension is particularly important in the case of larger microorganisms, such as bacteria and parasitic protozoa, which may have settled in higher numbers. Whether resuspension causes health risks will also depend on the amount of time the pathogens spent in the sediment, where they may have been inactivated to some extent (see "Occurrence in surface water" in Section 2.1.1).

Chemicals dissolved in water may attach to suspended solids, and this mechanism ("sorption") can also increase the sedimentation of pathogens. In a catchment, such solids include soil particles, subsurface geological (aquifer) rock units (e.g. sand grains of a porous sandstone), riverbed or lakebed sediments, eroded sediment load during run-off and particulate organic matter (POM). Chemicals and pathogens can also sorb to gel-like organic material such as humic substances. Sorption is an overarching term that may encompass both "adsorption" (the adherence of a chemical or pathogen to the surface of a solid) and "absorption" (the dissolved chemical diffusing or partitioning into the absorbing material). The fraction of organic carbon (F_{oc}) in the solid is a key measure of its sorption potential for organic contaminants. Generally, the higher the F_{oc}, the higher the sorption.

The extent to which hazards are transported on suspended particles depends on the size and the mineral composition of the particles, and on the hydrochemical conditions. The mineral composition determines the surface chemical properties of the particles, and the extent to which they contain suitable sites for adsorbing hazards. For example, iron and aluminium oxyhydroxides and clay minerals generally have a large surface area per unit mass; hence, they are particularly effective at adsorbing and transporting hazards such as phosphorus and pathogens. Polar minerals poorly sorb contaminants that are hydrophobic, relatively nonpolar and organic, whereas they readily sorb ionic (polar) inorganic chemicals and metals.

Suspended sediments, colloidal material or POM carrying sorbed hazards may originate from surface run-off; for example, from rural and agricultural settings, from dust and dirt on urban road surfaces, or from erosion of (metals-rich) mining waste close to river systems. Once carried along by flowing water, such material moves with the flow, with the sorbed hazards being carried downstream in a river, or to the sediment in a deep reservoir with stable stratification. Strongly sorbed hazards are almost immobile when sorbed to a stationary rock unit or soil, but become highly mobile when they are sorbed to suspended solids – a process termed "facilitated transport".

This process is particularly relevant for organic chemicals that are hydrophobic (such chemicals are invariably highly sorbing), such as PAHs and PCBs, but also for certain metals and phosphorus. Facilitated transport can distribute hazards widely in the water environment. Transport from agricultural settings may involve a complex interplay of dissolved and particulate fractions including organic and colloidal phosphorus forms. For example, it might depend on precipitation and contributions of general run-off versus engineered field drainage (Heathwaite & Dils, 2000). Box 2.15 outlines some of the key processes influencing the transport and attenuation of phosphorus in waterbodies.

Box 2.15 Transport and attenuation of phosphorus within waterbodies

Complex limnological processes drive the transport and attenuation of phosphorus within waterbodies (Reddy et al., 1999). Phosphorus reaches surface waters through run-off from agricultural land treated with inorganic fertilizers or manure. It is mainly adsorbed to particles carried into the waterbody through erosion or run-off, rather than occurring as dissolved phosphate. These particles are mostly iron oxides and calcium carbonate, with the former having greater sorption capacity. Therefore, adsorption of phosphorus occurs most strongly in soil that contains large amounts of iron or aluminium oxides and hydroxides. Sorption may significantly retard phosphorus transport in soils and subsurface, thereby reducing risks to surface water from groundwater baseflow. A greater risk is typically from phosphorus sorbed to soil particles that are transported to surface waterbodies through erosion or run-off (see Section 2.2.1). Even if a large fraction of the phosphorus reaching a waterbody by this route remains bound to the particles and sinks to accumulate as sediment, desorption of a small fraction may still be sufficient to trigger algal and cyanobacterial growth. Concentrations of 25–50 µg/L can sustain cyanobacterial blooms in lakes and reservoirs (see Section 2.1.3), provided other factors (e.g. light or nitrogen) are not limiting. The rate of phosphorus release from sediment into water depends on the biodegradation rate of the organic material with which the phosphorus may be associated. Where phosphorus is sorbed to mineral particles, the release rate may also depend on the specific redox and geochemical conditions.

Box 2.16 describes how sorption processes can influence the presence of viruses in a surface waterbody.

Box 2.16 Adsorption affecting virus transport and attenuation

The role of sediments in the survival and transport of pathogens in water (particularly viruses) is a key area that remains poorly understood. Where virus adsorption to particles and colloids takes place, survival may be enhanced or reduced relative to suspended viruses, depending on the virus type. Pathogens can be transported vast distances. In one study, water with increased turbidity and a low temperature of about 4 °C allowed for the survival of pathogens for over 26 days, and mean velocity of poliovirus, coxsackie B virus and echovirus transport of 1 m/s over 2000 km (Dumke & Burger, 1995). Another study found viruses attached to suspended matter that had been carried in summer over long distances in Poland with average flow velocities of 20 cm/s (Schernewski & Julich, 2001). However, full models that predict and define the behaviour of both deposition and resuspension are not available and the processes are poorly understood.

Sorption also depends on the characteristics of the water, chiefly pH – particularly for metals, acidic or basic organic chemicals (e.g. phenols), viruses, salinity and redox conditions.

The sorption potential of contaminants is characterized by the solid-water partition coefficients K_d and K_{oc}. The K_d-value describes the distribution between any solid surface (i.e. soil, particles or sediment) and water. It provides information on the sorption of a substance onto the complete solid matrix (i.e. how much of the substance can adsorb to 1 kg of soil, particles or sediment). The K_{oc}-value denotes distribution between the organic matter content of the soil, particle or sediment and water, and takes into account only the organic carbon of the solid (i.e. how much of the substance adsorbs to 1 kg organic carbon). K_d and K_{oc}-values are only valid for the respective sorbents (e.g. sand and clay). The K_{ow}-value describes the distribution of a substance between water and a nonpolar solvent (octanol). It is a measure of the water solubility of a substance. K_{ow} provides information on the fat and water solubility of a substance, tested using a two-phase liquid mixture of octanol (lipophilic) and water (hydrophilic). K_{ow} depends on which concentration of the tested substance can be measured in one or the other phase. DT_{50} describes the time needed for 50% of the substance to be degraded in a particular medium (see "Degradation of chemical hazards" in Section 2.2.3).

Data on these coefficients are available in the literature for many substances, and Table 11 provides an overview of possible ranges of the respective values. The table shows that concepts such as "high solubility" or "moderate degradation" may vary between studies. Thus, for risk assessment, quantitative data should be used wherever possible. Using such information to assess the likely persistence of a contaminant downstream of its input into a surface waterbody is best done with support from experts in soil science, environmental chemistry and hydrogeology.

Table 11 Relevance of a given substance to raw water for drinking-water supplies based on different parameters

	Solubility in water [mg/L]			Mobility Log K_{OW}		Degradation or persistence DT_{50}	
Assessment	[1]	[2]	[3]	[1]	[3]	[1]	[2]
Low	<1	<0.1	–	>4	–	Days–weeks	<1 day
Moderate	1–1000	0.1–1	–	1–4	–	Weeks–months	Days–weeks
High	>1000	>1	>100	<1	<3	Months	>Weeks

Source: adapted from Kuhlmann, Skark and Zullei-Seibert (2010).

Information sources:
[1] US EPA (2009)
[2] Committee on Drinking Water Contaminants et al. (1999)
[3] Litz and Dieter (2009)

Models of sedimentation rates of particles and colloids in relation to flow and turbulence may be useful in estimating how sedimentation affects contaminant concentrations at a given point of interest (Droppo et al., 2011; Fries, Characklis & Noble, 2006; Hipsey et al., 2004; Jamieson et al., 2005).

Chemicals and microorganisms sorbed to suspended sediments may progressively accumulate in riverbed or lakebed sediments. Besides the characteristics of the suspended matter (in particular, grain size and density), the flow velocity and turbulence of the waterbody influence the speed of the settling or sedimentation process (Chapman, 1996). Whereas the concentration of a chemical or pathogen in the water will typically decrease rapidly once input of that hazard has stopped, a chemical sorbed onto sediment can persist for long periods, depending on its degradability (see Table 11 for time scales of degradation). However, contaminants sorbed to sediment are also released; the balance between sorption and release depends on conditions in the sediment. Under some conditions, such release may continue for an extended period after input of a hazard has ceased.

Riverbed sediments may thus act both as a sink and a source of hazards, sometimes alternating between both functions as conditions in the waterbody change. When buried by cleaner sediment, a hazard will become increasingly less available to the overlying water. However, if sediment is resuspended (e.g. during a storm or flood event), the hazard may be released. In particular, POPs such as PAHs and PCBs (see "Anthropogenic organic chemicals" in Section 2.1.2) and metals may be found in both the water and the sediment for periods of years to decades, and be found far downstream (kilometres to tens of kilometres) of the original input. Elevated sorption explains why such hydrophobic contaminants are retained in riverbed sediments and widely dispersed downstream.

Dilution and dispersion

Dilution of a hazard (e.g. from discharged wastewater into a river) depends on the discharge rate and the flow rate of the river. Where these data are available, calculating dilution is straightforward. Where the data are incomplete, default values may serve as a basis for an estimate; for example, Schijven et al. (2005) used three values for dilution of wastewater that are applicable in the Netherlands as default values for a small, medium and large wastewater treatment plant, and for a small, medium and large river (Table 12). Generally, rates of discharge of wastewater and rivers may be obtained from local engineers.

Table 12 Default values for sizes of wastewater treatment plants, rivers and dilution

	Wastewater treatment plant		River			
Size of river	Person equivalents	Wastewater discharge (m^3/d)	Flow rate (m^3/d)	Width (m)	Depth (m)	Dilution factor
Small	$\leq 2.5 \times 10^4$	2×10^3	5.8×10^3	10	1.5	44
Medium	2.5×10^4–10^5	9.6×10^3	1.7×10^4	50	2.6	226
Large	$>10^5$	4.3×10^4	4.8×10^4	125	3.8	529

Source: Schijven, Rijs and de Roda Husman (2005).

Dispersion – comprising mechanical mixing and diffusion – dilutes hazard concentrations in the water environment. Mixing processes apply to both dissolved chemicals and to particles suspended in the water (e.g. pathogens), whereas diffusion is a process of molecules dissolved in water moving slowly (i.e. diffusing) along a gradient of their concentration. Dispersion of hazards may occur within the surface waterbody or during transport to it, within both run-off and subsurface groundwater. Diffusion is a slow process, and mechanical mixing usually far overrides the effects of diffusion. However, diffusion may be important for hazard fluxes and attenuation in environments with little flow; for example, a low-permeability riverbed, a silty lakebed or clay-based geological units.

Within the surface waterbody, even minor water movement will disperse and dilute discrete chemical inputs; for example, from pipe effluent discharges or groundwater plumes discharging within baseflows. The volumetric flow of the discharge relative to the bulk surface-water flow controls dilution. However, the dispersive-mixing capacity of the surface water controls time scales and length scales over which dilution is realised.

Dispersion results in the spreading of chemicals during bulk water flow, and is caused by non-uniform flow fields. Entry of point-source inputs to a river or lake can lead to significant differences in the vertical and horizontal concentrations of chemicals present in surface waters unless they are well mixed. Most rivers are well mixed; hence, point-source chemical discharges become fairly uniformly distributed across a river channel after a short mixing zone. Such mixing zones may be estimated as a length of river equivalent to 10–20 times its width, and will vary depending on the hydrology and hydraulics of the river channel.

In stagnant waterbodies such as lakes and reservoirs, thermal stratification is the key to dispersion. It causes vertical concentration gradients of chemicals, with higher concentrations either in the epilimnion or hypolimnion water layer, depending on the specific density of the chemical substance and the layer into which it is released (see "Shape, size and stratification of lakes and reservoirs" in Section 2.2.2). Diffusion can play a role in quiescent zones of a waterbody, particularly at the sediment–water interface. Frequently, even there, minor currents will quickly intermix molecules released from the sediment. Hence, understanding the mixing characteristics of the waterbody is key to estimating the dispersion of contaminants within it. Temperature profiles over depth are useful for assessing mixing. They can be measured at discrete intervals in time and space by submersing a probe. More detailed information can be gathered through measuring the temperature by thermistor chains that continuously record the temperature at predefined depth intervals. Information on waterbody mixing is important for positioning and operating drinking-water offtakes, to avoid intake of water with higher concentrations of undesired chemicals.

Chemical concentration gradients may be pronounced in the sediment of a lake or reservoir, or in a riverbed. Mixing between surface-water and groundwater flow may cause chemicals to migrate into the sediment or riverbed from the overlying surface water. Where chemicals are highly sorbing, they may accumulate in riverbed or lakebed sediments (see "Sedimentation and sorption" in Section 2.2.3).

Volatilization

VOCs may volatilize (partition) from contaminated water to an adjacent air phase such as the atmosphere. Volatilization is the key loss process for VOCs and some pesticides. Chemicals may also be effectively lost to the air phase; for example, through formation of methane or degassing of carbon dioxide. Volatilization losses occur during chemical application on land (e.g. the spray application of pesticides and subsequent evaporation from plants or soil), from storage tanks or subsurface spills, and from contaminant plumes in shallow groundwater. Such losses from an open surface waterbody are likely to be significant and potentially rapid, particularly at higher temperatures, whereas those from a river will depend on the contaminant, water velocity, flow depth, temperature and turbulence relationships (Aisopou et al., 2015; Rathbun, 2002).

Volatilization is characterized by the vapour pressure of a substance and by the Henry's law constant, which describes the distribution of a contaminant between air and water. Both parameters are strongly dependent on temperature. A high value of the Henry's law constant implies a high volatilization potential of the substance, whereas a low value indicates a high dissolved fraction. Nonetheless, in surface layers, even VOCs with comparatively low Henry's law constants will transfer to the atmosphere. Where surface water has a floating oil phase (i.e. an LNAPL), its transfer to the air phase will be largely controlled by its vapour pressure. For volatile fuels such as petrol, this is relatively high (~60 kPa at 20 °C), and spills of such fuels will be lost to the overlying air phase more rapidly than spills of less volatile heating or lubricant oils.

Degradation of chemical hazards

Degradation of chemicals may occur via abiotic chemical reactions or by microorganisms (biodegradation). Abiotic degradation reactions include photolysis and hydrolysis, as well as chemical reactions that transform a molecule and thus change its toxicity.

Degradation by abiotic reactions is generally of minor importance compared to biodegradation. For example, although some chemicals may be susceptible to photodegradation (i.e. photolysis – breakdown through light exposure), this is typically far less relevant in water than in the atmosphere. Because light is rapidly attenuated with increasing water depth, photolysis is effective only in a thin surface layer. Substitution reactions (i.e. where atoms or atom groups of a chemical compound are replaced by another atom or functional group), including hydrolysis (i.e. breakdown of a chemical compound through reaction with water), are possible for some bromine- or sulfur-based chemicals, and for a more limited number of chlorine-based organic chemicals. Some pesticides may be susceptible to hydrolysis or nucleophilic reactions. Hydrolysis is generally most effective at pH values beyond the range of pH 5–9 found in most surface waters. Abiotic reactions may lead to partial degradation, and further biotic reactions may be necessary to reach non-toxic products. Distinguishing between abiotic and biotic contributions is often difficult.

Biodegradation may attenuate a range of organic chemicals; however, reaction half-lives may vary enormously, from minutes to years. Bacteria preferentially attach to solid phases (rather than "free swimming"), and may have significant activity as biofilms on soils, subsurface aquifers and the lakebed or riverbed. Ideally, biodegradation leads to deactivation in toxicity and complete mineralization, to form benign products (e.g. bicarbonate, water and chloride). Multiple reaction steps lead to the formation of intermediate (transformation) products, some of which may persist and be toxic. Besides the presence of populations of bacteria able to cause biodegradation, the process requires electron donors – these are typically the chemical hazard, or other organic matter and electron acceptors (e.g. oxygen, nitrate, sulfate and iron). Biodegradation in surface waters may be limited because microbial densities are often low compared to those in sediments. However, it may occur if, for example, microbiota (i.e. the diverse community of microorganisms residing in an environmental niche such as a surface-water environment) have adapted to continuous inputs of readily degradable contaminants, labile bioavailable POM and nutrients. In bed sediments, biodegradation is often significant.

Although metals are not biodegraded, microbial activity may alter their speciation and thus their toxicity. Additionally, other geochemical changes (e.g. induced complexation or precipitation) may alter metal mobility and attenuation. Many hydrocarbons (e.g. alkanes and aromatics) and oxygenated hydrocarbons (e.g. phenols, alcohols and acids) are relatively biodegradable. Although degradation rates of the more persistent compounds (e.g. chlorinated VOCs, PAHs and PCBs) are generally low, there is much literature to indicate that degradation may still be significant under certain, often anaerobic, conditions. Degradation rates are usually characterized by first-order half-life data, and are used in contaminant transport risk-assessment models. Degradation of chemical hazards is characterized by DT_{50} values (Table 11). Because degradation is affected by several parameters, these values are approximate. Additional expertise for assessing the degradation potential of contaminants may be obtained by consulting chemists or microbiologists.

2.2.4 Drinking-water abstraction from surface waterbodies

This section describes how water abstraction may influence the quality of raw water for drinking-water supplies, and the subsequent level of post-abstraction treatment that is required. Surface waterbodies are particularly vulnerable to contamination, and the way in which drinking-water is obtained from these sources has a major bearing on treatment requirements. Abstraction schemes can strongly influence turbidity and concentrations of pathogens and chemicals. Where treatment options are poor, the abstraction scheme chosen can greatly influence the overall health and disease burden of communities that rely on surface-water sources for potable use. Examples of abstraction solutions are presented in Box 2.17.

Box 2.17 Abstraction solutions

This box describes various approaches to raw-water abstraction. The approach chosen will depend on the quality and possibly also the quantity of water.

Bank filtration – Where river sediments are sufficiently permeable (e.g. sands and gravels), bank filtration can effectively reduce hazards. This method physically removes particles by filtration; it also removes many dissolved chemicals by sorption and degradation. Bank filtration is achieved by installing a number of wells near the river, and pumping to draw river water through sediments to the wells. Success depends on careful design that allows sufficient travel time through the sediment for harmful microorganisms to be inactivated and chemical hazards to be either adsorbed onto sediments or biodegraded.

Aquifer storage and recovery (ASR) – In certain regions, water can be periodically pumped from a river, treated, and then infiltrated or injected into an aquifer for storage and ongoing use for water supply. ASR is used in regions where either the flow or quality of river water is highly variable (e.g. in densely populated urban regions or in arid regions where river flow may be seasonal) and geological conditions are suitable. Depending on in-situ hydrogeochemical conditions, some treatment may be necessary upon re-abstraction.

Dry rivers – In arid or semiarid regions where rivers flow infrequently or for a short period each year, and the riverbed is sandy, water can be obtained from saturated sediments beneath the riverbed for some time after river flow ceases. The main abstraction methods are as follows:

- *Subsurface dam* – This is a raised impermeable structure across the dry river that accumulates sand upstream during river flows. The sand beneath the surface will store water for long periods after the river flow has ceased, and the water can be accessed via dug wells or specialized extraction pumps (e.g. pumped spear points).
- *Infiltration galleries* – These are horizontal structures constructed beneath the riverbed, which collect water drained from the overlying sediments. The water then flows to a large well, constructed near the river bank that stores the water.
- *Groundwater abstraction* – Water supply wells constructed within a dry riverbed can abstract water by pumping during dry periods. The pumps are removed and the wells sealed before a river flow occurs.

Lakes and reservoirs

When investigating options for optimal drinking-water offtake sites within the waterbody, it is important to:

- *take seasonal patterns into account* – this will capture the predominant condition rather than only a rare, coincidental one;
- *construct variable offtake sites* – this will enable a flexible response to shifts in water quality between layers or shores; and
- *check the influence of extreme weather events* – rainstorms or snowmelt in the catchment may add further inflows, which may dramatically alter not only hazard loads and water residence times but also patterns of water flow through a reservoir or lake.

Water quality within a given reservoir or lake may show substantial variation, which may influence the choice of drinking-water offtake sites. These variations include the following:

- *Horizontal variations* – these arise from the irregular shapes often encountered in larger lakes and reservoirs; for example, water quality in the bays of lakes and reservoirs may vary, depending on tributaries feeding a reservoir and prevailing wind conditions that lead to higher concentrations of scum-forming cyanobacteria in a particular bay during bloom periods.
- *Vertical variations* – lakes and reservoirs may stratify due to thermal (or chemical) density gradients (see “Shape, size and stratification of lakes and reservoirs” in Section 2.2.2); offtakes are therefore often sited at the depth of the metalimnion, although, as described earlier, these layers show seasonal patterns.

- *Seasonal variations* – lakes and reservoirs may show pronounced seasonal patterns of water quality:
  - because of seasonal differences in the quality of the inflows from the catchment and thermal stratification affecting water quality; and
  - because organisms in the water grow and multiply in response to seasonal fluctuations of physical and chemical conditions (e.g. as algal biomass accumulates over a growing season and eventually dies off, decays and consumes oxygen, oxygen deficiency affects geochemical processes at the water-sediment interface, leading to release of chemical hazards).
- *Response to wet weather events* – augmented inflow of stormwater (particularly during storm events) may affect the water quality and flow patterns within a reservoir or lake (see Box 2.12 in Section 2.2.2), and residence times within the waterbody may be reduced from months to days due to density currents. For drinking-water offtake in such situations, it is important to be aware of this risk and of the potential response (i.e. to use the buffering capacity of a pre-reservoir, additional treatment steps or an alternative water supply).

Such variations must be considered when choosing optimal drinking-water offtake locations within a waterbody. The best choice is to build offtakes at multiple or variable depths to allow for flexible use of the layer with the seasonally best water quality. If changes in drinking-water offtakes are not possible, alternative water sources may need to be used in times of compromised water quality (see case example from Indonesia in Box 2.18).

Box 2.18 Hazards associated with ponds, irrigation channels and drains

In many communities, ponds, irrigation channels and drains are an important source of water for use in the household and for drinking. Due to the many potential uses of these waterbodies (e.g. washing clothes and bathing), and their potential proximity to open defaecation areas and to livestock, the risk for waterborne diseases from water contact may be high. Further, water quality in canals and drains can vary greatly, depending on the frequency of fresh water releases for agriculture and on the range of commercial enterprises (e.g. tanneries) that discharge wastes into the canals.

The example described here highlights the risks associated with acidification of soil and water, and the subsequent mobilization of toxic metals in drinking-water, following the excavation of soils rich in iron sulfide minerals for drain and channel construction.

The effect of acid sulfate soils on the use of drinking-water sources in Kalimantan, Indonesia (adapted from Haraguchi et al., 2007)

The soils in large areas of the catchments of the Sebangu and Kahayan rivers in **Kalimantan** in **Indonesia** contain significant concentrations of iron sulfide minerals. The excavation of agricultural drains and irrigation channels – also used as sources of water for drinking, cooking and washing by local inhabitants – has disturbed these soils and caused the sulfide minerals to oxidize. Now, in each wet season, the soils leach pulses of acidic water into surface waterbodies, significantly affecting water quality in these waterbodies.

Interviews with residents in the affected river catchments indicate that these seasonal changes in the acidity of surface waterbodies affect the way in which water supplies are used throughout the year. Use varies locally, depending on the level of awareness of water-quality issues and on access to chemical analysis, as shown by the following examples:

- In the Paduran area, in a catchment affected by seasonal variations in acidity, more than 70% of the residents have recognized that acidic water poses health risks and is unsuitable for drinking or for prolonged skin contact. Residents realize that the quality of surface water is more suitable for use in the dry season than in the wet season, and they use groundwater or rainwater when they consider that surface water is unsuitable for use. The changes in water quality throughout the year are assessed by measuring the sulfate concentration of the water.
- By contrast, in the Pangkoh area, which is also affected by seasonal variations, only 11% of residents recognized that water contaminated by leachate from acid sulfate soils poses a health risk when used as a source of drinking-water. In this area, residents detect changes in water quality only by the taste, colour and odour of the water. Although the residents avoid using surface water when changes in acidity are great enough to affect its taste, they otherwise have a low level of awareness of the health risks associated with the high concentrations of metals in the water supply under acidic conditions.

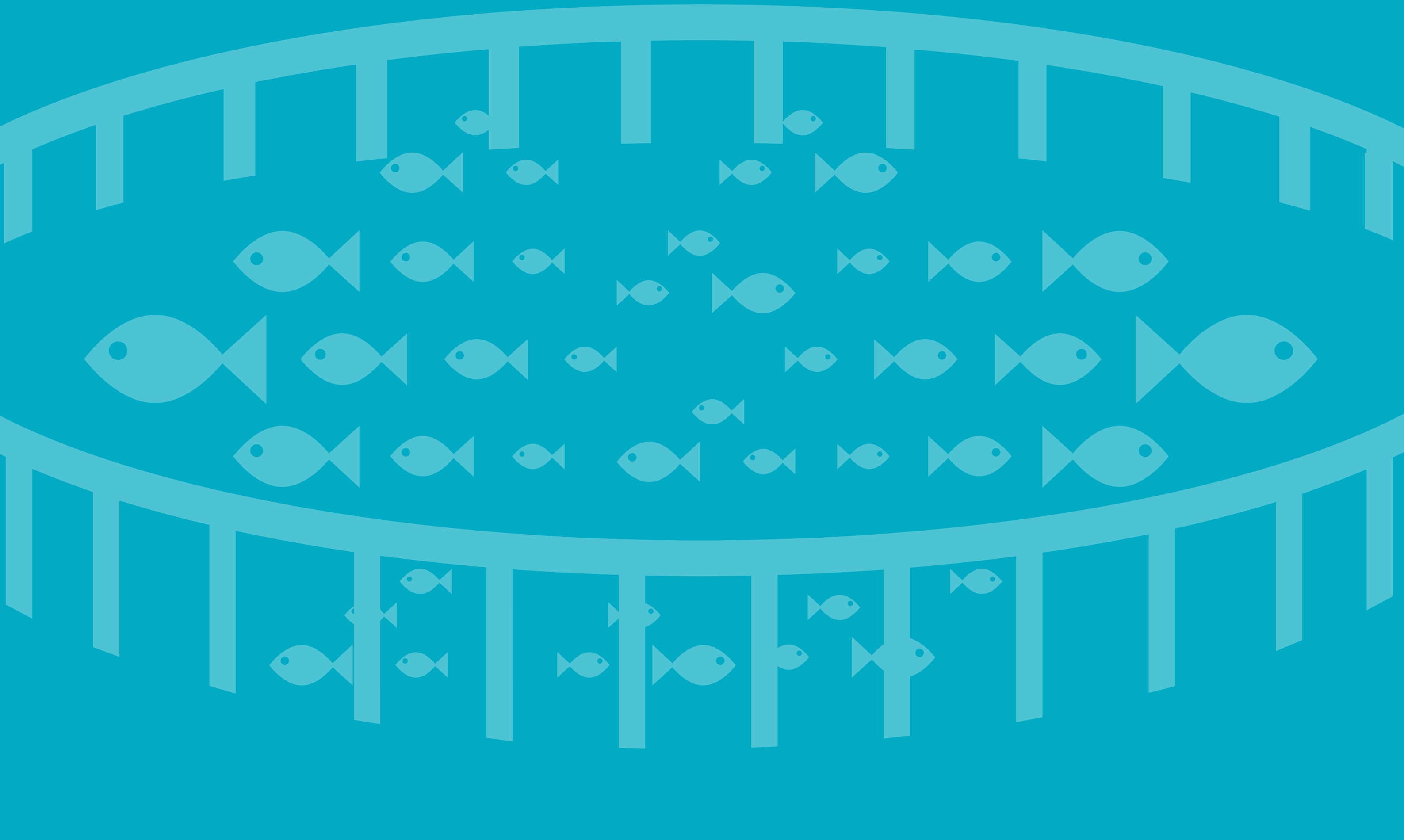
Rivers

Water offtakes are best located upstream of any discharges (e.g. from wastewater or industrial sites). However, many river valleys are densely populated, meaning that settlements needing drinking-water are inevitably downstream of such discharges. Maximizing distances between discharges and offtakes can help to make use of natural attenuation processes; that is, pathogen inactivation and degradation of chemicals.

A further consideration when locating drinking-water offtakes is early warning; that is, the time needed to detect an accidental release of contaminants and initiate an emergency response (see "Stream flow" in Section 2.2.2). The vulnerability to contamination makes it particularly important to understand the hydrology of the river, so that travel times of a "contaminant wave" can be estimated and offtakes can be shut down until the wave has passed.

CHAPTER 3

HAZARDOUS ACTIVITIES IN THE CATCHMENT AND THEIR CONTROL



This chapter provides guidance on how to establish an inventory of major polluting activities in a catchment that may affect surface-water quality, and of the events that may lead to the occurrence of hazards in raw water. Section 3.1 describes where some of the major hazards discussed in Section 2.1 may originate, and highlights the fact that a particular contaminant may arise from multiple sources. Section 3.2 provides guidance on conducting a catchment inspection to identify the conditions and activities in a catchment that may introduce hazards to the waterbody. Sections 3.3 to 3.8 discuss major catchment-polluting activities, the hazardous events associated with each activity, and the control measures required for managing the risks that the activities pose to surface water.

Template checklists are provided for each activity. The checklists can be used to identify and document:

- potentially polluting activities and events;
- existing control measures; and
- catchment and waterbody characteristics that influence the extent to which hazards may reach a drinking-water offtake point.

3.1 Main sources of hazards and main pathways by which hazards are introduced into waterbodies

Surface waterbodies may be contaminated by a variety of chemical, microbial and sometimes even physical and radiological hazards from human activities. Contamination may be caused or influenced by the combination of several activities. For example, a particular hazard may be introduced by different activities, and a change in the hydrological regime (e.g. impoundment) may affect the retention and reduction of hazards within the waterbody. There may also be links between activities; for example, the use of sludge from wastewater treatment in agriculture and aquaculture, or industrial activities generating wastewater. Inspections to identify activities and pathways that may cause hazards for water quality are the most important basis for hazard analysis and risk assessment. Data on waterbody conditions, as well as concentrations of pathogens or chemicals (or both) can support site inspections with useful information about the extent to which hazards actually reach the waterbody.

This section focuses on those, typically anthropogenic, activities in catchments that may be sources of pollution, and that can be readily influenced and limited if necessary. However, contamination of raw water may also originate from natural sources; for example:

- microbial contamination from wildlife;
- chemical and physical contamination from volcano eruptions;
- chemical (and possibly also radiological) contamination from natural geological formations; and
- humic substances from forests and wetlands.

The list of activities described here is not exhaustive. In a given catchment, other activities, not discussed here, may be potential sources of contamination. For example, this publication does not cover solid waste landfill sites located in water catchment areas that may pose a risk to surface water contamination through leachate – for information on landfill, see *Protecting groundwater for health* (Schmoll et al., 2006). Similarly, there may be land uses that could facilitate pathways for contaminants from land to water. For example, this publication does not cover sports grounds and golf courses located in water catchment areas that may affect surface water through soil erosion, increased water flows across land surface, or chemical contamination by herbicides or fertilizers.

Table 13 gives an overview of a selection of contaminants, contaminant groups (e.g. pesticides), indicators and pathogens that may be found in surface waterbodies, together with the types of contaminating activity that typically introduce them into watercourses.

Table 13 Overview of potential hazards in surface-water catchments and their typical sources

		Typical source (and section reference)					
Hazard class	**Examples**	**Agriculture (3.3)**	**Aquaculture (3.4)**	**Wastewater (3.5)[d]**	**Industry (3.6)**	**Traffic (3.7)**	**Recreation (3.8)**
Microbial	*E. coli*[a,b]	●		●			●
	Thermotolerant coliform bacteria[a,b]	●		●			●
	Intestinal enterococci[a,b]	●		●			●
	Clostridium perfringens[b]	●		●			●
	Coliphages[b]	●		●			●
	Bacteroides fragilis phages[c]			●			●
	Enteric viruses[c]			●			●
	Bacterial pathogens[b]	●		●			●
	Viral pathogens[c]			●			●
	Protozoan pathogens[b]	●		●			●
	Helminth pathogens[b]	●		●			●
Chemical	Cyanobacterial toxins[e]	●	●	●			●
	Ammonia	●	●	●	●[f]	●	
	Arsenic	●			●[g]		
	Petroleum products (BTEX)				●	●	
	Cadmium	●		●	●		
	Halogenated hydrocarbons	●			●[h]	●	
	Chloride	●		●	●[h]	●	
	Chromium				●		
	Cyanide	●			●		
	Fertilizers	●			●		
	Lead				●	●	
	Mercury				●		
	Manganese	●		●	●[h]	●	
	Nickel				●		
	Nitrate/nitrite	●		●	●[f]	●	
	Pesticides	●	●		●	●	
	Phosphorus	●	●	●			
	Sulfate				●		
	Total dissolved solids			●[i]	●[h]	●	
	Uranium	●			●[g]		
Physical	Turbidity	●		●[i]	●	●	
	Iron	●		●	●[g,h]	●	
Radiological	Radionuclides				●[g,h,i]		

BTEX, benzene, toluene, ethylbenzene and xylenes

See Appendix 1 in *Chemical safety of drinking-water: assessing priorities for risk management* (WHO, 2007) for a more comprehensive list of primary sources of chemical contaminants (although not all are relevant for surface-water sources).

[a] Faecal indicator parameter.
[b] Occurring in human and animal faeces typically.
[c] Occurring in human faeces typically.
[d] Includes wastewater from human settlements and wastewater application in agriculture or aquaculture as well as its generation in the context of other activities such as traffic, industry, recreation, and on military sites.
[e] Consequence of excessive phosphorus and nitrogen loads from these activities.
[f] Includes waste management activities such as landfill operations.
[g] Includes mining activities.
[h] Includes industrial effluents.
[i] Includes natural ore bodies.

This list can be used if monitoring results are the starting point, and may provide guidance about which catchment activities require more attention. For example, if monitoring shows high levels of phosphorus in a surface waterbody, the activities to focus on would be agriculture, aquaculture and wastewater, covered in Sections 3.3, 3.4 and 3.5, respectively. More detailed information on contaminants is available in Section 2.1.

Generally, direct introduction of hazards into surface waterbodies (direct discharge) can be distinguished from indirect introduction via overland flow and/or groundwater that feeds the surface waterbody. Hazardous events are often combinations of several conditions. They may be one-off events (e.g. accidental spills of chemicals at an industrial site near the surface waterbody, leading to run-off of the chemical into the water), or continuous conditions (e.g. continuous direct discharge of untreated wastewater into the surface waterbody). Hazardous events that are specific for the respective activities are described in Sections 3.3 to 3.8. In addition, hazards may originate from generic hazardous events within the catchment. Examples of hazardous events related to catchment, climatic and other general conditions include:

- storm, heavy rainfall or snowmelt, leading to increased overland flow and subsequent introduction of one or more hazards to the surface waterbody;
- reduced vegetation cover and increased land uses such as forestry, agriculture and urban development (which accelerate erosion), leading to increased introduction of hazards to surface waterbody;
- landslides (which accelerate erosion), leading to increased introduction of hazards to surface waterbody;
- climatic or seasonal variations, leading to increased or reduced water flow or flooding, which in turn influences hazard transport or the quantity of water available;
- major run-off (and hazards contained therein) from sealed surfaces close to offtake zones or extraction points, leading to raw-water contamination;
- extended drought periods, leading to accumulated deposition on surfaces and greater run-off due to reduced absorption capacity;
- surrounding soil or groundwater, introducing hazards (e.g. humic material, arsenic, fluorine, iron, manganese, sulfate and radiological agents) to the surface waterbody;
- hydraulic connections (between trenches, creeks, ponds, lakes and moors), introducing hazards to the surface waterbody;
- fires and volcanic eruptions, increasing, for example, the deposition of dust, turbidity and introduction of chemical hazards; and
- changed catchment conditions (e.g. climatic changes, reduced vegetation cover, increased surface sealing and landscaping activities), creating new or changed hazardous events.

Generally, information for catchment assessment needs to be obtained through two complementary exercises: inspecting the catchment, and collecting existing data on the catchment and the activities within.

3.2 Inspecting the catchment and establishing an inventory of activities

This section provides general guidance on how to conduct a catchment inspection and how to establish an inventory of activities and hazardous events that may introduce hazards into the waterbody. Such an inventory is the basis for assessing risks and for improving measures to control them, or for implementing new measures (as described in Sections 4.3 and 4.4). Developing the inventory involves two phases: preparing a catchment inspection (Section 3.2.1) and conducting a catchment inspection (Section 3.2.2).

3.2.1 Phase 1: Preparing a catchment inspection

To prepare a catchment inspection:

- complete general checklists for activities and conditions in the catchment, and a general inventory of catchment activities;
- select which activity-specific checklists are needed;
- adapt the respective checklists, as required;
- draft additional checklists for activities not covered in Sections 3.3 to 3.8;
- select people to inspect the catchment, and ensure that everyone has the same understanding of the checklists, so that information collection is unified; and
- obtain and review information already available before the catchment inspection(s).

For an overview of the activities in the catchment, it is useful to begin with a general checklist, such as Checklist 1. This checklist can be used to summarize the information that needs to be collected on activities in the catchment, before the actual inspection is undertaken in Phase 2. Checklist 1 can be adapted for the specific case; it will later be complemented with the information gathered during the site inspection and documented, for example, in Table 14a: *General inventory for catchment inspection*.

Completion of Checklist 1 provides a picture of the situation in the catchment, including which activities to review more closely and which activity-specific checklists to consider while inspecting the catchment. This information will inform the system description in the WSP process (i.e. WSP Module 2; see Section 4.2). It is important to also collect information on geomorphological and hydrological conditions in the catchment, because these conditions strongly affect the extent to which hazards will reach a waterbody or a drinking-water offtake within that waterbody; they also influence hazardous events.

Checklist 1 General checklist for activities in the catchment

Presence and distribution of activities in relation to the waterbody

- ☑ Based on documentation available, what are the locations, spatial distribution and scale of potentially hazardous activities identified (generate map if possible)?
- ☑ Are there trends or changes in land use, including population forecast studies?
- ☑ What is the linear distance to the surface waterbodies and to the drinking-water offtake point(s) from activity points?
- ☑ What is the hydrological distance to the surface waterbodies and to the drinking-water offtake point(s) from activity points?
- ☑ Are any spills, complaints or deficiencies observed, reported or documented?

How are potentially contaminating activities in the catchment managed and regulated?

- ☑ What national, regional, local or catchment-specific legislation, rules, recommendations, voluntary cooperation agreements or common codes of good practice are in place?
- ☑ Are restrictions of land uses in place for the catchment and the waterbody?
- ☑ Is access restricted to particular parts of the catchment and raw water?
- ☑ Are management practices in place? How effectively do they control hazard release to the environment, particularly to watercourses?
- ☑ What is the level of implementation of land-use restrictions (e.g. water protection zoning; restricted access; passive communication via signage; area directly or actively policed by rangers intermittently or continuously; restrictions successfully or poorly communicated)?
- ☑ Are measures applied for integrated catchment management (ICM) or catchment management (i.e. enabling impacts on water quality to be managed across an entire catchment)?
- ☑ Is relevant environmental information on the activities available (e.g. environmental impact assessment [EIA])?

What other controls for reducing impacts are in place?

- ☑ Are education programs implemented to increase local awareness (e.g. information for users about sensitivities of drinking-water catchment)?
- ☑ Is there indication of user response to communication and education programmes?
- ☑ Are any catchment management groups established?
- ☑ Are planning and environmental protection statutory control measures for proper storage and handling of hazardous materials used (e.g. chemicals and manure)?
- ☑ Are training programs for operators of activities in place?
- ☑ Is the drinking-water subject to treatment before delivery to the consumers?

Much of the relevant data may be available from different sources (e.g. maps, geographical surveys and the authorities responsible for waterbody management) and can be collated before catchment inspection. Examples of information sources for determining catchment and waterbody conditions are presented in Section 4.2. It is important to check whether such information appears plausible and up to date when inspecting the catchment, and whether any other features so far not considered might be important. Checklist 2 can be used for this purpose and can be adapted to the specific case.

When completing the general checklists (Checklists 1 and 2) it is useful to consider whether specific expertise and competence will be needed when conducting the catchment inspection. For example, it may be possible to enter certain premises (e.g. farms, manufacturing sites or industries) only with staff from specific public authorities that have this right or power. However, if these authorities conduct inspections as part of their responsibility, it is useful to seek to collaborate with them to obtain their inspection results, rather than conducting an additional inspection. It may also be useful to include experts with relevant experience in, for example, assessing the impact of geographical and hydrological features on transport and attenuation of hazards. Where site inspection is performed in the context of developing a WSP, the WSP team will lead this activity, often with support from scientific experts, particularly in the areas of hydrology and water management. If necessary, the team may also include experts for activities in the catchment, in order to better analyse which hazards those activities are likely to release (see Section 4.1).

Compiling a general inventory of activities and conditions in the catchment

The checklist in Table 14a gives examples of key pollution-generating activities with relevance to catchments and waterbodies. These activities are agriculture; aquaculture and fisheries; wastewater and stormwater effluents; commerce, industry, mining and military; traffic; and recreation at waterbodies. These activities are discussed in Sections 3.3 to 3.8, which provide detailed checklists for catchment inspection.

Table 14a uses two approximate indicators of the potential impact of an activity in the catchment on water quality: the distance from the waterbody, and an estimate of the land's slope from the respective activity towards the waterbody. Both parameters strongly influence the extent to which contaminants from an activity will be retained in the catchment or be flushed into the waterbody; hence, they can be used for rough prioritization of activities to control. The generic inventory given in Table 14a may be adapted as required; that is, issues may be added or removed, depending on what is relevant for a particular activity. For a closer estimate of the extent to which hazards from an activity are likely to reach the surface waterbody, further information on the geographical and hydrological conditions is necessary (see Section 2.2). Such criteria can be added to the inspection checklist for a more elaborate assessment. It is important to note visible conditions in the catchment that may influence hazard transport to the waterbody. These conditions include gullying, erosion, damaged vegetation cover or hydraulic engineering structures such as channels, ditches or pipes carrying water of unclear origin into streams (see Table 14b).

The scale of activities is a further important factor for the potential for surface-water pollution. Dispersed small-scale activities are usually more difficult than large-scale activities to monitor and control, but the large-scale activities typically have a greater local impact.

Completing Checklists 1 and 2 based on information and documents available before the site inspection, and the inventories given in Tables 14a and 14b, will provide an overview of the main challenges in the catchment. This will, in turn, provide an indication of which types of activities should be inspected in more detail, using the activity-specific sections and checklists in Sections 3.3 to 3.8.

Checklist 2 General checklist for characterizing the catchment and waterbody

What are the local climatic and hydrological characteristics?

- ☑ What main local climatic data are available on rainfall regime, average temperatures, relative humidity?
- ☑ What is the rainfall depth, duration and intensity; are hydrographs available?
- ☑ What is the typical dry weather discharge and the typical pattern of stream flow?
- ☑ How frequent are wet weather events, and what is their impact on the raw-water quality and quantity (e.g. reduced flow rate due to decreased precipitation and evaporation during hot dry seasons, siltation or sedimentation due to run-off during rainy season)? Also, what is the impact and frequency of severe weather events based on historical data and future climate change forecasts.
- ☑ What are the stormwater quality parameters?
- ☑ What is the distribution and magnitude of groundwater discharge into surface waterbodies in the catchment?

Which catchment characteristics are relevant to hazard occurrence and pathways?

- ☑ What is the extent of the catchment and potentially subcatchments if there is more than one significant tributary to the waterbody?
- ☑ What are the discharge volumes (including seasonal patterns) of main inflows (as far as available)?
- ☑ What topographical data are available on drainage areas, slopes and lengths, and groundwater levels?
- ☑ What are the types of soil, and what is the erosion potential?
- ☑ What proportion of land is covered by vegetation?
- ☑ What proportion of land has steep slopes?
- ☑ Are signs of erosion and degradation visible in the landscape?
- ☑ What is the extent of gullying, soil scouring and land-slipping in steep areas in the catchment (including changes over time)?

Is the catchment subject to flooding (data on frequency, extent)?

- ☑ What are the details of urban and periurban areas in the catchment, and what is the population density in its rural areas?
- ☑ What other land uses and activities are present in the catchment?
- ☑ Are details available on wildlife populations, including with respect to their potential for introducing pathogen hazards into the waterbody?
- ☑ Is information available from previous catchment and sanitary inspections?

Which surface waterbody characteristics and uses of the waterbody potentially lead to hazards reaching the drinking-water offtake? Collect information on:

- ☑ Type of surface waterbody (e.g. stream, river, lake, reservoir, channel)
- ☑ As far as available, area, depth, water volume and water retention time (i.e. dilution capacity)
- ☑ Eutrophication status of the surface waterbody
- ☑ Uses of the surface waterbody (e.g. drinking-water, irrigation of crops, recreational purposes, ritual acts, impoundments) and their patterns of abstraction under normal and drought conditions
- ☑ Location and number of drinking-water offtake points; options for switching between offtake points depending on water quality
- ☑ Changes in water quantity available, including seasonal patterns and extreme event (historical data and future scenario analysis)
- ☑ Purposes for which the waterbody is used downstream of the discharge (e.g. distance, type of use, change in the concentration of contaminants in the receiving watercourse, change in the quality of the water before its use)
- ☑ Results from screening or monitoring programmes (e.g. indicators of faecal contamination).

Table 14a General inventory for catchment inspection

	Activity present		Scale					Slope towards waterbody
Potential source of pollution	**Yes**	**No**	**Large**	**Small**	**Local**	**Dispersed**	**Distance from water body [m]**	**Flat/undulating/ steep/very steep**
Agriculture (see Section 3.3)								
Livestock								
Crops								
Feedlots/intensive animal feeding/calving/ lambing								
Tillage/ploughing								
Storage and application of fertilizers								
Storage and application of pesticides								
Storage and application of manure								
Application of wastewater or sludge (or both) (please also refer to Section 3.5)								
Irrigation								
Clear-cutting								
Drainage								
Significant wildlife populations								
Other (please specify)								
Aquaculture (see Section 3.4)								
Fish ponds								
Integrated aquaculture systems								
Flow-through systems								
Recirculating aquaculture systems								
Cage culture systems								
Other (please specify)								
Settlements, wastewater and stormwater (see Section 3.5)								
On-site sanitation (improved)								
On-site sanitation (unimproved)								
Off-site sanitation (combined wastewater/surface run-off)								
Off-site sanitation (separate, i.e. sewage only)								
Wastewater treatment								
Use of wastewater sludge (please also refer to respective sections for activities that sludge is applied for)								
Wastewater from households								
Wastewater from commercial/industrial activities								
Wastewater from medical activities (e.g. hospitals)								
Cemeteries								
Construction activities releasing (potentially polluted) sediment								
Other (please specify)								

Table 14a **General inventory for catchment inspection** (continued)

	Activity present		Scale					Slope towards waterbody
Potential source of pollution	**Yes**	**No**	**Large**	**Small**	**Local**	**Dispersed**	**Distance from water body [m]**	**Flat/undulating/ steep/very steep**
Commerce, industry, mining and military (see Section 3.6)								
Food processing (including slaughterhouses)								
Textiles								
Tanneries								
Oil/petroleum (including garages)								
Metal processing								
Mining								
Military								
Impoundments (e.g. hydroelectric power)								
Other (please specify)								
Traffic (see Section 3.7)								
Main roads								
Railway lines								
Airports								
Shipping and boat traffic								
Pipelines (please specify content)								
De-icing (please specify: roads, airports, aircrafts)								
Ancillary activities (e.g. fuelling, repair workshops)								
Other (please specify)								
Recreational (see Section 3.8)								
Cruise ships								
Motor-boating/jet-skiing/water-skiing								
Rowing/sailing/canoeing/touring/paddling/ rafting								
Surfing/windsurfing								
Bathing/swimming								
Fishing								
Land-based recreational activities (e.g. picnics, walking, birdwatching, quad bikes)								
Sub-aqua diving or snorkelling								
Infrastructure for recreation								
Other (please specify)								

Table 14b Conditions inventory for catchment inspection

	Condition present		Extent		
Potential conditions influencing pollution pathways	**Yes**	**No**	**Minor**	**Medium**	**Large**
Deforestation					
Erosion					
Gullying					
Ditches or channels draining land					
Pipe outfalls potentially carrying water of unclear origin					
Surface sealing					
Damage of vegetation cover					
Water turbidity					
Water colouring					
Very low or high water level in reservoir					
Cyanobacterial (algal) blooms					
Other (please specify)					

Preparing detailed checklists for specific activities in the catchment

Sections 3.3 to 3.8 discuss examples of key pollution-generating activities relevant to catchments and waterbodies, with respect to:

- potential hazards to waterbodies associated with specific activities;
- a model detailed checklist listing specific factors to consider when evaluating the activities in the catchment; and
- examples of hazardous events and control measures, with options for monitoring the effectiveness of these measures.

If an activity is present, readers should refer to the relevant section within Sections 3.3 to 3.8, and the additional detailed checklist for assessing pollution from that particular activity. The checklists can be adapted as needed, to suit the particular situation under study. They focus on information that can be collected while in the field for inspection of the catchment and activities (e.g. through visual assessment of whether features are present, or talking to people on-site), and on data to be collected and assessed before or after the inspection.

Typically, there will be numerous interfaces between the activities. It is therefore helpful to carefully consider which activities one expects to find and which sections and checklists are relevant. For example, wastewater can be generated at industrial premises (i.e. Sections 3.5 and 3.6 are relevant) and stormwater can occur at traffic areas (i.e. Sections 3.5 and 3.7 are relevant). It may also be helpful to cross-check with the information on catchment activities contained in the publication *Protecting groundwater for health: managing the quality of drinking-water sources* (Schmoll et al., 2006), because contaminating activities can affect surface waterbodies through the groundwater path.

This publication discusses only the major potential (human) polluting activities. However, it is important to determine whether any other significant activities are present in the catchment under study. Using the checklists in this chapter as a template, additional checklists for these other activities can be developed as required.

Obtaining, reviewing and compiling information before catchment inspection

To ensure that the field inspection is efficient and targeted, it is useful to determine in advance what information needs to be obtained about activities and conditions in the catchment. As much information as possible should be collected and reviewed in advance. This helps to identify questions to be asked on-site, and helps to specify the further information that needs to be collected. In fact, much of the work on the checklists will involve compilation and assessment of data. Further details of information to be collected and possible data sources are given in Section 4.2.

The amount and type of information available at the beginning of the data collection will vary. However, if insufficient information is available, it is important not to get discouraged, but to start collecting and assessing the data, to identify crucial information gaps. The information that is available can be used for a system description, hazard analysis and risk assessment as part of a WSP. The risk assessment will prioritize information gaps to close through further research, catchment inspection and communication with stakeholders.

Where data are available from contaminant screening programmes or from regular monitoring, they are valuable, particularly for identifying health hazards from activities that were not recognized during site inspection. In some cases, these data can be used to find the source of discharges, to assess their quantitative relevance, or as a basis for effective mitigation measures. Data from previous inspections of the catchment or of specific activities in it, including summarizing information from other authorities, provide valuable information for prioritization of certain activities and for identifying the most relevant hazard sources. Contamination incident reports from water supplies, industry, inhabitants or public authorities may be useful in identifying historical problems in the catchment.

Even if detailed documentation is available, inspection of the catchment and of sites with activities causing specific risks is crucial. The inspection is vital to confirm that the documentation describes the current situation, to gather additional information and to gain an overall impression of the status of the situation.

3.2.2 Phase 2: Conducting a catchment inspection

To conduct a catchment inspection:

- gather available data in the field and complete respective checklists;
- if possible, take photos to document conditions;
- if several people are involved in the catchment inspection, combine the data gathered;
- document results; and
- use the data to feed into the system description, hazard analysis and risk assessment steps of WSP development (see Section 4.3).

Catchment inspection, including interviews with stakeholders, is fundamental for developing a reliable inventory of the relevant conditions and activities that are present. Depending on the information available beforehand, the nature of the inspection may range from an initial compilation of information to an opportunity to verify and complete lists available from existing documentation and previous inspections. Although data assessment will probably take place before or after the inspection, it may be necessary to request data while in the field, because operators of activities will have a lot of this information available. However, operators may not necessarily have submitted the data nor will they necessarily volunteer it unless asked. People living in the area are generally a useful source of information, particularly those who have lived there for a long time. It is important to contact such people, and take time to listen to what they have to say about the area and what has happened there. They may be able to reveal information about activities that have not been documented in official sources, and that are not evident upon site inspection because, for example, they occur only sporadically or are illegal.

The inspection can highlight which pollution pathways to explore in more detail and where to look for data. For example, if the inspection identifies commercial production sites with discharges to the catchment, it may be worth exploring whether permits for such discharges exist and what requirements they encompass. Likewise, identifying agricultural activities is the first step in discovering the extent of application of agrochemicals and manure.

When inspecting the catchment, it is also useful to confirm and, if necessary, amend the map showing the location and spatial distribution of potentially hazardous activities. Photographic evidence of the conditions encountered in the field will help to document findings, compare the actual situation with the description in the documentation available, and make it easier for people who have not been to the field to understand the circumstances.

After the inspection is completed, it is important to evaluate, collate and document the information obtained, as outlined in Checklist 3.

Checklist 3 **General checklist for documentation and visualization of information**

- ☑ Consolidate information from checklist points and summarize in a report, including data gaps to close with high priority for improving the information base
- ☑ Summarize hazards (microbial, chemical or physical) expected from activities in the catchment, and hazards identified in the surface waterbody
- ☑ Summarize amounts of hazards intentionally applied or non-intentionally released
- ☑ Summarize conditions encountered in the catchment that increase the likelihood of reaching the waterbody
- ☑ Summarize conditions observed in the waterbody that increase the likelihood of hazards reaching the drinking-water offtake point(s)
- ☑ Consider mapping spatial distribution of general land use (use geographical information systems [GIS] if possible) in relation to contamination pathways to the waterbody.

Issues newly identified, observed conditions and information collected during inspections will need to be assessed after the catchment inspection.

Including existing control measures when inspecting activities

If activities that may cause pollution have been identified, this does not automatically mean that pollution has occurred or is occurring. Hazards related to activities in the catchment may already be well controlled or be limited; for example, by amending processes that are part of the activities, replacing hazardous substances applied in the catchment with less hazardous alternatives, or preventing hazards from reaching the waterbody. Examples of efficient control measures to reduce the risk at the location where hazards may be released are described in each activity-specific section. These are not exhaustive lists, because the activity checklists typically cover a wide range of activities (e.g. from small to large scale). Rather, they provide an excerpt of how activities can be controlled, and they need to be completed and adapted to local circumstances. The control measures discussed in the following sections are presented under three process-step headings: planning, design and construction, and operation and maintenance.

Planning

Planning future activities in the catchment – and regulating them accordingly – can be an efficient way to control the combination of activities. For example, setting drinking-water protection zones to exclude or restrict potentially contaminating activities, particularly close to the water offtake point, is a powerful way to influence the extent of future activities and their impact on drinking-water. It is important to consider competing uses and the basis of local people's livelihoods in order to identify planning measures that are realistic but do not compromise other targets of health and well-being. Such issues require communication with stakeholders who may have other potentially interfering interests (e.g. local food production) to find suitable solutions.

Design and construction

Adequate design and construction of installations for potentially contaminating activities (e.g. containment for hazardous goods) can be critical for effective control of potential risks. This is easiest to achieve when new facilities are being introduced or existing ones are being reconstructed. Investing capital in improving design and construction to protect water quality can often be coupled with investment in improving the efficiency of the overall production process. In many cases, this has quickly proven cost-effective, with amortization occurring within a few years.

Operation and maintenance

Control measures for operation and maintenance are important, to avoid hazard release from activities already in place. As with design and construction measures, they allow for potentially contaminating activities to be controlled, not by banning them from the catchment completely, but by making sure that the risk they pose is minimized.

Selecting effective control measures requires an understanding of which hazardous events (or combinations of events) are likely to lead to contamination, combined with analysis of which events can be influenced. Thus, it is important to assess:

- the extent to which control measures are in place;
- how well control measures are working; and
- whether the functioning of control measures is being monitored regularly and at time intervals sufficiently tight to allow a response if monitoring indicates failure, to avoid discharges into the catchment's watercourses (see also Section 4.5).

Particularly where larger enterprises (e.g. major industries) or many smaller ones could cause major contamination, it is important to identify control measures that have the potential to be upgraded; for example, in the course of WSP development.

Whereas regulators and authorities can exert their influence chiefly during the planning phase, operators of potentially contaminating activities have more influence during and after construction. The major responsibility for day-to-day operations and regular maintenance will be with operators and staff in the facility, whereas authorities at this stage typically exert control only by spot-checks to confirm compliance. In a catchment setting where the influence of water suppliers is limited, it is particularly important to ensure that those who can influence potentially contaminating activities understand the impact those activities can have and follow best management practices for their operation. Hence, awareness raising and training activities are important in catchments, to ensure that all stakeholders contribute to increase water safety.

Table 15 shows typical control measures in the areas of planning, design and construction, and operation and maintenance. The measures span the catchment, waterbody and point of offtake. The table can be used as a template for compiling options for control measures for other potentially contaminating activities that are not covered in Sections 3.3 to 3.8.

Sections 3.3 to 3.8 give an overview of selected human activities through which hazards may be introduced into the catchment and subsequently into the waterbody, and which should therefore be looked for when inspecting the catchment. They include examples of typical hazardous events that may lead to a risk from these activities, and options to control those risks. Sections 3.3 to 3.8 do not provide exhaustive lists of potential hazards and hazard sources; rather, they are intended as guidance for planning local catchment assessments.

Table 15 **Typical measures to control risks from human activities in the catchment of surface waterbodies**

Step	Examples of control measures	Options for monitoring their functioning
Planning	Preventive regulations to minimize and control the establishment of potentially contaminating activities (e.g. permit requirements, bans and restrictions), and requiring safe operation of potentially contaminating activities	Review (applications for) permits Review regulations and their enforcement
	Planning of activities in catchment, including zoning (e.g. drinking-water protection zones)	Authority to inspect catchment and raw water, monitor land use Review plans and zoning
	Management plans for activities applying chemicals, nutrients and pesticides	Review or audit management plans
	Planning investments and funding for required measures, including clean-up	Review and approve investment plans
	Requirement of emergency/accident response plans	Review or audit emergency/accident response plans at regular intervals to ensure they are up to date. Assess adequacy of plan post implementation
	Awareness raising and education programmes	Review communication concepts to check acceptance/practicability
	Planning catchment structure and management, potentially including engineered structures to enhance attenuation of hazards along flow paths	Review management plans
Design and construction	Protective structures/measures enhancing attenuation of hazards along flow paths, minimizing surface-water pollution; for example: • containment and safe storage installations • dams or trenches (or both) to intercept surface run-off carrying hazards • geo-engineering measures to reduce erosion (e.g. terraces) and to reduce contamination (e.g. geo-textiles) to groundwater and subsequently surface water • ring channels around reservoirs to intercept all wastewater inflows (and divert them downstream for joint treatment) • restoration of meandering flow of tributaries and floodplain to enhance hazard attenuation in the river • creation of riparian buffer strips covered with dense vegetation and of sufficient width (depending on slope of terrain) to intercept surface run-off carrying hazards • reservoirs designed to include a pre-reservoir for sedimentation of suspended solid loads • reservoirs designed and constructed to have multiple or variable offtake depths in order to allow adaptive offtake to the water layer currently having the best water quality	Inspect adequacy/integrity of protective structures/ measures during design and construction, and condition after completion at intervals sufficient for response if defects are detected
	Treatment of effluents or wastewater	Inspect construction/adequacy of treatment facilities Monitor effluent volume and quality
	Apply best management practices for design and construction	Check compliance with best management practices
	Posting information or warning signs and limiting access (e.g. through installation of fences)	Check legibility of signs and integrity of fences and effectiveness of these measures
Operation and maintenance	Measures controlling risks posed by activities already in place; for example: • apply least contaminating input materials	Check use of least contaminating input materials
	• apply best management practices for operation and maintenance	Check compliance with best management practices
	• develop response plan for anomalies found during routine audits and monitoring	Conduct regular reviews of the plan
	• training[a]	Record and evaluate participation at trainings; monitor effectiveness of related activities post training

[a] Requiring minimum qualification or regular training for those involved in potentially polluting activities (e.g. through legislation) can significantly contribute to safe operation and reduce the risk of contamination. It can, for example, keep farmers from applying pesticides at excessively high rates, and through ensuring safe storage, handling and disposal of hazards prevent their release into the catchment.

3.3 Agriculture

Agricultural practices are often the most significant sources of pollution of surface-water supplies. Typically, more than 40% of the land area in a catchment is for agricultural production; in densely populated countries this figure can be as high as 70% (Schmoll et al., 2006). In agriculture, inefficient water usage, excessive use of agrochemicals and high livestock stocking rates have caused widespread pollution of many of the world's freshwater resources.

The main hazard from agriculture that may contaminate surface-water supplies is pathogens from faecal material derived from stockyards, storage of silage and manure, or direct access of stock to the waterbodies. Other hazards include soluble, particulate and adsorbed contaminants comprising, for example, pesticides, nutrients such as nitrogen and phosphorus, and veterinary pharmaceuticals.

Hazards – such as waste from feedlots or sewage sludge causing surface-water pollution – are generally greatest when agricultural activities are poorly sited (e.g. on unvegetated sloping land within a short distance of a waterway, with contaminant transport potentially increased by heavy rainfall), in a poorly constructed environment (e.g. lack of or poor control of run-off) or poorly managed (e.g. excessive numbers of stock and poor manure management practices).

3.3.1 Agricultural practices that may affect surface-water quality

Ploughing, excessive grazing and clear-cutting

Farming practices that can lead to large losses of sediment include deep ploughing (with the greatest losses when ploughing occurs before heavy rainfall) and intensive grazing (Haygarth & Jarvis, 2002). Slash-and-burn agriculture or intensive logging on steep slopes often causes slopes to become highly unstable and to erode rapidly in rainy seasons (particularly in tropical settings). Similar problems can occur if hilly land in semiarid regions is overgrazed. Such activities can lead to severe erosion that can be difficult to remedy due to the scale of the damage and the cost of reconstructing hillsides.

Agriculture can lead to increased pathogen loads, pesticides (adsorbed to sediment particles) or phosphorus, which may lead to eutrophication (Smith & Schindler, 2009) (see Section 2.1.3).

Clear-cutting of forests and woodlands to create agricultural land may also cause erosion of soils, leading to high levels of turbidity and, possibly, to disruption and change of the hydrological regime; for example, loss of perennial streams with the potential loss of drinking-water resources. It may also accelerate eutrophication through the same mechanisms as described above for ploughing and excessive grazing.

Spreading of manure and slurry

Animal manures and slurry are widely used as fertilizers and to improve soil. The application of these materials to soils can reduce the use of expensive inorganic fertilizers. It can also be a useful method for disposing of animal wastes, particularly from intensive animal rearing.

Manure can contain several constituents that are either directly or indirectly of health concern, including pathogens (bacteria, viruses, protozoa and helminthic worms), nitrate, phosphorus, metals, growth hormones, antibiotics and other veterinary pharmaceuticals, endocrine-disrupting chemical compounds, and pesticides used for vermin control in feedlots. These constituents may cause high levels of contamination of receiving waters and the nutrient loads may lead to eutrophication. Although *E. coli* is commonly detected in manure, most strains are not virulent; however, these bacteria may indicate the presence of other pathogens that are more long-lived and resistant to manure treatment and storage. Rotaviruses are commonly found in swine manure, as are the protozoa *C. parvum* and *G. lamblia*. The extent to which viable pathogens occur in manure depends on the effectiveness of composting practices (Bernal, Alburquerque & Moral, 2009). Even without further treatment, many pathogens die off during storage.

The WHO *Guidelines for the safe use of wastewater, excreta and greywater* provide information on pathogen survival in faeces, urine and greywater (WHO, 2006a). The guidelines also list inactivation rates for common pathogens, which range from 20 to 125 days for 90% inactivation (Table 16).

Table 16 "Die-off" of selected pathogens in faeces and soil

Pathogen	T_{90} faeces (days, mean ± standard deviation)	T_{90} soil (days, mean ± standard deviation)
Salmonella	30 ± 8	35 ± 6
Enterohemorrhagic *E. coli*	20 ± 4	25 ± 6
Rotavirus	60 ± 16	30 ± 8
Hepatitis A virus	55 ± 18	75 ± 10
Giardia	27.5 ± 9	30 ± 4
Cryptosporidium	70 ± 20	495 ± 182
Ascaris	125 ± 30	625 ± 150

Source: adapted from WHO (2006d).

Much of the nitrogen in manure is present as ammonia or ammonium compounds. In calcareous soils, more than 30% may be lost by volatilization soon after excretion. The remainder of the ammonia and other organic nitrogen compounds may be microbially oxidized by a process known as "nitrification", to form highly soluble nitrates (Haygarth & Jarvis, 2002). Nitrate concentrations in surface drinking-water sources rarely reach levels of direct health concern in subtropical or tropical areas because denitrification is rapid at high temperatures (although nitrate concentrations can contribute to the formation of toxic cyanobacterial blooms in these conditions). However, in rivers and lakes in temperate regions, nitrate concentrations often exceed the WHO guideline value of 50 mg/L for drinking-water (e.g. see Kay et al., 2012).

Phosphorus occurs in manure as soluble phosphates or low molecular weight organo-phosphorus compounds that are usually adsorbed to soil particles. However, surface run-off from agricultural areas can carry high concentrations of both dissolved and adsorbed phosphorus into streams and rivers. Where there is low flow and reducing conditions, adsorbed phosphates may be desorbed and become available for algal and cyanobacterial growth.

Concentrations of heavy metals derived from animal feeds vary, depending on livestock age, type and the feeding regime. Metals derived from manure are generally not of health significance in drinking-water resources, provided that feeds contain the bare minimum of trace metals necessary to sustain good animal health (Goss et al., 2001). In some cases, zinc may be used in feed to prevent diarrhoea in piglets, which may result in elevated levels of zinc in manure.

Manure can contain significant concentrations of naturally occurring endocrine-disrupting compounds (Combalbert & Hernandez-Raquet, 2010), obtained mainly from feed (particularly phytoestrogens). Antibiotics, hormones and other pharmaceutical compounds are commonly used to promote growth in livestock due to the endocrine activity of these substances and their antibacterial behaviour, and can be excreted in manure. Although the concentrations reaching raw-water offtakes are rarely of demonstrable health concern, endocrine effects are poorly understood, and the increasing numbers of pathogen strains becoming resistant to antibiotics means there is a need to reduce the opportunities for pathogen exposure to antibiotics.

Feedlots and other intensive animal feeding operations

Animals are often maintained in pens in a controlled environment to optimize growth and facilitate feeding, in so-called feedlots. The pens may be open-air facilities, or may be completely enclosed within large buildings. Dairies are similar to feedlots in that a large number of cows are gathered together for milking, although the cows are generally allowed to run free when not being milked.

Stock housed in animal feedlots generate a great amount of waste that can become an unintended but substantial source of widespread water pollution if it is not managed properly (Burkholder et al., 2007). Hazards potentially introduced into surface waters from feedlots carrying manure and slurry are similar to those discussed above (although the risks may be greater where large numbers of animals are involved); that is, a variety of pathogens (parasites, bacteria, viruses), metals, pharmaceuticals, antibiotics, pesticides and growth hormones (contained in urine and faeces) and nutrients that can lead to eutrophication. Further major sources of pollution from feedlots are animal carcasses, process wastewater (e.g. dairy waste), feed (particularly effluent from silage storage) and bedding materials. Leaking liquid waste from wastewater holding ponds or from silage effluent can cause severe environmental damage in waterways because of their high biochemical oxygen demand (BOD) and nutrient content. Moreover, foul water lacking oxygen is unsuitable as drinking-water because of the toxic products of anaerobic decay; hence, it is likely to be rejected by consumers. However, under oxygenated flow conditions, and if the flow path is sufficiently long and turbulent, there may be natural degradation of organic matter (see Section 2.1.3). This may remedy such contamination before the water reaches the point of raw-water offtake.

Intensive grazing and animal access to watering points near rivers can cause severe erosion of river banks and the destruction of riparian vegetation, in turn enhancing flow paths for contamination. The pathogen load in rivers can also be greatly increased if large numbers of stock are allowed to wallow and defaecate directly into the water

Fertilizer and wastewater use

Inorganic and organic materials that are used for fertilizing crops may introduce a variety of potentially toxic chemical compounds into surface waterbodies that can lead to contamination of drinking-water sources. Chemical compounds in these materials that can either directly or indirectly affect health include nitrates, cadmium, uranium, ammonium ions (which can be oxidized to nitrate in surface waterbodies) and phosphates (which may trigger toxic algal blooms).

As with animal manure, the use of large amounts of sewage sludge as fertilizer can lead to nitrate leaching into groundwater, and the surface run-off of phosphorus can increase eutrophication, resulting in algal growth and cyanobacterial blooms in surface waterbodies. If the sludge is derived from a catchment with high industrial activity or widespread use of household chemicals, it may also contain heavy metals and organic contaminants, although generally not at concentrations that would be of concern for human health. However, raw water in catchments where large amounts of sewage sludge has been applied often contains a range of endocrine-disrupting compounds, including pharmaceuticals and personal-care products (Benotti et al., 2009). Depending on the type of sludge treatment and on the health of the community shedding pathogens in the catchment, sludge may also contain a range of waterborne pathogens – possibly an even wider range of human pathogens than animal-derived manures. Information on the safe use of wastewater, excreta and greywater in agriculture can be found in the relevant volumes of the WHO *Guidelines for the safe use of wastewater, excreta and greywater*: Volume 2, *Wastewater use in agriculture* (WHO, 2006b); and Volume 4, *Excreta and greywater use in agriculture* (WHO, 2006d). Such practices may also be addressed as part of the process of developing a sanitation safety plan (SSP), which may be complemented by or be part of the development of a WSP for a given catchment (for more information on SSPs, see Box 1.4 in Section 1.1.4).

Chemical fertilizers contain inorganic salts of nitrogen, phosphorus, potassium and sulfur, plus some trace metals necessary for healthy plant growth. Generally, nitrogen is present in inorganic fertilizers in the form of soluble salts of ammonium and nitrate. Nitrogen in fertilizer is generally more available for plant uptake than from manures, but is also more easily leached into groundwater if used in excess.

Although more expensive than manure, artificial fertilizers have an advantage, in that the precise nutrient content is known. Thus, delivery of fertilizers can be precisely targeted to meet uptake by the crop and minimize run-off into drinking-water sources. Timing of application is critical to ensure that the fertilizer is available when the plants require nutrients. Excessive use of nitrogenous fertilizer over a long period can increase the acidity of soil. The soil then leaches naturally occurring metals (Hogbom, Nohrstedt & Nordlund, 2001), which may be mobilized during rainfall events and washed into surface-water storages.

Pesticide use

The main hazardous substances in pesticides include arsenic, carbamates, chlorinated insecticides, cyanides, ethylbenzene, lead, naphthalene, organophosphates, phenols, phthalates, toluene and xylene. Many pesticides also have endocrine-disrupting effects, with potential health consequences that are poorly understood and characterized. The physical and chemical properties of these substances vary enormously, but typically (with some notable exceptions) they are sparingly soluble in water and are not readily leached from soil profiles.

In addition to the application of pesticides, dumps of pesticides may pose a threat to nearby surface drinking-water sources. Most health problems from pesticides are caused by inappropriate handling or disposal of these chemicals, or through storage of drinking-water or food in empty pesticide containers, rather than through normal pesticide use for crop spraying. However, contamination of drinking-water sources can occur, as is well known from the use of highly persistent pesticides such as DDT (e.g. for malaria control). Pathways by which the agricultural use of pesticides can contaminate surface drinking-water sources include:

- *spraying adjacent to waterbodies* – the spray from on-ground or aerial pesticide application can fall directly onto the surface of the water, particularly if spraying is done in windy conditions;
- *residue disposal and equipment washing* – tank residues after spraying may be disposed of into waterbodies used as drinking-water sources, and equipment may be washed in the same water sources;
- *inappropriate application rates* – in regions where there is little or no training, farmers often apply pesticides at excessively high rates or, unintentionally, just before heavy rainfall; and
- *inappropriate storage and mixing* – pesticides are sometimes stored or mixed in open areas with no containment.

Where public health is also affected by the consumption of contaminated fish, a lower tolerable daily intake may be allocated to drinking-water.

Leaching of naturally occurring inorganic chemicals from soil due to irrigation and drainage

The large volumes of water used in irrigation – often between 5000 and 15 000 m^3 per hectare per year (Romijn, 1986) – allows solutes in irrigated soil profiles to be readily leached into surface waterbodies. It may lead to leaching of salts and thus to salinization of surface waters. In areas where soils contain significant concentrations of selenium, the infiltration of irrigation water can leach selenium, cause local contamination of surface-water sources and affect human health. Irrigation may also lead to run-off and leaching of fertilizers and pesticides, as explained above.

Long-term irrigation of crops may progressively increase both the sodicity of soils beneath irrigation areas and the alkalinity of water that percolates through soils to groundwater in a process known as “alkalization” (the salinity of the percolating water also typically increases). The increased alkalinity of water in the soil profile beneath irrigated agricultural areas can, in turn, leach a number of naturally occurring chemicals of health concern from the soil into shallow groundwater. Such chemicals include fluoride (Jacks et al., 2005), uranium (Jurgens et al., 2010) and selenium (Bajaj et al., 2011). Shallow groundwater, in turn, reaches drainage ditches and river pools where it may be used as a source of drinking-water. In India, contaminated sources of drinking-water are likely to be contributing to the widespread incidences of fluorosis (Jacks et al., 2005) and selenosis (Bajaj et al., 2011) recorded in some parts of the country.

Drainage

Drainage may increase concentrations of any soluble soil component in the receiving waterbody. The main negative effects of drainage are to increase groundwater salinity and nitrate concentrations; and increase concentrations of certain pesticides, sulfate, iron and heavy metals in certain areas, as explained below.

In irrigation areas, water collected in drains can have a salinity up to 10 times that of the applied irrigation water (Romijn, 1986), and in arid or semiarid areas, the salinity of drainage can further increase through evaporation as water moves in open channels from the irrigated fields to the waterbody. Leakage of water from drainage channels can contaminate groundwater and surface waterbodies at some distance from irrigated areas with salt and nitrate and, in some areas, with other contaminants such as fluoride and selenium.

Soil drainage commonly leads to better aeration of overlaying soil and thus to increased mineralization of soil organic matter and release of nitrate and sulfate into run-off (Kopacek et al., 2014; Kopacek, Hejzlar & Posch, 2013). Where the surface water is near groundwater, the contaminants can also seep into adjacent waterbodies.

The drainage of soils containing pyrite and other sulfide minerals can cause severe environmental and health problems through the release of sulfuric acid and toxic levels of heavy metals and arsenic, caused by the oxidation of sulfides. Such soils are referred to as "acid sulfate soils". The acidic drainage from acid sulfate soils not only contains high concentrations of metals of health concern, it can also greatly increase mosquito breeding because of its low pH.

3.3.2 Checklist for assessing pollution risk from agricultural activities

Checklist 4 is based on the information presented above in Section 3.3.1. It provides guidance on factors to consider when evaluating issues related to agriculture in the catchment in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

Checklist 4 Assessing pollution risk from agricultural activities

What types of agricultural activity are found in the catchment?

☑ Determine the proportion of land covered by agriculture

☑ Compile information on types of agriculture (e.g. pasture land, arable land, irrigated or drained agriculture, horticulture and market gardening)

☑ Identify main crops cultivated (including changes over time)

☑ Compile (and, if possible, map) information on location, spatial distribution and scale of agricultural land and different cultivation types

☑ Identify extent to which stock have access to waterways, including location of major access points

☑ Determine whether manure is applied in the catchment

☑ Estimate livestock densities, animal species and amount of manures produced

☑ Characterize storage conditions and handling practices for manures

☑ Evaluate patterns of manure application:
- Assess adequacy of application rates: check whether criteria are based on
  (a) nutrient budgets and crop uptake rates, or
  (b) merely the need for getting rid of manure in areas with high livestock densities or intensive livestock farming
- Assess timing of application in relation to hydrological events and to seasonal aspects (e.g. presence or absence of vegetation cover, frozen ground)
- Assess adequacy of spreading methods.

Are fertilizers applied in the catchment?

☑ Characterize amounts, types and products of fertilizers used

☑ Check composition of fertilizers (e.g. content of nitrogen and phosphorus)

☑ Evaluate patterns of fertilizer application (see 'Evaluate patterns of manure application' above in this checklist for adequacy of application rates, timing, spreading methods and irrigation practices).

Checklist 4 **Assessing pollution risk from agricultural activities** (continued)

Are feedlots, dairies or other intensive animal feeding activities operated in the catchment?

☑ Estimate livestock densities and animal species present in the catchment

☑ Determine locations of the animal feeding activities in relation to surface waterbodies

☑ Assess adequacy of design, construction, condition, operation and maintenance (e.g. sealing and lining of surfaces and containments, open-air or closed facilities)

☑ Quantify and characterize wastes generated

☑ Evaluate availability, storage capacity, treatment efficiency and adequacy of wastewater-treatment facilities

☑ Check and assess disposal practices for treated or non-treated wastewater (e.g. irrigation) (see 'Is sewage sludge or wastewater used in the catchment?' below)

☑ Check and assess disposal practices for manures (see 'Evaluate patterns of manure application' above).

Is sewage sludge or wastewater used in the catchment?

☑ Estimate amount and composition of sludges and treated or non-treated wastewaters

☑ Evaluate adequacy of sludge treatment (e.g. composting) or storage time before land application

☑ Evaluate patterns of land application: see checklist for manure application above for adequacy of application rates, timing, spreading methods and irrigation practices

☑ See also Checklist 6 on assessing pollution risk from wastewater and stormwater effluents for further information to be collected on wastewater.

Are pesticides used in the catchment?

☑ Characterize amounts, active ingredients and commercial products of pesticides

☑ Assess adequacy of design of, and practices at, handling and mixing sites, and whether there is indication of inadequate disposal practices of residues, surplus pesticides or drums

☑ Assess adequacy of siting, design, construction and condition of storage facilities

☑ Assess whether there are any stockpiles of obsolete and banned pesticides

☑ Check whether there are indications of illegal use of banned pesticides

☑ Check location of dip sites for livestock treatment, and assess adequacy of practices employed

☑ Check whether there is indication of abandoned pesticide stocks

☑ Assess patterns of pesticide application:
- Assess adequacy of application rates: check whether criteria are based on
  (a) recommendations of producer or licensing authorities
  (b) merely the need for getting rid of surplus pesticides, or
  (c) preventive spraying practice
- Assess timing of application in relation to hydrological events, seasonal aspects (e.g. presence or absence of vegetation cover, frozen ground), and crop needs
- Assess adequacy of spreading methods.

Checklist 4 Assessing pollution risk from agricultural activities (continued)

Are irrigation and drainage practised in the catchment?

- ☑ Determine the scale to which irrigation and drainage is practised (amount of water used and distribution)
- ☑ Compile information on irrigation and drainage techniques employed
- ☑ Assess adequacy of irrigation practices (if employed)
- ☑ Check for indications of leaching of naturally occurring substances
- ☑ Check whether acid sulfate soils occur in the catchment.

Are ploughing, grazing or clear-cutting practised in the catchment?

- ☑ Determine the scale and extent to which ploughing, grazing or clear-cutting is practised, and where it is practised
- ☑ Compile information on the ploughing, grazing or clear-cutting techniques employed and their timings.

3.3.3 Examples of hazardous events and control measures for agricultural activities

The hazards that typically reach surface waterbodies from agricultural activities are introduced through characteristic hazardous events, for example:

- spreading of manure, especially on saturated and frozen soils, and application of sewage sludge;
- direct access of livestock to the waterbody (see case study from Ontario, Canada, in Box 3.1);
- heavy rain events flushing faecal matter into watercourses through overland flow;
- nutrient loads leading to eutrophication;
- inappropriate application and storage of manure, sludge, pesticides, fertilizers and so on; and
- leaching of substances from the subsoil due to the application of irrigation water and drainage.

Fresh liquid manure or manure slurries applied to the soil surface generally pose the greatest risk of contaminating surface waterbodies with pathogens. This is because the material may flow overland and directly into the waterbody if large amounts of liquid are applied to soil.

Box 3.1 Implementing control measures in agriculture

Rainy River First Nations in Ontario (Canada) is an aboriginal community of just over 300 people that became concerned about the water quality of the rivers and streams in its catchment. Through a review of land use in the catchment, community members identified farms where cattle had unrestricted access to streams and rivers. Discussions with the local farming association revealed that local farmers understood the long-term benefits of restricting the access of cattle to streams and rivers, and were interested in helping to solve the problem. The barrier was the cost of fencing supplies and renting equipment. Once this barrier was identified, the community was able to work together with the farmers to obtain government grants for the necessary resources. Community members and farmers worked together to install fencing, pumps and troughs, thereby controlling the access of cattle to rivers and streams.

In regional **Victoria (Australia)**, stock access near to a raw-water offtake was identified through the WSP process as a high risk to source-water quality. Stock-exclusion fencing and subsequent revegetation of the riparian buffer zone were identified as appropriate control measures. However, critical sections of a waterbody close to the offtake point were not fenced. Accordingly, a stock-exclusion agreement was developed among three key stakeholders: the local catchment management authority, the water utility and the landholder, whereby:

- the catchment management authority provided fencing along the stretch of waterway deemed to be at risk; subsequently, the authority was responsible for revegetation and maintenance of the riparian zone;
- the water utility provided an off-stream watering system to supply raw water for watering troughs for the livestock; and
- the landholder was responsible for maintaining the fencing, and agreed to pay a nominal volumetric charge for raw water for livestock watering, to cover the operation and maintenance of the off-stream watering system.

Weather events such as heavy rainfall can exacerbate transport of hazards into surface waterbodies, or within them to the offtake point for drinking-water supplies.

Table 17 provides examples of hazardous events related to agriculture, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

Table 17 Examples of hazardous events in agriculture, control measures, and options for their monitoring

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Agricultural activities in vulnerable zone in proximity to waterbody (e.g. potential for transport of pathogens from intensely farmed agricultural land to waterbody via run-off) (M)	Define criteria for exclusion or restriction of agricultural activities (e.g. stock density, age) in vulnerable drinking-water catchments	Monitor land use within vulnerable areas/ protection zones and ensure that restrictions are implemented (site inspection)
		Require permits for the location, design and operation of feedlots in vulnerable drinking-water catchments	Review plans and applications for permits for agricultural activities in relation to vulnerability of drinking-water aquifer
	Presence of high densities of juvenile animals upstream of offtake contaminating waterbody during wet weather conditions (M, C)	Restrict agricultural activity in vulnerable drinking-water catchments (e.g. restricting numbers of livestock)	Monitor stock numbers within vulnerable areas and protection zones, and ensure that restrictions are implemented
	Inappropriate manure, wastewater, sludge nutrient or pesticide application practices leading to contamination of waterbody via run-off (M, C, P)	Require nutrient and pesticide management plans with specific limitations on amounts and timing of fertilizer, agrochemical, manure, wastewater and sludge application	Audit nutrient and pesticide management plans and compliance with best management practices for nutrient management, applying the correct amount of fertilizer at times of the year when plant uptake occurs
		Replace persistent pesticides with others Conduct training for staff in handling agrochemicals Restrict wastewater and sewage sludge usage in vulnerable areas	Check whether wastewater and sludge is only applied at times of the year when crop uptake rates are high, and where risk of heavy rainfall events is low
	Presence of stock near waterbody (M, P)	Set financial incentives (subsidies, credit, low-interest loans) to fund changes, compensation for lost income during transition periods to new practices (e.g. off-stream watering)	Check compliance with practices negotiated before granting financial incentives
		Set financial disincentives (e.g. increased penalties) for pollution caused by agricultural practices	Check compliance to restrictions set in regulations
		Fence waterbody, particularly near offtake point, to avoid animal access, and provide water for animals outside fenced area	Visual inspection of integrity of fence

Table 17 Examples of hazardous events in agriculture, control measures, and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Design and construction	Agrochemical/liquid manure spill in proximity to waterbody (M, C, P)	Construct and maintain safe containments for agrochemicals and adequately sized, impermeable and bonded sites for pesticide mixing and cleaning of equipment	Inspect structures and review management plans
		Install and maintain safe storage tanks for liquid manure	Inspect structures and review management plans
		Apply best management practices for storage of agrochemicals/ liquid manure, preventing storage/use near surface waterbodies	Ensure features are fenced off with appropriate set-back distances through statutory controls and inspections
	Run-off containing stock effluent from intensive animal feeding operations (M, P)	Apply best management practices for treating wastewater from feeding operations	Check compliance of treatment structures with best management practices
Operation and maintenance	Excessive sediment run-off to waterbody as a result of poor tillage practices (M, C, P)	Apply best management practices for erosion and sediment control	Check if contour ploughing or conservation tillage are applied
	Spray-drift from pesticide application during inappropriate weather conditions (C)	Apply best management practices for pesticide application	Check compliance of pesticide application practices with best management practices Monitor targeted pesticide use, inspect farm records of agrochemical application
	Excessive nutrient loading to waterbody as a result of over-irrigation (C)	Apply best management practices for irrigation and drainage, matching irrigation to crop needs	Check irrigation management plan, scheduling and capturing of run-off Check compliance of existing irrigation practices with best management practices Check appropriate irrigation system controls in place Inspect farm records, audit irrigation plans
	Excess levels of nitrogenous compounds reaching waterbody following inappropriate nutrient application practices (C)	Apply best management practices for nutrient management Grow winter cover crops to consume excess soil nitrogen	Check compliance of existing irrigation practices with best management practices Check appropriate irrigation system controls in place Review irrigation management plan and documentation

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

3.4 Aquaculture and fisheries

As the world's population grows, aquaculture and fisheries are becoming increasingly significant as sources of protein. In many regions, inland aquaculture is one of the main uses of freshwater resources. Inland aquaculture comprises a broad spectrum of systems, practices and operations, ranging from simple backyard pond systems in small households to large-scale, highly intensive commercial operations. Table 18 gives an overview of typical aquaculture systems.

Table 18 Main types of aquaculture and their potential impact on surface-water quality

Type of aquaculture	Operation mode	Potential impact and options for reducing it
All systems	• All operation modes	• Discharge of nutrient-rich effluent • Discharge of therapeuticals (particularly antibiotics) and sometimes poorly degradable chemicals
Pond systems	• Widespread use for aquatic food production • Use of natural food (e.g. plankton) produced via fertilization (e.g. manure, agricultural by-products or fertilizers)	• Predominant where regular water flow is available, often where soil quality is low • Effective options to control nutrients if ponds are enclosed and impermeable • Release of nutrient-rich water may occur during discharge or harvesting • Fish-pond sediment may act as nutrient trap if periodically removed • Effluent impacts may be minimized via reuse of water or treatment
Wastewater-fed systems (often termed "integrated aquaculture")	• Use of sewage and organic wastes mainly from households, thus enriching natural food stock in an extensive pond system	• Increased risk from pathogens (e.g. use of faecal waste as feed) • May be controlled by, for example, optimizing system retention times (and thus pathogen attenuation) and chlorination • Use of greywater can be an option to avoid pathogen transfer
Flow-through systems	• High flow rate manages oxygen demand and metabolic waste removal	• May significantly impact downstream water quality via release of excess feed, metabolic wastes, excreta and chemicals • Require sufficient flow of water
Closed recirculating aquaculture systems (RAS)	• Intensive production via complete formulated feed and optimal growth conditions • Water quality managed via biofilter for nitrification, optional disinfection via UV, effluent treatment and recirculation	• Potential water-quality impacts during sludge reuse/disposal • Continuous treatment and recirculation results in maintenance of consistent good water quality • System requires a daily renewal of nutrient-rich process water by freshwater depending on the system between 2% (including a denitrification unit) and 15% of the volume and a periodic desludging • Appropriate sludge management required to minimize water-quality impacts
Aquaponics	• Combination of aquaculture and horticulture – Conventional single recirculation aquaponics system (SRAPS): effluent of fish tanks floats to hydroponics where nutrients are used and the purified water goes back to fish units – Double recirculation aquaponics system (DRAPS) consists of separated RAS and hydroponics units being uni-directionally connected via a one-way valve	• Potential water-quality impacts during sludge reuse/disposal • Fish wastewater is used as fertilizer for plants and thus no discharge of nutrient-rich water is needed; SRAPS are hampered by low productivity but DRAPS can produce similarly as separated systems • Periodic desludging as for RAS
Cage culture or net systems	• Use of floating cages or nets placed in natural waterbodies (e.g. reservoirs, lakes, rivers) • Use of formulated dry feeds (e.g. fish meal, oil, soya with vitamins and minerals) • Widespread use in marine waters (e.g. for salmon production) and freshwater reservoirs; use in freshwaters is legally restricted in some countries because of environmental concerns	• High pollution risk as excreta and metabolic wastes enter waterbody directly causing eutrophication • Potential transfer of pathogens/parasites of farmed fish to wild populations • Requires sufficient water flow or a sufficient relationship of stocking and volume of the waterbody to maintain a good water quality by rapid natural self-purification

Inland aquaculture can affect the quality of water resources by introducing nutrients from fish food, excreta, fertilizers (resulting in eutrophication), and chemicals and therapeuticals. Some pathogens causing human illness can be transmitted from fish to those consuming and handling them (Lehane & Rawlin, 2000). Also, in aquaculture systems that use wastewater and excreta, the latter may directly introduce human pathogens into the water. The impact of aquaculture on waterbodies used for drinking-water supplies or recreation depends strongly on the amounts and quality of the aquaculture effluent reaching the waterbody. In cage culture (net pen) systems, the impact depends on the size and intensity of the operation in relation to the water volume and exchange rate in the waterbody.

Fisheries need to manage fish stock directly in lakes, reservoirs and sometimes rivers. Depending on intensity, fish stock management can have impacts similar to aquaculture, particularly where it includes feeding or even fertilization. Additionally, a fishery may affect food chains; that is, it may lead to an increase in the density of planktonic algae by reducing zooplankton populations that would otherwise graze on the algae.

3.4.1 Aquaculture and fisheries activities that may affect surface-water quality

Hazards from feed, wastes and fish excreta

Wastes in aquaculture systems comprise uneaten food (Table 19 shows potential amounts) and fish excreta, resulting in suspended and settled particulate organic matter (POM), as well as dissolved organic carbon (DOC) and nutrients. Nutrients taken up by fish in excess of their requirements are excreted; such nutrients include phosphates and nitrogenous compounds. The amount of substances excreted also depends on the type of fish farmed. When determining the level of discharge of wastes derived from aquaculture, it is important to know the feed composition and the feed conversion coefficient ratio (i.e. the ratio between the production of biomass and the weight of feed used).

Overall, the chemical substances introduced into water with feed or by the fish are:

- *inorganic carbon* – as CO_2;
- *organic carbon* – including undigested lipids;
- *nitrogen* – particularly ammonia and urea from fish excreta, and nitrite and nitrate if ammonia can be converted by aerobic bacteria;
- *phosphorus* – as particulate and soluble phosphates; and
- *potential additives of feed* – these include trace elements (e.g. zinc and copper) and vitamins.

Beside the high toxicity of ammonia for fish, other factors that affect water quality are organic carbon, ammonia and urea (which consume oxygen), and phosphates and, in some regions, nitrate (which cause eutrophication). Medicated feeds that contain antibiotics release most of the antibiotic into the environment in its active form, in part because they are not well accepted by the fish, and in part because little of the ingested feed is metabolized (Boujard, 2002). Also, the feed may contain microorganisms and, depending on its origin, pathogens.

Table 19 Estimates of unconsumed feed from intensive farming of rainbow trout in earth ponds

Feed method	Feeding loss (%)
Trash fish hand-fed	10–30
Moist pellet automatic feeding	5–10
Dry pellet automatic feeding	1–5

Source: adapted from Beveridge, Phillips and Clarke (1991).

Hazards from fertilizers, manure and sewage

The main sources of fertilizers used in extensive and semi-intensive aquaculture systems are organic livestock manure, human sewage and inorganic chemical fertilizers. The use of human waste for fish farming is an old practice in some regions. The human waste is applied in the fish ponds in the same way as manure; however, some treatment (e.g. settling and oxidation) is often used before the sewage is introduced into the ponds. The use of fertilizers, manure and sewage to increase fish yields in pond aquaculture is similar to the use of manure in agriculture to increase crop yields. Therefore, the associated risks for surface-water quality are similar; they include eutrophication (as discussed above for feed and fish excreta) and of spreading infectious disease through pathogens.

Feachem (1983) describes three potential infection risks associated with the use of wastewater and excreta in aquaculture:

- passive transfer of excreted pathogens by fish and cultured aquatic macrophytes;
- transmission of trematodes whose life cycles involve fish and aquatic macrophytes (principally *Clonorchis sinensis* and *Fasciolopsis buski*); and
- transmission of schistosomiasis.

Public health risks arising from the use of wastewater in aquaculture chiefly affect those consuming the aquatic products, those operating the aquaculture systems (who might be exposed to diluted or treated wastewater), and those who are handling and processing the products. The pathogen transmission risk can be controlled if adequate measures are adopted to reduce the pathogen load (Strauss, 1997) and to minimize human exposure to the water after application. Information on assessing microbial hazards and toxic chemicals and managing the associated risks can be found in the WHO *Guidelines for the safe use of wastewater, excreta and greywater*; Volume 3: *Wastewater and excreta use in aquaculture* (WHO, 2006c).

Hazards from chemicals for disease control and other purposes

Chemicals to control diseases (e.g. bactericides, fungicides and parasiticides), aquatic vegetation (e.g. algicides and herbicides) and other organisms (e.g. insecticides, piscicides and molluscicides) are widely used in aquaculture, particularly in intensive systems that have a high animal density (Table 20). Other chemicals used include compounds to reduce handling trauma to organisms (anaesthetics) and to induce spawning or promote growth (hormones).

Various compounds are used to disinfect water, improve water quality and increase productivity (e.g. lime and fertilizers) (Bergheim & Asgard, 1996). Other measures used for disinfection are treatment of process water with UV light and with peracetic acid. Hydrocarbon contamination from a diesel oil spill may be a further potential risk at intensive pond farms, where mobile pumps and other equipment are used.

Among the various chemicals used in aquaculture (Table 20), antibacterial drugs are those that are most commonly applied. This is a cause for concern because many of the antibiotics typically used are also important in treating human diseases and infection, and their widespread environmental occurrence fosters the development of resistance.

Effects on waterbodies

The major effect of aquaculture on surface waters is effluent discharge or diffusion by net cages. The quantity and quality of effluent varies enormously. Also, effluent characteristics can change dramatically as a result of routine operations; for example, when cleaning tanks and backwashing filters, 70% of the daily BOD, 75% of the total phosphorus, and 10% of the total nitrogen could be discharged during a 30-minute period (Alabaster, 1982). Monitoring of aquaculture effluents can provide data on, for example, suspended solids, BOD, chemical oxygen demand (COD), ammonia (NH_3), phosphorus and dissolved oxygen (DO). Data on other constituents are rarely available, but their potential relevance for the quality of the affected waterbody can be inferred from inventories of aquaculture operations (e.g. from feed, fertilization and medication).

Aquaculture effluents are of some concern due to the harmful chemicals and pathogens they potentially carry into the waterbody, as discussed above. However, even where system assessment shows that the risk to human health from these effluents is minor or negligible, there can be other risks. For example, effluents can substantially change the saprobic and trophic character of a waterbody (as described in Section 2.1.3); in particular, they can cause algal proliferation as well as biomass "die-off" and oxygen deficiency.

Table 20 Common types of chemicals used in freshwater aquaculture of relevance to surface water

Chemical	Remarks
Therapeutants	
Acetic acid[a]	Used with copper sulfate in hard-water areas
Peroxyacetic acid[a]	Degradation within 1–2 hours
Formaldehyde/methanol[a]	165 to 250 ppm up to 1 hour
Malachite green[a,b]	Banned in many countries; where still permitted, it is used for the treatment of ornamental fish
Acriflavin (or proflavine hemisulfate)[a,b,c]	Mostly for surface bacteria, fish and eggs, occasional use only
Salt[a]	Occasional alternative to formaldehyde/methanol
Buffered iodine[c]	Use to disinfect eggs: 10 minutes 1000 ppm
Oxytetracycline[c]	Antibiotic widely used for systemic disease
Oxolinic acid[c]	Antibiotic widely used for systemic disease
Sulfadimethoxine orthomeprim[c]	Antibiotic for systemic disease
Trimethoprim/ sulfadiazine[c]	Third most widely used antibiotic
Quaternary ammonium compounds[c,d]	Used for treating bacterial gill diseases
Benzalkonium chloride[c]	Surface antibacterial
Tosylchloramide[c]	Surface antibacterial, also effective for some protozoa
Vaccines	
Enteric redmouth vaccine	Widely used in trout culture
Anaesthetics	
Tricaine methane-sulfonate	Widely used, approx. 1:10 000 dilution
Benzocaine	Widely used, requires acetone to dissolve
Disinfectants	
Calcium hypochlorite	General disinfectant (e.g. for tanks)
Liquid iodophore	For equipment disinfection
Sodium hydroxide	Most commonly used for earth ponds
Peracetic acid	General disinfectant without residues
Water treatment	
Potassium permanganate	Oxidizer and detoxifier
Copper sulfate	Algicide and herbicide
pH regulators (acid, lime)	Lime is commonly used in earth ponds, acid used occasionally in inflows
Pesticides	Used in tropical ponds
Predator control agent (tea seed cake)	Control predators in ponds
Hormones	
Androgens such as methyltestosterone	Widely used in tilapia hatcheries to masculinize fish
Luteinizing hormone-releasing hormone, human chorionic gonadotropin pituitaries	Widely used for artificial spawning in fish hatcheries
Pigments	
E.g. synthetic carotenoids	Colouring fish flesh
Antifoulants	
E.g. trybutilin copper	Used in cages and pen nets

[a] Used for control of ectoparasites.
[b] Used for control of fungi.
[c] Used for control of bacteria.
[d] Used as surfactant.

These water-quality impacts from aquaculture may be similar to those caused by sewage outfalls, or run-off from agricultural areas with feedlots or intensive use of manure and fertilizers. Where discharge from aquaculture is periodic, the pulse-wise loads to the receiving waterbody present an additional challenge to aquatic organisms and their natural ecosystems, hampering the establishment of species adapted to particular conditions.

Fisheries that simply remove fish that naturally grow in the waterbody impact water quality, but this impact is limited to the changes caused by the reduction of the preferred species (often large predatory fish) on the food chain. Reduced populations of predatory fish allow more zooplankton-eating fish to survive and grow, and these can substantially reduce the populations of daphnia, which "graze" on phytoplankton. Hence, populations of algal phytoplankton may increase. In contrast, cyanobacteria will be less well grazed and so will tend to be less affected by this mechanism; they may even benefit from reduced competition for light and nutrients if there is a decrease in planktonic algae. Such mechanisms may be intensified through stocking the fish species relevant to fisheries. For these reasons, fisheries are often restricted in drinking-water reservoirs. For example, they may be limited to angling for hobby or subsistence purposes, or periodic removal of naturally occurring fish.

The impacts of intensively managed commercial fisheries tend to be substantial and similar to those described for aquaculture above, particularly with feeding or even fertilizing. Thus, they conflict with the use of a waterbody as a drinking-water resource. Where the outcome of a situation assessment is that such activity should be banned from the waterbody, decision-makers should assess the relevance of fisheries to the nutritional needs of the local human population and their livelihoods. The human health outcomes from lack of fish should be weighed against those from the deterioration of drinking-water quality from the fishery operations.

3.4.2 Checklist for assessing pollution risk from aquaculture and fisheries

Checklist 5 provides guidance on factors to consider when evaluating issues related to aquaculture and fisheries in the catchment, in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

Checklist 5 Assessing pollution risk from aquaculture and fishery activities

What types of aquaculture and fisheries are practised in the catchment or waterbody?

☑ Compile information on the number of aquaculture operations in the catchment, on their type (pond, flow-through systems, recirculating systems, cages, integrated systems), location and size (in terms of pond area, fish production or whatever information is available)

☑ Are large-scale intensive aquafarms or fisheries operated in the catchment? If so, compile information on the water sources they use (e.g. surface water, groundwater, geothermal water, wastewater from other industries such as power stations), how water is exchanged (flow-through, recycling, partial recycling), which feed and feeding methods they use, and what data are available on effluent quantity, quality and discharge patterns

☑ Compile information on occurrence, intensity and type of fisheries in the water resource.

Is feeding applied?

☑ Characterize the feeding strategy (supplementary or basic/regular)

☑ Characterize the applied feed (amount, type, source, presence of any chemicals).

Are fertilizers applied in fish ponds?

☑ Characterize amounts, types, products and composition of fertilizers used (see also Checklist 4 on assessing pollution risk from agricultural activities, for further information to be collected on fertilizers).

Is manure applied in fish ponds, and if so, how?

☑ Characterize the applied manure (source, amount, composition, presence of veterinary pharmaceuticals, application patterns) (see also Checklist 4 on agriculture, for further information to be collected on manure).

Checklist 5 Assessing pollution risk from aquaculture and fishery activities (continued)

Is sewage or wastewater used in fish ponds?

☑ Collect available information on the wastewater (e.g. amount; is it raw or has it undergone some treatment or ageing; is it pure domestic wastewater or might it contain commercial effluents?) (see also Checklist 6 on assessing pollution risk from wastewater and stormwater effluents, for further information to be collected on wastewater).

Are other chemicals and drugs used in fish ponds?

☑ Characterize amounts, types, active ingredients and commercial products of chemicals used.

3.4.3 Examples of hazardous events and control measures for aquaculture and fisheries activities

The hazards typically reaching surface waterbodies from aquaculture are introduced through hazardous events such as:

- direct discharge of human pathogens from systems that use wastewater in aquaculture and from fish excreta;
- transfer of excreted pathogens by fish and other aquatic organisms;
- flow of fish-pond water or diffusion of compounds from net cages into the surface waterbody from which drinking-water is abstracted, particularly during flooding;
- direct discharge when fish ponds are harvested and water is drained at the end of the growing season; and
- regular discharge where ponds have a throughflow.

Short-term activities with high discharge rates include cleaning tanks and backwashing filters. Farming practices may also introduce sediment into the surface waterbody. Heavy rainfall can flood fish farms, causing transport of these hazards into surface waterbodies or within them to the offtake point for drinking-water supplies.

The operation of aquaculture facilities, especially flow-through systems with a high water requirement or intense net caging, may adversely affect the water quality of reservoirs and creeks in a region using these surface waters for drinking-water supply. The quality of drinking-water may also be affected through unintentional flow of pond water into the waterbody during flooding.

Table 21 provides examples of hazardous events related to aquaculture and fisheries, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

Table 21 Examples of hazardous events in aquaculture and fisheries, control measures, and options for their monitoring

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Presence of facility in vulnerable zone in proximity to waterbody or within the waterbody; that is, potential for release of untreated or insufficiently treated effluent from facility in close proximity to raw waterbody, or within it (M, C, P)	Selection of site, size and system to minimize waterbody impact, including consideration of hazardous events (e.g. flooding)	Review plans and applications for permits for aquaculture and fishery facilities in relation to their proximity to the waterbody and their potential impact on its water quality
		Inclusion of treatment options for effluent (e.g. settling ponds, wetlands)	Check compliance of proposed treatment infrastructure with best management practices
	Release of hazards from medicated feeds (C)	Legally banning or limiting application of chemicals used in aquaculture and fisheries	Inspect storage and application sites

Table 21 Examples of hazardous events in aquaculture and fisheries, control measures, and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Design and construction	Seepage from poorly constructed or ageing ponds (M, C)	Reline or line ponds with impervious material	Inspect structures as to suitability of design for the purpose and their integrity Monitor water balance to determine if seepage is occurring
	Pond embankment failure following severe weather event leading to release of effluent to waterbody (M, C, P)	Protect from storm and flood damage; for example, through stormwater bypasses	Inspect structures as to suitability of design for the purpose and their integrity; inspect structures following severe weather events
	Release of nutrient-rich effluent from inappropriate feeding/stocking regimes (C)	Construct closed recirculation system with treatment, aeration, sustainable stocking rates and controlled feeding rates (operational control measures: see below)	Inspect design and operation; review management plan for stocking and feeding rates
	Release of untreated liquid effluent from facility resulting in contamination of raw waterbody (M, C, P)	Avoid discharge of untreated effluent (via treatment or reuse; for example, as liquid fertilizer on field crops or as aquaponics)	Monitor effluent flow and quality; review designation information
	Discharge of untreated sludge from facility resulting in particulate contamination of raw waterbody (M, C, P)	Construct and maintain particle traps in tanks (with separate sludge outlet) and collect waste from cages	Inspect structures; review records of waste collection and effluent quality
		Reuse sludge as fertilizer on land areas that are not susceptible to run-off and leaching	Inspect storage and application sites; review records of sludge application
Operation and maintenance	Release of nutrient-rich effluent from inappropriate feeding/stocking regimes (C)	Match amount of feed to intake, using feeding methods and patterns adapted to satiation time, transit rate and subsequent return of appetite	Inspect feed used; discuss practices (e.g. timing and amounts) with operator; if available, inspect records of feed purchasing and application
		Use low-polluting feed, optimal levels of lipid and protein content for each species and distinct life stages, typically with best digestibility value, low in phosphorus	Estimate fish stock density; discuss practices and use of specific diets with operators and feed supplier
	Run-off from inappropriate on-site waste-disposal practices (M, C)	Treat or recycle waste	Inspect treatment or recycling system Check compliance of existing waste management practices with best management practices If available inspect records of waste management and application

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

3.5 Wastewater and stormwater effluents

Wastewater and stormwater usually comprise:

- *wastewater* from different origins (water that contains faecal matter or other contaminants, having been used, for example, in households, institutions, commercial activities or industrial premises);
- *greywater* (wastewater generated from domestic activities such as laundry, dishwashing and bathing but contains no faecal matter; greywater differs from water from toilets, which is designated "blackwater" to indicate that it contains human waste); and
- *run-off or stormwater* (water that originates from precipitation, such as snowmelt and rainfall, often from impervious areas).

The extent to which pathogens from human excreta and hazardous chemicals from wastewater and stormwater reach a given surface waterbody depends on:

- the catchment characteristics;
- the wastewater characteristics and resulting hazard loads and concentrations; and
- the design and operation of sanitation and drainage of built-up areas.

Wastewater and stormwater disposal systems are generally classified as:

- *on-site systems* (usually individual or servicing a few households at the location where the wastewater is generated); and
- *off-site systems* (usually collective; wastewater and stormwater are either collected together in a combined system or separately, and are sometimes treated before being discharged to surface waterbodies at outfall locations).

Contaminants from on-site sanitation systems and open defaecation tend to be retained in the soil (and possibly pollute shallow groundwater). However, depending on the site of their release and local hydrogeological characteristics (see Section 2.2), surface run-off may wash such contaminants into the waterbody. A concern also arises from the sludge removed from on-site systems (latrines and septic tanks) if it is not properly treated and disposed of (Stenström et al., 2011; Strande, Ronteltap & Brdjanovic, 2014). In settlements with a piped drinking-water supply, larger amounts of wastewater are generated; hence, larger removal systems are required. These may be on-site (e.g. underground septic tanks), or may be collective systems with discharge to a surface waterbody. Covered or piped systems for wastewater and stormwater disposal reduce the risk of direct human contact with contaminated waters that could cause waterborne diseases. However, if these systems do not include treatment, they transport to the waterbody pathogens and chemicals that would otherwise be (partially) retained and degraded in the underground or latrine compost. This transport may be through many small pipes or channels, possibly informal and undocumented (e.g. where settlements are spread along a river course or lakeshore), or through municipal sewerage systems leading to major sewage outfalls (e.g. for larger cities), preferably through a sewage treatment plant.

The chief hazard in domestic sewage is pathogenic organisms, because these can lead to disease outbreaks even from a single contact. Depending on the characteristics of the wastewater, and the type and efficacy of the sewage treatment process, sewage treatment plants may reduce pathogen concentrations by only about two Logs (Von Sperling & Chernicharo, 2005); that is, to 1/100 of the concentration in raw sewage. Given that pathogen concentrations are typically high in raw sewage (Table 3), even treated sewage is still highly infectious. Even in high-income countries, only 70% of wastewaters generated are treated, and in low-income countries this figure may be as low as 8% (Sato et al., 2013). Thus, for the most part, untreated wastewater contributes high loads of pathogens to surface waters. Information on the occurrence of pathogens in faeces, wastewater and raw (untreated) water is included in Section 2.1.1. Even where wastewater is disinfected chemically, this will not inactivate disinfection-resistant parasites and viruses. Although bacteria generally are more sensitive to disinfection, the process will also be less effective if bacteria are shielded from the disinfectant within particles.

After discharge, concentrations of waterborne pathogens in wastewater are reduced by dilution and inactivation ("die-off") in surface water. Dilution of discharged wastewater is a function of the volume of wastewater and the discharge of the river, although mixing of discharged wastewater with surface water may be incomplete. In a river, a plume of partially mixed wastewater may extend for many kilometres.

Depending on the cultural patterns, economical status and lifestyles within the community, and the types of wastewater collected in the sewerage system, domestic wastewater may also contain a range of chemicals that thus can reach drinking-water resources. Their concentrations are rarely high enough to be acutely hazardous, but some of them may be of health concern if the water is consumed over extended periods. Chemical hazards are inevitable components of human excreta, but can also originate from chemicals used in the household, such as detergents and personal-care products. These long-recognized issues are increasingly being addressed by sewage treatment, but more recent concerns include health effects from trace concentrations of substances such as pharmaceuticals (some of which are inevitably excreted by those who use them). Concern about the spread of antimicrobial resistance from antibiotic residues in the environment is discussed in "Emerging issues in relation to chemical hazards in surface-water catchments" in Section 2.1.2.

The composition and volume of wastewater generated can vary widely. For example, tourists may increase the size of the local population many-fold in peak seasons. Where this overloads sanitation systems, sewage overflows may occur, resulting in faecal contamination of recipient waterbodies.

Generally, wastewater constituents reaching a surface waterbody have two implications for human health where this waterbody is used as drinking-water:

- they may affect health directly; and
- they may compromise drinking-water treatment (e.g. as particles shielding pathogens from disinfectants, as a turbidity load challenging flocculation and filtration, or as an organic load reacting with oxidants to form undesirable by-products).

Examples of wastewater and stormwater constituents relevant to surface-water contamination are presented in Table 22. Pathogenic organisms found in wastewater are excreted by humans and animals that are infected or are carriers of a particular infectious disease. The occurrence and concentrations of pathogenic organisms reflect disease prevalence in the community. Therefore, large variations in occurrence are expected from place to place, as reflected by the wide concentration ranges presented in Table 3.

Table 22 Main constituents of wastewater and stormwater and their relevance for surface waters

		Source/relevance			
		Wastewater			
Constituents	**Main representative parameters**	*Domestic*	*Industrial*	**Urban stormwater**	**Possible effect of the hazard**
Pathogens	*E. coli* Coliforms	High	Variable	Medium	• Waterborne diseases
Suspended solids	Total suspended solids	High	Variable	Medium	• Aesthetic problems • Sludge deposits • Hazard adsorption • Shielding of pathogens against disinfectants; affecting treatment
Biodegradable organic matter	Biochemical oxygen demand	High	Variable	Medium	• Oxygen consumption • Death of fish • Septic conditions
Nutrients	Nitrogen Phosphorus	High	Variable	Medium	• Excessive growth of cyanobacteria and algae • Toxicity to fish (ammonia) • Oxygen consumption • Illnesses in new-born infants (nitrate) • Pollution of groundwater (nitrate)
Poorly biodegradable organic matter	Some pesticides Some detergents Pharmaceuticals	Medium	Variable	Low	• Toxicity (various) • Foam (detergents) • Reduction of oxygen transfer (detergents) • Reduced or non-biodegradability • Offensive odours (e.g. phenols)
Heavy metals	Specific elements (e.g. arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc)	Medium	Variable	Low	• Toxicity • Inhibition of biological sewage treatment • Contamination of groundwater
Inorganic dissolved solids	Total dissolved solids Conductivity	Medium	Variable	Not relevant	• Excessive salinity – harm to plantations (irrigation) • Toxicity to plants (some ions) • Problems with soil permeability (sodium)

The discharge of wastewater to surface water may also favour other disease-transmission mechanisms. Mara and Feachem (1999) discuss geohelminthiasis, taeniasis, water-based helminthiasis (e.g. schistosomiasis), excreta-related insect-vector diseases (e.g. bancroftian filariasis or faecal–oral diseases transmitted mechanically by flies and cockroaches) and excreta-related rodent-vector diseases (e.g. leptospirosis or faecal–oral diseases transmitted mechanically by rodents).

Table 22 shows the variable impact of industrial wastewater. Since there are different types of industries and processes, the characteristics of their effluent cannot be generalized, so each industry type must be analysed individually.

Stormwater tends to contain fewer hazards than domestic wastewater. However, depending on local conditions, stormwater can be quite polluted, particularly from run-off during heavy rainfalls after extended dry periods. Rain can pick up pollution from the air; sometimes the pollution is of natural origin (e.g. erosion by wind, volcanic activities and fire in forests), but more often it is of anthropogenic origin (e.g. industry, exhaust from motor vehicles and agriculture). More importantly, stormwater washes hazards and sediments from impervious areas into waterbodies, and erodes unpaved surfaces. Thus, the hazards that stormwater carries strongly depend on the deposits on the surfaces it flushes. Often, run-off contains animal excreta and, where open-air defaecation is practised near waterbodies, it may contain human excreta and pathogens. It may also contain sufficiently high concentrations of biodegradable organic matter to deplete oxygen in the receiving waterbody, particularly run-off from major rainfall after extended dry periods (referred to as the “first flush effect”). Therefore, it is advantageous to retain and potentially infiltrate stormwater into the underground water on the spot, where possible. Where space is lacking and stormwater is collected through a sewerage system, it may be better to feed the stormwater into intercepting settling basins rather than to directly discharge it into the surface waterbody; an alternative may be to gradually send it through wastewater treatment, as capacity allows. Stormwater may also carry, for example, wastes from commercial enterprises and the chemicals these contain.

Many cities collect wastewater and stormwater discharge in combined sewerage systems. The advantage of such systems is that, up to a certain flow, surface run-off undergoes the same level of treatment as wastewater. The disadvantage is the challenge of managing pronounced variation of stormwater volumes. If the capacity of combined systems is large, this creates high costs as well as undesirable sewage stagnation. If the capacity is small, then during peak events the mixture of sewage and stormwater will overflow directly into receiving watercourses, and this can lead to substantial pollution by untreated human excreta.

The WHO/United Nations Children’s Fund (UNICEF) Joint Monitoring Programme (JMP) for Water Supply and Sanitation used the classification for sanitation systems given in Table 23 to monitor progress towards the MDG relating to drinking-water and sanitation, which was to: “halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation”. Listing of a system as “improved” does not mean that it no longer pollutes nearby surface waterbodies; however, the classification given in Table 23 indicates that the system hygienically separates human excreta from human contact. More detailed information, including information on how to apply this classification, is available from the JMP (WHO & UNICEF, 2016).

Table 23 Classification of sanitation systems used by the WHO/UNICEF Joint Monitoring Programme

“Improved” sanitation systems	“Unimproved” sanitation systems
Connection to a public sewer	Public or shared latrine
Connection to a septic system	Open pit latrine
Pour-flush latrine	Bucket latrine
Simple pit latrine	No facilities or bush or field
Ventilated improved pit latrine	

Source: UNICEF and WHO (2004).

3.5.1 Wastewater and greywater disposal practices that may affect surface-water quality

The sanitation systems listed above include on-site and off-site systems. Whereas on-site systems are more frequently associated with groundwater pollution, off-site systems are usually associated with surface-water pollution through effluent discharge. A region with widespread on-site wastewater disposal has two important differences compared with off-site systems: a much higher number of wastewater disposal points and a potentially more disperse environmental impact. On-site disposal systems typically purify effluent by underground filtration, pathogen attenuation over time or composting for agricultural use. Nevertheless, on-site systems may pollute surface waterbodies through:

- inadequate conception, design or construction, resulting in contamination reaching groundwater and passing groundwater to surface water;
- inadequate operation; for example, not removing retained solids (sludge) on time, causing overflowing of effluents;
- malfunctioning, due to poor maintenance of the system, leading to a reduced capacity to retain wastewater;
- inadequate disposal of the sludge generated in some on-site processes;
- inadequate application or disposal of the compost from composting latrines; and
- inadequate disposal of greywater when the on-site system is designed to receive excreta only, leading to reduced degradation performance or overflowing.

A contamination pathway from on-site sanitation through groundwater to the surface waterbody is likely if the soil is highly porous, bedrock is fractured or karstic, groundwater levels are shallow, the population density is high, infiltration units are located close to surface waters, or surface waters have low flow, resulting in a low dilution capacity. Where this is not the case, on-site systems (e.g. well-designed and well-maintained dry latrines) may be the safer option. A typical scenario for settlements improving their standard of living is that latrines are replaced by flush toilets and sewerage. However, if sewage treatment is inadequate, pathogens, organic load and nutrients will be discharged directly to the nearest waterbody. If this waterbody is large or has a high rate of water exchange, this may not visibly affect water quality (e.g. with algal blooms); however, it may cause a substantial risk of exposure to pathogens, particularly through recreational activities. Furthermore, in many settings, soils on-site are more effective in retaining pathogens than standard sewage treatment plants.

Generally, off-site sanitation focuses the risk of dispersed pollution (i.e. from diffuse sources) to fewer sewage outfalls. Point sources of wastewater that is untreated or treated insufficiently and has high hazard concentrations, particularly of pathogens, create local high-risk situations. However, point sources also provide the opportunity to reduce risk through wastewater treatment before discharge. Given sufficient time, natural processes in waterbodies also effectively reduce the key hazards of concern in domestic sewage. Pathogens are consumed by zooplankton, adsorb to particles and settle to the sediment or simply die off without creating degradation products of concern.

Wastewater treatment generates solid by-products, referred to as sludge, which requires adequate handling and disposal. Sewage sludge is a good fertilizer, but its application in agricultural activities may affect surface-water quality, particularly with plant nutrients that lead to eutrophication. If the sludge contains harmful chemicals, these may contaminate both agricultural produce and water quality. Additionally, sewage sludge is likely to contain pathogenic organisms that were removed from the liquid in the treatment plant and transferred to the sludge. The most common disposal options for the sludge and the potential environmental risks or impacts are presented in Table 24. The impacts depend on the quantity of the sludge disposed; the physical, chemical and biological characteristics of the sludge; and the frequency, duration and extent of disposal. (All of these factors, in relation to the hydrological conditions of the disposal area and receiving waterbody, are discussed in Section 4.3.3.)

Some of the disposal routes shown in Table 24 may be associated with surface-water pollution. The association is usually indirect, via:

- surface run-off of contaminated liquids from the soil to the waterbodies; and
- percolated contaminated liquid that reaches the groundwater and, subsequently, surface water.

Since sludge contains most of the contaminants originally present in the wastewater, pathogenic bacteria and chemical compounds may appear in the surface water. Their presence will depend on their fate through the soil and groundwater, where substantial attenuation may occur.

Table 24 Sludge disposal alternatives and potential environmental and health impacts

Sludge disposal alternative	Potential negative environmental and health impacts
Incineration	• Air pollution • Impacts associated with the ash disposal locations
Sanitary landfill • Dedicated • Co-disposal with urban wastes	• Surface-water and groundwater pollution • Air pollution • Soil pollution • Disease transmission • Aesthetic and social impacts
Landfarming	• Surface-water and groundwater pollution • Soil pollution • Air pollution • Disease transmission
Land reclamation	• Surface-water and groundwater pollution • Soil pollution • Odour • Contamination of food • Disease transmission
Agricultural reuse	• Surface-water and groundwater pollution • Soil pollution • Contamination of food • Disease transmission • Aesthetic and social impacts
Ocean disposal	• Disease transmission • Water and sediment pollution • Alteration of the marine fauna communities • Contamination of food

Source: after Von Sperling and Chernicharo (2005).

3.5.2 Checklist for assessing pollution risk from wastewater and stormwater effluents

Checklist 6 provides guidance on factors to consider when evaluating issues related to wastewater and stormwater effluents in the catchment in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

Checklist 6 Assessing pollution risk from wastewater and stormwater effluents

Are the systems in place used, and are they sufficient?

☑ Assess amount of wastewater and stormwater generated, and whether systems in place are sufficient to meet these amounts in the catchment

☑ Assess extent of open-air defaecation

☑ Compile information on scale, condition, maintenance and user acceptability of the systems

☑ Compile information on periods of peak loading (e.g. during festivals and other large gatherings), and assess sufficiency of the systems in peak loading situations.

Checklist 6 **Assessing pollution risk from wastewater and stormwater effluents** (continued)

Is on-site sanitation practised in the drinking-water catchment area?

☑ Assess size and proportion of population using on-site sanitation, including settlement structure, numbers and distribution of on-site sanitation systems

☑ Compile inventory on coverage with different types of on-site sanitation systems

☑ Assess whether water used for washing is collected and disposed of separately from human excreta, and where it goes.

Are contaminants from on-site sanitation likely to reach the waterbody?

☑ Assess whether seepage or overflow to the surface waterbody is likely on the basis of information on slope, distance of sanitation systems to the waterbody, population size using the systems, operation and maintenance of the systems, and whether the soil characteristics render retention or breakthrough more likely

☑ Check for indication of spills or overflow and whether they are likely to reach surface waters, especially in rainy seasons.

Do the on-site systems require periodical removal of solids or sludge?

☑ Identify who carries out the removal (e.g. owners, public entity, small private companies)

☑ Identify the criteria for definition of the removal time

☑ Identify amounts of solids or sludge generated, and what happens to them. If composted, is the process effective in inactivating pathogens? If spread on fields, how likely is transport into the waterbody? If disposed of, how far away is this from the waterbody and can transportation to the waterbody be affected, especially in rainy seasons or during heavy rainfall?

Is wastewater collected and transported off-site?

☑ Assess size and proportion of population connected to the system

☑ Determine why some properties are not connected to the system, and how such properties dispose of their wastewater and excreta

☑ Assess condition, capacity and maintenance of these systems. Is there a need for maintenance, upgrading or, for example, an increase in storage capacity? Is the condition, capacity and maintenance of the collection system sufficient to avoid leakage or overflow directly to the waterbody (including during the peak tourist season)?

☑ Identify whether stormwater collection is separated from wastewater collection. If yes, are there unintended cross-connections that might challenge the wastewater system with excessive amounts of stormwater or contaminate stormwater with wastewater?

Is stormwater collected and channelled to the waterbody?

☑ Identify and delineate urban and periurban catchments connected to the system

☑ Assess the connected area for topographical features (e.g. drainage areas, slopes and lengths)

☑ Assess potential sources of specific contamination from the drained surfaces (e.g. fuel stations, hazardous materials stored in courtyards – see also Section 3.7)

☑ Identify location of outfalls and of the outfalls' discharge into the waterbody

☑ Identify whether upstream settling structures and retention basins are present that retain part of the load. If yes, check for sediment deposits and practices for maintenance and clearance

☑ Assess frequency, seasons, volumes and loads of collected stormwater reaching the waterbody. How does this amount relate to river flow?

☑ Assess condition of these systems. Is there a need for maintenance, upgrading or, for example, an increase in storage capacity?

☑ Identify whether response plans are in place for major stormwater events that cannot be retained by the system. Are plans adequate and being followed in the case of such events?

Checklist 6 **Assessing pollution risk from wastewater and stormwater effluents** (continued)

Additional checks for combined wastewater–stormwater systems:

- ☑ Identify what amount of rainfall triggers overflow. How frequently, in which season and with what amounts of water do overflow events occur?
- ☑ Estimate the pollution load of overflow events that occur more often than once a year
- ☑ Identify whether response plans are in place for combined sewer overflow events (e.g. for affected bathing sites and drinking-water offtakes). Are plans adequate and being followed in the case of such events?

How does wastewater transported off-site reach the waterbody?

- ☑ Identify the location of sewage outfalls (particularly in relation to drinking-water offtakes and recreational sites). Are they all registered, or is there indication of illegal outfalls?
- ☑ Identify whether wastewater is discharged to a treatment plant
- ☑ Gather and assess quality data for the (treated or untreated) wastewater.

What wastewater treatment is in place and how effective is it?

- ☑ Identify types of treatment systems in place, their location, and how much wastewater each system treats (e.g. compile data on population connected, flow and loads)
- ☑ Identify types of treatment processes in place. Are they appropriate for the quality needed in the waterbody, or is upgrading necessary? How much improvement can be achieved by adoption of better operational practices?
- ☑ Compile available quality data on influent and effluent concentrations and removal efficiencies, including an assessment of the monitoring concept (e.g. grab or composite samples, frequency, methods, and amount and reliability of data)
- ☑ Identify whether discharge standards exist and, if so, what the percentage of compliance is
- ☑ Assess effectiveness of day-to-day operation. What problems exist? Is the plant in good condition, and what improvements or upgrades are necessary to ensure surface-water quality?
- ☑ Identify the frequency of use of bypasses or overflows of untreated sewage
- ☑ Identify the amount of sludge produced, its characteristics and destination
- ☑ Identify whether the effluent is disinfected. If so, how and with what target?
- ☑ For systems combined with stormwater, how does the treatment capacity relate to the dry-weather flow; that is, how much capacity does the system have to absorb stormwater flow? Compile data on measured flows (average, minimum, maximum).

Are contaminants from sewage sludge likely to reach the waterbody?

- ☑ Check whether sludge is used as fertilizer, and what the related practices are (if yes, also refer to Checklist 4)
- ☑ If sludge is disposed of, check the adequacy of the site and method to avoid waterbody contamination.

Is wastewater reuse affecting the waterbody?

- ☑ Identify whether treated or untreated wastewater is used for irrigation, aquifer recharge, fish ponds or other purposes and, if yes, what the amounts are, and whether there is potential for run-off from these uses to reach the waterbody (also refer to Checklists 4 and 5)
- ☑ Identify whether there is indication of surcharging and flooding.

3.5.3 Examples of hazardous events and control measures for wastewater and stormwater effluents

The hazards typically reaching surface waterbodies from wastewater and stormwater effluents are introduced through hazardous events, which may vary. For on-site systems, these include indirect discharge via groundwater, particularly if those sites are poorly sited, designed and/or maintained. Collective sanitation systems tend to have a larger potential for direct contamination of surface waterbodies through direct discharge, including in cases of system overflow; the effects depend largely on the level of treatment applied to the wastewater before discharge.

Faecal material reaches surface waterbodies directly through untreated wastewater discharges or surface run-off, and indirectly through insufficiently treated wastewater discharges. During heavy rainfall events, off-site wastewater treatment plants may overflow; this may lead to discharge of raw wastewater, which in turn can lead to peak concentrations of pathogens in the surface water.

Many commercial and industrial enterprises discharge into municipal sewers. Such effluents may include pathogens and chemicals of concern, with pathogens a particular hazard in wastewater from hospitals, clinics or dental units. Chemicals can be an issue in wastewater from:

- small enterprises such as tanneries, automobile servicing operations or metal processing plants; and
- large-scale industrial operations that may use the public sewer, or discharge directly into a stream or river (for the impact of direct discharge see Section 3.6).

Many urban communities worldwide have achieved excellent coverage for sewerage and wastewater. Nevertheless, capacity for stormwater remains a challenge even for wealthy communities in temperate climates. The capacity for retention basins to collect stormwater and allow settling of particulate matter is rarely sufficient to intercept major floods, and there is often a lack of both space and financing of retention capacity for extreme weather. Consequently, response plans for overflow situations are important. These may range from checking for pathogens at bathing sites to temporarily closing drinking-water offtakes if contaminants not removable by drinking-water treatment are flushed into a watercourse. The impact of the discharges to the receiving surface waterbody will depend, to a large extent, on:

- efficiency of on-site sewerage systems to control spills and contamination of surface water directly or through seepage from contaminated groundwater;
- coverage of the off-site wastewater sewerage system;
- coverage of the off-site stormwater sewerage system;
- coverage of the off-site wastewater treatment plant(s);
- origin and composition of the wastewater;
- prevention of generation of high hazard loads of stormwater, particularly with pathogens, by keeping human excreta separate from stormwater;
- efficiency of the pollution-control measures for wastewater;
- efficiency of the pollution-control measures for stormwater flows (e.g. street sweeping, control of animal faeces and management of solid waste);
- pathogen removal or inactivation in wastewater treatment;
- efficiency, stability and reliability of the wastewater treatment plant;
- percentage of the stormflow that can overflow in combined sewer overflows;
- efficiency of the pollution-control measures for combined sewer overflows; and
- existence and degree of illicit connections (leading to untreated wastewater in stormwater discharge and to stormwater overloading wastewater sewers).

Box 3.2 describes examples of control measures that may be applied along the sanitation chain to control the risk to human health (see also Box 1.4 on SSPs in Section 1.1.4).

Wastewater treatment to reduce the load of constituents that are harmful to health or the environment includes several steps or stages, typically classified as preliminary, primary, secondary and tertiary treatment. Preliminary treatment is the removal of coarse solids only (e.g. through screens and grits). Primary treatment aims to remove solids that can settle, including part of the organic matter. Physical hazard removal mechanisms are predominant in both preliminary and primary treatment levels.

Box 3.2 Controlling health risks from water reuse

Reuse of wastewater or greywater is practised globally. When done in a planned and safe way, reuse may be particularly beneficial in water-scarce areas, including rural areas where incomes are low. Reuse can also be an efficient way to use nutrients and water, and examples of possible uses include agriculture, aquaculture, groundwater replenishment, household uses (e.g. toilet flushing) and even drinking-water.

Risks to human health may arise if reuse-related hazards reach water sources used for drinking-water. Risks can also come from direct contact with sanitation waste, and from foods grown using such waste.

Safe management of the sanitation chain during collection, transport, treatment, disposal and use of sanitation waste can reduce and control the risks to human health. The WHO publication *Sanitation safety planning. Manual for safe use and disposal of wastewater, greywater and excreta* lists the following options for control measures (WHO, 2015a).

Classification	Control measure
Treatment	• Physical settling (e.g. settling tank) • Bacterial process (e.g. activated sludge) • Adsorption (e.g. in constructed wetlands) • Biological inactivation (e.g. composting) • Chemical inactivation (e.g. sludge drying – controlled by pH and temperature – and disinfection)
Non-treatment	• Crop selection • Irrigation type • Withholding times • Control of intermediate hosts and vectors • Vaccination and preventive chemotherapy
Non-technical	• Use of personal protective equipment • Restricted access to treatment or use sites • Disinfection, washing and cooking of produce Note: Behavioural controls are often used in combination with the treatment and non-treatment barriers. Behavioural practices depend on individual values and preferences (e.g. fears, phobias and habits), constraints (e.g. cost, time and interest), sense of responsibility, and social-cultural perceptions and practices. Positive practices can be reinforced by promoting health and hygiene.

Adapted from Stenström et al. (2011).
See also Godfrey et al. (2010) and Pecson et al. (2015) for additional information on water reuse.

In secondary treatment, the aim is to use mainly biological methods to degrade organic matter (that would otherwise deplete oxygen when degraded in the waterbody) and, to some extent, nutrients (nitrogen and phosphorus).

The objective of tertiary treatment is to remove pathogenic organisms or specific hazards (nutrients as well as toxic or non-biodegradable compounds) and, as a complementary effect, to remove hazards that were not sufficiently removed in the secondary treatment (e.g. through ozone treatment or membrane filtration). Tertiary treatment is rare in developing countries and even in many developed countries, although in some countries disinfectant is added to inactivate those pathogens that are sufficiently sensitive, leaving only those that are resistant to disinfection.

Concentrations of phosphorus in raw sewage range from 3 to >20 mg/L. Biological steps in wastewater treatment typically reduce those concentrations to about 2–8 mg/L, and tertiary treatment can achieve effluent concentrations of 0.5–2.0 mg/L. Wastewater treatment typically reduces pathogen concentrations only by about one to two Log (a reduction of a factor of 10 to 100), unless advanced technologies are applied. Drinking-water treatment can remove pathogens effectively but, depending on the treatment process and plant conditions, this may not fully occur. The sensitivity of pathogens to disinfection varies widely. Some pathogens (e.g. *V. cholerae* and *S. typhi*) are effectively inactivated through disinfection whereas others (e.g. *Giardia* and some viruses) are more resistant or need special disinfection measures, such as UV for inactivation of *Cryptosporidium* oocysts. This highlights the importance of multiple barriers (i.e. a sequence of treatments to reduce pathogen concentrations) in the supply system. Any reduction of pathogens in raw water for drinking-water supplies – at best the prevention of their introduction into the raw water – is likely to contribute to public health protection and to the safety of the overall water supply. If pathogens do occur, multiple barriers in treatment are the most effective way to reduce risk.

When developing sanitation systems there is a need to decide whether the system should be largely on-site or sewered and off-site. In making such decisions, it is important to assess the treatment options available and to weight the likely outcome for surface-water quality against the health risks from on-site sanitation, including options for upgrading an on-site system. One option is to design sewage treatment so that it effectively eliminates oxygen-consuming organic carbon compounds and the nutrients that cause eutrophication (i.e. phosphorus and nitrogen). Another option is to address pathogen contamination by introducing effluent sufficiently far from the point of human contact; for example, abstracting potable water far from drinking-water offtakes and recreational uses, so that travel time is sufficiently long for pathogen reduction (see "Occurrence in surface water" in Section 2.1.1 for guidance on how to estimate the time necessary).

Table 25 provides examples of hazardous events related to wastewater and stormwater, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

Table 25 Examples of hazardous events for wastewater and stormwater, control measures and options for their monitoring

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Proposed developments or settlements in vulnerable zone in proximity to waterbody (e.g. potential for transport of pathogens from run-off as a result of inappropriate wastewater or stormwater management) (M)	When planning new systems, assess which off-site or on-site sanitation is preferable under the given conditions Locate off-site sanitation collection and treatment systems at safe distance from the waterbody or the abstraction point (e.g. outside drinking-water protection zones) or require safe containment or disposal	Review plans with respect to impact on potentially affected water sources, expected development of the community, public opinion and participation Inspect protection zones for compliance
	Release of untreated effluent as a result of insufficient stormwater network or wastewater treatment plant capacity (M, C, P)	Plan sufficient coverage and adequate capacity for on-site systems (accepted by the population) or sewerage and treatment to avoid open defaecation Plan sufficient collection and treatment capacity to avoid sewage overflow Include designation of greywater when planning capacity Plan capacity for stormwater interception and discharge either in separate or combined systems; develop response plans for overflow situations	Review existing systems and/or plans and permit applications for new ones in relation to demand, including peak loads (e.g. at tourist season) Review plans for capacity in relation to demand Review capacity, plans and permits in relation to precipitation patterns and local discharge patterns
	Influx of hazards, including nutrients to waterbody as a result of seepage from inappropriate application of sludge or biosolids (M, C)	Designate areas for sludge disposal or reuse options based on an assessment of proximity to waterbodies	Review plans for disposal or use in agriculture in relation to hydrological parameters reflecting likelihood of sludge reaching the waterbody
	Influx of hazardous material (e.g. fuel) from stormwater network (C)	Require safe containment or require stormwater from areas where such materials are stored to pass an interceptor	Review plans and permits for construction of facilities using hazardous materials

Table 25 Examples of hazardous events for wastewater and stormwater, control measures and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Design and construction	Open defaecation in proximity to waterway due to lack of sanitation option or of public acceptance of that which is provided (M, C, P)	Design and construct on-site systems in consultation with community representatives so that they are accepted and used by the local population	Review plans of new systems and acceptance of available systems in discussion with community
	Release of untreated effluent due to leakage, clogging or overflow from inappropriately designed sanitation systems (M, C, P)	Design and construct on-site systems to avoid overflow and leakage	Inspect during construction; monitor selected parameters in effluent (indicator organisms, substances typically occurring in the sewage) that would indicate releases or seepage
	Run-off of untreated effluent from households not connected to sewerage reticulation system (M, C, P)	Where sewerage systems exist close to homes, require connection; incentivize as appropriate	Inspect for connection or illicit sewage disposal
	Direct input of inadequately treated wastewater or stormwater to waterbody (M, C, P)	Design and construct treatment plants to comply with effluent quality targets defined in their planning	Review plans and permits; inspect plants during construction and operation; effluent flow and quality monitoring
	Cross connection between sewerage or stormwater system and drinking-water system resulting in overloading of wastewater treatment facility (and subsequent release of partially treated effluent to waterbody) (M, C, P)	Prohibit illicit connections between sewerage and stormwater systems, and sewerage or stormwater and drinking-water systems	Inspect during construction and check integrity during operation Illegal connection inspection programme
	Inappropriately treated effluent entering waterbody (M, C, P)	Plan steps in sewage treatment chains in relation to vulnerability of the receiving waterbody and its uses	Review expected treatment performance against required water quality for the expected waterbody use
Operation and maintenance	Lack of sanitation facility maintenance resulting in run-off from partially treated effluent (M, C, P)	Maintain sanitation facilities in good condition and encourage use, removing retained solids on time	Inspect and maintain regularly, checking for indication of overflow; discuss removal practices with local operators (including their own safety from con¬tact); discuss use impediments with community
	Contamination of stormwater channels with hazardous household waste flowing directly into waterbody (C)	Keep surfaces flushed by stormwater clean Monitor or prosecute those practising illegal dumping	Inspect surfaces for wastes and illicit storage of wastes and hazardous materials
	Overflow from sewerage reticulation system as a result of clogging (M, C, P)	Clean sewers and drains at intervals necessary to avoid clogging and leakage (including camera inspection and tree root removal programmes) Household awareness programme to minimize introduction of inappropriate items into the sewerage network (including information on safe disposal of food, pharmaceuticals)	Inspect conditions; review records of cleaning and maintenance
	Carryover of sediment from stormwater retention basins due to lack of cleaning or maintenance (P)	Remove sediment from stormwater retention basins at appropriate intervals; develop maintenance programme	Inspect condition of retention basins; review records of sediment removal and maintenance programme
	Direct input of inadequately treated wastewater to waterbody (M, C, P)	Keep wastewater treatment plants operating effectively	Inspect plants; monitor discharge quality parameters
	Run-off from unauthorized sludge disposal in proximity to waterbody (M, C)	Implement disposal of sludge as designated	Inspect and monitor sludge disposal practices

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

3.6 Commerce, industry, mining and military sites

The activities discussed in this section include large- and small-scale commercial, public, governmental or military facilities engaged in manufacturing, chemical processing, power generation, mining and related services. A large facility may adversely affect surface water in several ways, with potentially catastrophic consequences both in the case of an emergency (e.g. process spills, pipeline leaks, lagoon ruptures and explosions) and through ongoing normal operations (e.g. waste disposal, materials storage and general housekeeping). Mining operations may have impacts through similar pathways, but may also drain large amounts of water – often with specific contaminants – to watercourses. Small-scale commercial activities may have impacts of similar significance through their aggregate effects – even a single small facility can severely impair local surface-water quality. Furthermore, decommissioned or abandoned former activities may still be a source of water contamination.

Contaminants may reach surface waters and sediments by one or more of the following processes, each depending upon the specific industrial facility, the local topography and the local hydrogeology:

- direct discharge from the facility to surface water (permitted or unpermitted);
- run-off of contaminated soils or water from the facility or surrounding areas;
- indirect discharge or seepage of contaminated groundwater to lakes, streams and rivers; and
- large-volume, short-term or catastrophic releases such as failure of lagoon dykes.

Activities may also re-shape the landscape and affect water quality; for example, through damming or impoundment of otherwise free-flowing surface waterbodies and – particularly in the case of mining – through drainage.

The degree to which a facility poses contamination risks to streams, rivers, ponds and lakes depends on factors such as:

- specific production processes and characteristics of chemicals currently or formerly in use;
- age, size, construction and state of maintenance of buildings, pipelines and storage structures;
- handling and environmental management practices; and
- local surface topography, and geological and hydrogeological characteristics.

3.6.1 Sources of contamination and pathways to surface waterbodies

Hazards can be released to waterbodies during any of the production steps; for example, from process leaks in manufacturing, treatment, handling, storage and transportation of raw materials, wastes and finished goods. Many industrial processes involve storage (e.g. piles of raw material, above-ground storage tanks, and storage drums and other containers) and handling of a wide range of chemicals in various quantities. Such chemicals can include fuels, hydraulic oils, lubricants, cooling agents, adhesives, inks, dyes and paints, metals, non-chlorinated and chlorinated solvents, and wood-preserving chemicals. Releases may continuously, regularly or occasionally reach watercourses and then flow to drinking-water sources through, for example, continuous small spills, improper routing of wash waters and process overflow, or through emergency release situations. The contamination risk depends on various factors or combinations of factors, including the location of spills, the drainage system in place, the geological setting, whether the handling area has any containment and how robust this is, the type and amount of substances spilled, and the emergency response planning in place. Specific contaminants may reach water from firefighting chemicals applied at industrial sites or on training grounds for firefighters. Although any single event may not necessarily be significant, the cumulative effects can be severe, especially in cases where one chemical may act as a solvent for another, thereby enhancing its mobility in the environment.

Larger facilities may have significant activities not related to production that may be associated with use of chemicals that can lead to contamination. Examples of such activities are vehicle traffic (including cleaning and maintenance), power generation, water withdrawal and possibly treatment, and grounds maintenance. Depending on their water solubility and toxicity, chemical contaminants may become health hazards in drinking-water resources or substantial challenges for treatment. Furthermore, activities similar to those in any larger settlement (e.g. human excreta from the workforce, traffic on the premises, and pesticides or fertilizers from lawn maintenance) may lead to microbial or chemical contamination.

Common household products also contain substances that can adversely affect water quality. Although individual quantities per household are small compared to those generated by some industrial facilities, the large number of households in developed areas may represent equal or greater potential hazards if methods of disposal are inadequate (see Section 3.5). Historical examples of contamination have been well documented (EC, 2002; Health Canada, 2002; US EPA, 2002).

Military bases often resemble both industrial facilities and small municipal operations in terms of the use, storage and disposal of materials. Military chemicals include explosives, lead and other metals, as well as acutely toxic chemicals (e.g. warfare agents). The abandonment of military facilities in some areas of the world has left a legacy of contaminants that have the potential to affect water quality. Military conflicts may inherently involve the release of hazardous and toxic substances that will affect all environmental compartments, including water. Measures to protect surface-water resources on military sites typically have been implemented afterwards rather than as preventive measures. However, during peacetime, military bases are increasingly following the criteria for commercial activities presented in this section, as well as those for sanitation (Section 3.5) and traffic (Section 3.7).

Table 26 lists chemicals that are commonly associated with industrial processes that historically have caused surface-water contamination.

Table 26 Potential surface-water contaminants from common industrial operations

Industry type, industrial process and substances	Examples of potential surface-water contaminants
Adhesives	Acrylates, aluminium, chlorinated solvents, formaldehyde, isocyanates, mineral spirits, naphthalene, phenol, phthalates, toluene
Car washes and petrol stations	Soaps, detergents, waxes, oils, solvents, fuels
Electrical components	PCBs, acids, aluminium, arsenic, beryllium, cadmium, caustics, chlorinated solvents, cyanides, lead, mercury, nickel, selenium
Explosives	Ethyl acetate, HMX, methanol, nitrobenzenes, nitroglycerine, nitrotoluenes, pentaerythritol nitrate (PETN), nitroamines (e.g. RDX), tetrazene, tetryl, 1,3-dinitrobenzene
Fabrics	Acetic acid, acetone, acrylates, NH_3, chlorinated solvents, copper, formaldehyde, naphthalene, nickel, phthalates
Foods and beverages	Chlorine, chlorine dioxide, nitrate/nitrite, phosphorus, pesticides, biogenic amines, methane, dioxins, general organic wastes
Furniture repair and manufacturing	Paints, solvents, gasoline and diesel fuel from vehicles and storage tanks, fuel oil
Inks and dyes	Acrylates, NH_3, anthraquinones, arsenic, benzidine, cadmium, chlorinated solvents, chromium, ethyl acetate, hexane, nickel, oxalic acid, phenol, phthalates, toluene
Laundry and dry-cleaning	Sodium hypochlorite, calcium hypochlorite, DCE, PCE, Stoddard solvent, surfactants, TCE, vinyl chloride
Maintenance and metal workshops	Oils, waste oils, solvents, acids, paints, cutting oils, metals, VOCs, SVOCs
Medical surgeries, veterinary practices	X-ray developers and fixers, pathogens, radiological and biological wastes, disinfectants, beryllium, dental acids
Metal refining, production and fabrication	Acids, arsenic, beryllium, cadmium, chlorinated solvents, chromium, cyanides, lead, mercury, mineral oils, nickel, sulfur
Paints and coatings	Acetates, acrylates, alcohols, aluminium, cadmium, chlorinated solvents, chromium, cyanides, glycol ethers, ketones, lead, mercury, methylene chloride, mineral spirits, nickel, phthalates, styrene, terpenes, toluene, 1,4-dioxane
Paper manufacturing	Acrylates, chlorine, chlorinated solvents, chlorinated dioxins and furans, mercury, phenols, styrene, sulfur
Petroleum refining	Alkanes, benzene, ethylbenzene, nickel, PAHs, sulfur, surfactants, toluene, xylene
Pharmaceuticals	Alcohols, benzoates, bismuth, dyes, glycols, mercury, mineral spirits, sulfur
Photo processing/printing	Cyanides, solvents, inks, dyes, oils, photographic chemicals
Rubber and plastics	Acrylonitrile, antimony, benzene, butadiene, cadmium, chloroform, chromium, dichloroethenes, lead, phenols, phthalates, styrene, vinyl chloride
Slaughterhouses	Organic loading (consuming oxygen in the waterbody), pathogens, nutrients, potentially veterinary pharmaceuticals
Solvents (chlorinated)	Carbon tetrachloride, chlorofluoroethanes, methylene chloride, DCE, PCE, TCE, vinyl chloride, 1,1,1-trichloethane
Solvents (non-chlorinated)	Acetates, alcohols, benzene, ethylbenzene, ketones, toluene, xylene
Tanneries	Chromium, copper, sodium chloride, sodium sulfate, chrome sulfate, vegetable oils, lime, dyes, fungicides, bactericides, naphthalene
Wood preserving	NH_3, arsenic, chromium, copper, creosote, dioxins, PAHs, pentachlorophenol, phenol, tri-n-butyltin oxide

DCE, dichloroethene; NH_3, ammonia; PAH, polycyclic aromatic hydrocarbon; PCB, polychlorinated biphenyls; PCE, perchloroethene; SVOC, semi-volatile organic compound; TCE, trichloroethene; VOC, volatile organic compound.

Source: based on Schmoll et al. (2006); online information [list] available at the website of the Oregon Department of Environmental Quality, and Environmental Protection Department (2011).

Information on chemicals typically used in commercial and industrial activities may also be obtained from other sources, such as the reference documents under the Integrated Pollution Prevention and Control Directive (2008/1/EC) (EC, 2008) and the Industrial Emissions Directive (IED, 2010/75/EU) (EC, 2010). Contaminants most commonly reach surface water as a result of their direct discharge (e.g. pipes and canals), or as a result of initial discharge to the surface of the ground followed by run-off or leaching through and from soils directly to the surface waterbody. To a lesser extent, indirect releases to surface water can occur in some geological circumstances following subsurface releases to soils and groundwater from tanks, ponds, underground pipelines, injection wells and similar structures, and subsequent migration to the surface waterbody. For some substances (e.g. mercury), loads to waterbodies result from atmospheric releases by industrial facilities, followed by dry or wet deposition that results in surface-water contamination. The main sources of such contaminants are not always easy to identify.

The speed and manner with which industrial chemicals move to surface waterbodies in either overland flow or through subsurface pathways depends on a range of site-specific characteristics. These characteristics include roofing of storage and handling areas, type of ground cover (e.g. paved or unpaved) and its condition, presence of secondary containment and interceptor drains, structural integrity of piping, local precipitation rate, soil types and soil physical properties. The speed and manner of transport also depends on characteristics of the substances; for example, water solubility, vapour pressure, microbial degradability and partitioning of the chemicals between adsorption to soil and dissolution in water.

Spills or leaks of hydrocarbon fuel or oil (e.g. LNAPLs) may cause significant chemical loadings. Sources include commercial or leisure boat transportation, residual oils in pipe discharges or road run-off, leakages from industrial or retail storage tanks, or distribution losses via pipeline or tanker releases.

A frequent source of water contamination from commercial activities is liquid stored (or even disposed of) in pits, ponds, basins and underground tanks draining directly to a waterbody or through the subsurface. If containment structures for such storage are poorly constructed, become damaged, or are not securely lined (e.g. with clay or synthetic materials), it is likely that contaminants will percolate through the floor and walls of the structure, or through cracks in theoretically impervious tank materials (e.g. concrete and metal). Other factors that can influence the hazard's potential to leave the storage facility are the facility's type, age, design and proximity to the waterbody, care with which it was constructed or installed, and regularity of maintenance of the containment structure. Contaminated surface run-off can be a significant source of short-term but high-concentration chemical releases, either directly to a watercourse or through the public sewerage system (e.g. from firefighting).

The failure of pits, ponds, lagoons and tanks that store liquid raw material or waste (e.g. solvent-contaminated wash waters, oil or hydrocarbons, and acidic or caustic sludges) has often resulted in broad-scale environmental contamination through leakages and breaking of dams. Such incidents have occurred with water-soluble substances of health significance (e.g. arsenic, lead, mercury, chlorinated solvents, fuel components and acidic solutions) and with many substances of low water solubility (e.g. PAHs and PCBs). The latter do not reach the nearest watercourse as quickly as water-soluble substances, because they adsorb to soils. Nevertheless, they may travel with eroded soil particles and gradually desorb and become dissolved in water, unless their rates of biodegradation keep up with their rates of desorption. Underground storage or disposal (e.g. in injection wells) can be less susceptible to releases; however, if care is not taken, substances can still reach a watercourse through aquifer contact. In some situations, injection wells have been shown to introduce hazardous substances into groundwater.

Another significant source of surface or subsurface releases of contaminants is leakage from pipes at connections and valve locations, or as a result of rupture related to pressurization, corrosion and mechanical damage. Such pipeline releases can often go unnoticed and, over time, may contribute to significant surface or subsurface contamination.

Fire-training areas (e.g. at airports and locations where actual fire emergencies occur) may cause specific pollution, especially if drainage from the area is not contained and treated properly. The use of chemicals in firefighting and the large volumes of water involved can lead to contamination of the surrounding area and long-term pollution of groundwater. Depending on the type of fire extinguisher agents applied, frequently used chemicals include the highly persistent perfluorooctane sulfonate (PFOS), carbon tetrachloride, polyfluorinated carbons and anionic synthetic detergents.

Where treated timbers, pilings or retaining walls have historically been in contact with surface water, treatment chemicals (e.g. creosote, pentachlorophenol and arsenic) may leach locally to the surrounding water.

Physical impacts of commercial production or military activities potentially affecting surface-water quality include changes in:

- water quantity (where withdrawal rates are higher than stream flow rates);
- temperature (where water is used for cooling purposes);
- the size and shape of the waterbody (e.g. dredging, filling or channelization); and
- the rate and nature of regional water flow.

This can have marked consequences, by limiting dilution and changing the distribution pattern for contaminants, or by altering the overall assimilative capacity of the waterbody (e.g. through volume decreases, impoundment or rerouting).

Mining – a specific case of commercial activities affecting waterbodies

Mining is a commercial activity with specific, and often pronounced, impacts on landscapes, including waterbodies. In this document, mining is considered to include all activities related to extraction of resources from the earth's subsurface. It includes ore, coal, oil and gas mining, but also mining for construction materials (e.g. gravel, sand and clay) and heat mining. Mining sites often harbour on-site processing activities such as milling of rock and extraction of the target substance. Surface-water quality impacts of mining activities include loading with acidic water, suspended solids and inorganic or organic contaminants, as well as structural damage to waterbodies.

Of all the processes that occur during mining activities, sulfide oxidation is the cause of one of the most severe pollution problems. Sulfide oxidation happens when sulfidic minerals (e.g. pyrite) are exposed to air and water. In the absence of buffering material, pyrite oxidation results in acid mine drainage, which is an extremely acidic water with pH values approaching zero or even negative values (i.e. Log of a hydronium ion concentration <1 mole/litre). Also, the water is often enriched with elements such as iron, aluminium, arsenic, cadmium, lead, mercury and uranium.

Mining can affect surface water by reshaping the landscape, including the construction of drainages and channels. Particularly in the case of open-pit mines, diversion or destruction of rivers and creeks may occur, thus changing the normal hydrological system. An open-pit mine lake remains after mining operations have ceased, and is likely to contain acid mine drainage and rising levels of sulfate, arsenic and iron, depending on the ore. In arid and semiarid areas, any open-pit mine lake that forms will be subject to intense evaporation from the open water surface.

Salinization of river water as a consequence of mining activities, especially of salt mining, is also a common problem. In addition, some operators use cyanide and mercury for the extraction of gold, potentially leading to accidents with cyanide release. Accidental spills from mine operations, transportation, storage and disposal of materials in the mining area are a further concern, particularly in the case of oil and gas extraction. Examples of surface-water pollution from mining activities are shown in Box 3.3.

Box 3.3 Surface water pollution from mining activities

Discharges from poorly managed mines and rebounding mine water in abandoned mines pose major threats to surface waters worldwide. Many kilometres of surface water have been affected by discharges that are iron-rich, often low pH and also sometimes rich in heavy metals. Similarly, watercourses have been contaminated by chemicals widely used in mining, notably cyanide.

Baia Mare goldmine (Romania, 2000)
An event at the Baia Mare goldmine in **Romania** in 2000 led to 100 000 m^3 of mud and wastewater contaminated with cyanide and heavy metals entering the Lapus, Tisza and Danube rivers, as the pollution crossed into **Hungary** and **Yugoslavia**. In total, about 800 km of river was affected (Bogo, 2000), and the aquatic environment was devastated. Because some cities (e.g. **Szolnok**) were totally dependent on river supply for drinking-water, water-supply use from the rivers was promptly suspended, affecting at least 2 million people. River cyanide concentrations measured at the Hungarian border were over 30 mg/L, far exceeding the WHO drinking-water guideline value of 0.07 mg/L. This incident was closely followed by another nearby, when more than 20 000 tonnes of sediment laden with lead, zinc, copper, aluminium and cyanide were washed from a mine near the city of Borsa, Romania. This contamination impacted the upper reach of the Tisza River, which had not been affected by the earlier event at the Baia Mare mine.

Kolontar alumina facility (Hungary, 2010)
In October 2010, a spill of about 1.65 million m^3 of red sludge occurred at the containment reservoir of the alumina plant Magyar Aluminium Zrt (MAL Zrt) in **Kolontar**. The release flooded an area of more than 1000 hectares, including large parts of three settlements in the catchment of Brook Tarna and Marcal (tributaries of the Danube). It affected over 8000 residents and destroyed more than 360 houses; 10 people were killed and 242 people were injured. The caustic sludge (pH 12–14), rich in heavy metals, reached the outer drinking-water protection zone of a groundwater source that acts as drinking-water supply for some 220 000 people. Although no negative effects on drinking-water quality were identified at the time, monitoring with a special focus on heavy metals continued in order to assess risks in the medium and long term. No negative effects on the water resources were observed. The pollution was largely limited to the surface of the ground and to surface waterbodies, and did not intrude into the aquifer. Owing to successful containment interventions (i.e. construction of withholding cross-dykes, and application of gypsum and acetic acid) on the tributary Marcal, the Danube river was not affected. Large-scale remediation works to remove and dispose of sludge and replace soil helped to revive the affected area.

According to a parliamentary committee, both MAL Zrt and the environmental authorities were responsible for the event, which did not qualify as a natural disaster but rather as an industrial release caused by neglect and mismanagement. The sludge containment reservoir was overloaded, and this situation was further aggravated by the wet weather of the preceding months. The committee found that the environmental protection authority failed to exercise sufficient oversight when issuing the environmental permits, and that the authority's subsequent supervision was inadequate. An environmental fine of about € 480 million was imposed on MAL Zrt, which was deemed primarily responsible for the event.

For further information, see WHO (2010).

Both open-pit mines and underground mines may be associated with groundwater withdrawal. This in turn creates a cone of depression, significantly enlarging the zone of aeration, and leaving rocks and sediments exposed to oxygen, which may cause oxidation of sulfides and other minerals. This phenomenon may also occur with heaps or tailing piles from milling sites where minerals can be oxidized. The contaminants from mining that typically cause the most concern are summarized in Table 27.

In addition to operational mines, abandoned mines may be a threat for surface-water quality. Contamination may come from toxic waste, either from the mine site itself, or from former pits subsequently used as landfills after mining operations have ceased.

Table 27 Significant mining-related contaminants

Type of mining operation	Source of contamination	Contamination indicators	Possible contaminants of health concern
Open-pit and underground mining of base metal sulfide deposits, precious metal deposits or uranium deposits with sulfide minerals, sulfide-rich heavy mineral sands, coal deposits	Acid mine drainage from waste rock heaps and ammonium nitrate-fuel oil (AN-FO) explosive used for rock blasting	Low pH (<pH 4.5, possibly as low as pH 2) of water in springs, seeps, open cuts and streams draining from the mine site Extensive vegetation death, yellow or white salt crusts on the soil surface, pale blue cloudy appearance of surface water	Aluminium, arsenic, antimony, barium, cadmium, chromium, cobalt, fluoride, lead, mercury, molybdenum, nickel, nitrate, selenium, sulfate, uranium. Radon may be of concern where there are high uranium concentrations
Base metal and precious metal deposits	Flotation agents used to concentrate minerals from ore. The main sources of contamination are seepage from processing mills and tailings dams	—	Depends on the type of mineralization; contaminants from flotation agents of health concern include chromium, cresols, cyanide compounds, phenols and xanthates
Gold deposits	Chemicals used to extract gold from ore (cyanide and mercury), particularly from tailings dams	High pH of water (up to pH 10) when cyanide is used	Arsenic, free cyanide, weak acid dissociable cyanide, mercury
Uranium deposits	Acid leaching (especially sulfuric acid) used to extract uranium from ore	Low pH of water, high sulfate concentrations in water	Aluminium, arsenic, antimony, barium, cadmium, chromium, cobalt, fluoride, lead, mercury, molybdenum, nickel, radon, selenium, sulfate, uranium
Petroleum and natural gas	Disposal of brines associated with petroleum hydrocarbons	High salinity of water, high concentrations of hydrogen sulfide, methane or detectable hydrocarbon odours in water	Boron, fluoride, hydrocarbons, uranium

3.6.2 Checklist for assessing pollution risk from commerce, industry, mining and military sites

Checklist 7 provides guidance on factors to consider when evaluating issues related to commercial, industrial, mining and military activities in the catchment, in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

Checklist 7 Assessing pollution risk from commercial, industrial, mining and military activities

What potentially contaminating commercial, industrial, mining and military activities are present in the catchment?

☑ Compile an inventory of currently operating as well as abandoned industrial and mining sites, commercial facilities and disposal areas, and military sites, including information on the scale of activities

☑ If an inventory of small-scale enterprise is not possible due to limited information (e.g. not registered), estimate the numbers of, for example, tanneries, slaughterhouses, and metal and car repair workshops, and the hazardous materials they typically deal with, including their wastes that could contaminate surface water through direct run-off or via sewers

☑ For active and former operations, compile an inventory of permits for discharging effluents to watercourses, sewers, soils or injection wells (including predisposal treatment if known)

☑ For active operations, compile an inventory of goods currently produced and raw materials needed for their production (including potentially hazardous degradation products, if known), amounts, and locations of storage and handling

Checklist 7 **Assessing pollution risk from commercial, industrial, mining and military activities** (continued)

What potentially contaminating commercial, industrial, mining and military activities are present in the catchment? (continued)

☑ For former operations, compile whatever information is available to assess whether the site is likely to leach hazardous substances to a watercourse (e.g. type of former activities, materials handled and produced, time of operation, information from contaminated sites' registers)

☑ Compile information on how raw materials are transported to the facility

☑ Compile information on storage and transport of potentially hazardous products and wastes –also refer to Section 3.7 on traffic for the transportation of hazardous substances

☑ Compile an inventory of current and former number, size, type, age and contents of pipelines, storage tanks, oil-containing machinery, storage ponds, lagoons and tanks for liquids, including subsurface structures

☑ Estimate the amount of local groundwater and surface water withdrawn by local enterprises and industries, including uses if they are known (e.g. process water and cooling water), condition of water discharged subsequently, and receiving waterbody

☑ Check data about past accidents (e.g. fires, explosions and spillages), and storage and handling areas, which may have left potential "hot spots" of contamination that could migrate to surface waters

☑ Check whether information is available on soil, sediment and (ground)water contamination in the area, particularly for persistent chemicals

☑ Compile information on past and ongoing soil and groundwater remediation activities at the site and in the vicinity.

How well are the facilities and installations designed and maintained?

☑ Assess scale, age, construction and technical condition of production sites, mining operations and (where possible) military bases with respect to potential surface-water impacts (e.g. pavement, roofing of storage and handling areas, collection of surface drainage and mine damage)

☑ For mines, analyse water quality of drainage systems, including run-off from milling sites, heaps, piles and tailing ponds, particularly for pH and metal content; check whether heaps and tailings are capped to reduce leaching

☑ Check existence and condition of containment structures, and monitoring of their integrity for storage, tanks, pipelines, production, and transportation of hazardous goods and materials

☑ Check appropriateness of materials and structures used for chemicals storage

☑ Identify existence and applicability of written maintenance plans for the facility

☑ Compile information on how raw materials are transported to the facility

☑ Compile information on transport of potentially hazardous products and wastes off-site from the facility

☑ Is wastewater generated at the site treated before its release to surface waterbodies (e.g. oil or grease separators)? (see also Checklist 6 on assessing pollution risk from wastewater and stormwater effluents)

☑ Are standard operating procedures (SOPs) in place for handling hazardous substances?

Are good management practices implemented at individual facilities to protect surface-water resources?

☑ Check availability and implementation of environmental management concepts (eco-audits), and potential incorporation of health aspects

☑ Check whether there are audits for verification of best management practices, operational precautions and closure plans

☑ Check whether there is accounting for materials brought in, materials processed, wastes requiring disposal and long-term closure procedures

☑ Check availability and implementation of waste management concepts

☑ Evaluate whether there is clear definition of responsibility in written form for dealing with emergency releases

☑ Check whether there are developments towards recycling of water and reducing water demand

☑ Check for indications of episodic releases that have accumulated contaminants over time in soils, sediments, basins, etc.

Checklist 7 Assessing pollution risk from commercial, industrial, mining and military activities (continued)

Are side-effects of production processes or activities potentially relevant to contamination of surface-water resources?

☑ Identify characteristics of activities at the facility such as vehicular traffic, vehicle cleaning, power production, water withdrawal or treatment, and grounds maintenance

☑ Check type of grounds maintenance and use of chemicals (e.g. fertilizers for lawns)

☑ Evaluate sanitation systems present at the premises

☑ Evaluate emission of substances that act as co-solvents (e.g. fuels, acids) and are likely to mobilize other hazardous chemicals in the environment

☑ Identify construction activities on industrial sites that may physically affect surface or subsurface drainage to the waterbody, or cause hazardous emissions

☑ Consider whether groundwater abstractions (e.g. in the case of construction activities) may include contaminated groundwater or lead to mobilization of contamination, affecting surface waterbodies due to subsequent discharge

☑ Ascertain whether water treatment operations are conducted on-site, which may result in releases of chemicals (e.g. chlorine, flocculants and pH controls)

☑ Check whether firefighting training is conducted

☑ Refer to respective sections if relevant additional activities have been identified.

3.6.3 Examples of hazardous events and control measures for commerce, industry, mining and military sites

The hazards typically reaching surface waterbodies from commerce, industry, mining and military sites are introduced through common hazardous events such as:

- direct discharge to surface water (permitted or unpermitted) – including leachate from mining activities, run-off from contaminated soils, or water from facilities or surrounding areas;
- indirect discharge or seepage – for example, large-volume, short-term or catastrophic releases such as failure of lagoon dykes; and
- continuous small spills or other releases – for example, due to improper storage and handling practices.

Heavy rainfall can exacerbate transport of the hazards into surface waterbodies or within those waterbodies to the offtake point for drinking-water supplies.

During recent decades, substantial progress has been made in many countries towards reducing the environmental impacts of commercial and industrial activities of all sizes, but particularly of large-scale industrial operations. Many production technologies now use closed-circuit systems for cooling water, and process water rather than discharging it with contaminants. Hazardous chemicals are replaced by less hazardous ones wherever possible, and where this is not possible, containment has become safer and reuse has been established. Process-control and leak-monitoring systems have become widespread. Rigorous practices for the management of chemicals and wastes have been shown to provide an excellent organizational structure for controlling raw material and waste. Some approaches have both engineering implications (process design) and administrative elements (modification of employee practices). These approaches include substituting hazardous process chemicals with ones that are less hazardous, collecting and treating waste before discharge, and developing a recycling plan. Effective strategies to prevent contamination include:

- simple, often low-cost approaches, such as run-on and run-off controls (e.g. capping or covering hazardous waste sites to prevent leaching by precipitation; and the use of berms, swales and holding ponds);
- secondary containment structures around tanks;
- physical separation to reduce chemical reactions;

- chemical methods for contaminant control or remediation (e.g. oxidation, aeration or reduction); and
- capture of residues and surface run-off in properly designed and constructed holding areas before treatment.

Release can also be prevented or reduced by neutralizing, encapsulating or stabilizing contaminants, or by adding solidifying materials (e.g. process wastes, soils and sludges). Thus, improved production procedures such as closed water cycles tend to be linked to improved safety and health protection, and such upgrades have often resulted in a "win-win situation". Engineering and design changes (e.g. modernization of existing facilities) that may initially have been assessed as being too extensive and costly have often proven economically justified. This is not only because of the decreased risk and cost of environmental and human health impacts, but also because modernization for cleaner production usually goes hand in hand with increasing the efficiency of production.

An important measure for early detection of leakage is the monitoring of loss of product (or waste material). Such monitoring can include level indicators and leak detection of tanks and other storage containers, measurement of loss of product from piping or other transfer mechanisms, and integrity testing. Resources expended in monitoring often result in reduced remedial costs in the event of a release.

The training of personnel in safety measures and the handling of hazardous materials under routine conditions, as well as in the case of spills or leaks, has proven to be critical for ensuring the ongoing safe storage, handling and disposal of process chemicals, supplies and waste materials. Developing and implementing policies and procedures in collaboration with the staff responsible can contribute substantially to avoiding contaminated effluent, even where major investments are not immediately feasible.

Controlling releases from previous contamination

Even after improving practices in the production, transport and containment of hazardous chemicals, historical contamination can continue to reach waterbodies, and clean-up of such sites may be a major challenge. Where there is indication of such contamination, it is important to assess the magnitude of the environmental health risk they pose, including the potential for the contamination of water to which people are exposed. Information about the type of production that has occurred at the specific site is helpful, in order to estimate which contaminants of health concern are likely to be present. This provides a basis for developing screening programmes to detect hazards, since the choice of analytical methods depends on the types of chemicals sought. Without some idea of what to look for, screening programmes can miss crucial substances. Also, historical environmental data may be available for the facility, for adjacent facilities or for the region in which the facility is located, and those data can inform the planning process.

If contamination has reached soil, groundwater or surface water, a variety of in situ or ex situ methods can be used for remediation. Such methods include thermal and chemical treatments, biological remediation technologies, immobilization of contamination, soil washing, and filtration with activated carbon or synthetic polymers. The use of wetlands (either naturally occurring or constructed) is common throughout the world in more or less sophisticated forms for the capture of inorganic and organic chemicals. Such biological control may increase degradation of some organic contaminants, and reduce the mobility of inorganics. Maintenance and operation costs of such systems are lower than typical engineered systems over their relative operation times.

Remediation methods have some disadvantages. They often require the handling of large volumes of waste, contaminated water and soils; may extend over considerable timeframes; and may be costly. The priority of investments in site clean-up may depend on the use of affected waterbodies as drinking-water sources, the availability of alternatives for drinking-water supply, and other motivations such as intended uses of the site (e.g. for housing or recreation) or clean-up for reasons of environmental protection. Setting clean-up goals requires an individual assessment of the site in relation to drinking-water supply, local conditions and other land-use criteria. Where there is no immediate pressure to use a contaminated site, a decision from such an assessment may be to keep the contaminated site under control (e.g. implement regular monitoring of potential contamination of groundwater leaving the site) in the short term and delay the costs of remediation.

Table 28 provides examples of hazardous events related to commerce, industry, mining and military activities, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

Table 28 Examples of hazardous events for commercial enterprises, industry, mining or military sites, control measures and options for their monitoring

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Industrial developments in vulnerable zone in proximity to waterbody have, for example, potential for transport of chemical contaminants to surface water as a result of inappropriate storage of hazardous materials, containment, waste management, spills and accidents (C, P)	Require specific permits for discharge of commer¬cial or industrial wastewater to watercourses or sewers, specified for the contaminants it contains Require permits for the location, design and operation of industries, manufacturing enterprises, mining and military sites. Evaluate individual proposed sites in the context of industry-specific contamination risk Develop long-range comprehensive planning and zoning Regulate requirements for safe design and operations in relation to type of production If drinking-water protection zones are designated, enforce keeping industrial activities with hazardous substances out of them, or only allow in outer zones	Review applications for permits; conduct unannounced effluent controls (including sampling and chemical analysis for selected chemicals) Review applications for permit with respect to adequacy of siting, planning and design as well as public consultation Conduct inspections at irregular intervals for evaluating compliance to regulations and permit requirements
	Lack of effective clean-up programme following decommissioning of industrial site, military site or mine due to lack of funding (C)	For enterprises with substantial pollution risk, require financial commitment for future clean-up	Inspect financial reserves (deposits) for this commitment
Design and construction	Leaching of contaminants from inappropriate storage facilities (C)	For storage and handling of hazardous chemicals, explosives, mine heaps, tailings and ponds, install and maintain impermeable surfaces and temporary or permanent containment structures (tanks, caps, vaults) and roofing; ensure materials used are appropriate for the substances stored	Review adequacy of design and compliance with plans and regulations Inspect sites and enterprises for compliance with plans and regulations, and for structural integrity and functioning Review regular integrity testing of surfaces, sealings, tanks and pipes, and perform regular maintenance of these constructions Review documentation on potential loss of materials/ hazardous chemicals
	Contaminant run-off or leaching from lack of on-site remediation of contaminated matrices (C)	Remove or remediate contaminated soil and/ or groundwater Refill mine tunnels and shafts; remove/ stabilize potential contaminants; remove contaminants (e.g. fuel oil) from machinery before refilling Rehabilitate old heaps and tailings; treat leachate	Analyse residual soil and groundwater samples Conduct follow-up site inspection and monitoring

Table 28 Examples of hazardous events for commercial enterprises, industry, mining or military sites, control measures and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Operation and maintenance	Chemical contamination from inappropriate management of recalcitrant, mobile and toxic substances (C)	Control/restrict amounts and types of chemicals used in production processes and mining operations; encourage replacement with lower-risk chemicals	Review records/reports of chemical use, storage and removal of wastes and maintenance of systems Analyse in situ leachate for chemical concentrations Review chemicals inventory
	Regular spills of hazards due to inappropriate handling (C)	Develop SOPs for handling hazardous chemicals, and perform regular training for those involved in these activities	Inspect compliance to codes of practice and SOPs Check training records
	Hazardous spill during chemical/waste transportation and handling (C)	Control storage, handling and disposal of high-risk chemicals and wastes	Inspect compliance to codes of practice, SOPs and/or chemical management plans; require reporting
	Direct input of untreated effluent to waterbody (C)	Treat wastewater prior to discharge to surface waterbodies	Require monitoring of wastewater discharged for specific contaminants Check if treatment is operating adequately
	Acid leachate from mining dewatering practices (C)	Minimize acid leachate from mines by controlling dewatering cone of depression	Monitor water levels, pH or sulfide in the dewatering effluent Ensure best management practices for dewatering are adopted and enforced
	Contamination of groundwater from inappropriate waste management practices (with seepage into surface water) (C)	Treat contaminated groundwater from (active or closed) mining operations until contaminant concentrations reach acceptable levels prior to discharge to surface water	Monitor operational parameters for treatment system chosen (e.g. condition of artificial wetland and water flow) Analyse selected contaminants in treated water
	Leaching of contaminants over time following cessation of site activities (C)	Conduct post-operational management of sites potentially leaking hazardous substances	Include post-operational requirements as part of initial permit, and monitor compliance with requirements

SOP, standard operating procedure

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

Box 3.4 Environmental audits

Appropriate management practices that prevent hazards to surface water from commercial and industrial facilities, mining or military activities can be mere theory. Environmental auditing is needed to demonstrate that the industrial processes are adequate for their purpose, are in place and are working. Environmental and regulatory compliance audits are common practice in industrial and commercial settings under international programmes of environmental management and consumer product safety, such as ISO 14000 (Fredericks & McCallum, 1995; ISO, 2001). Although these audits target environmental protection and do not directly address risks to human health, they concern many areas relevant to protection of water resources. Thus, where such systems are effectively implemented, health protection typically benefits substantially (see Chapter 1).

In addition to outlining processes and procedures for routine operations, environmental and regulatory compliance audits include the development and maintenance of chemical contingency plans (i.e. "emergency response plans") for quick responses to small- and large-scale releases of hazardous agents. For example, the guidelines for the preparation and inspection of a safety report were developed under the UNECE convention on the transboundary effects of industrial accidents and the EU Directive 96/82/EC. The guidelines provide checklists for practical implementation of safety reports (UNECE, 2012). Regular auditing of a facility keeps management and staff "on track" in understanding their system, its hazards and its controls. This practice can be effective in reducing pollution from commercial and industrial operations.

3.7 Traffic

Transport activities potentially releasing hazardous chemicals or microorganisms (or both) include road traffic, railway lines, air traffic, inland waterway transport (rivers, lakes and canals) and the transport of liquids (particularly crude oil and oil derivatives) in pipelines. Hazards from these different types of transport include contamination with faecal matter, leakage and accidental spill of hydrocarbons and other chemicals, use of pesticides along traffic lines (particularly railways and sometimes roadsides) and de-icing (Table 29).

An important factor for the potential of traffic to pose a pollution risk is the extent to which containment technologies are used in the region, and if so, whether they are in good condition. Examples of such technologies are sewage tanks on boats and trains, and surface seals and drainage on petrol stations. Where release does occur, as for all hazards from activities on land, the extent to which hazards reach a surface waterbody depends on the hydrological conditions in the catchment, as discussed in Section 2.2. Shipping is different in that hazards released reach waterbodies directly and thus entirely.

Table 29 Common types of hazards that may reach surface water from different types of transportation

	Hazard type				
Transportation mode	**Faecal matter**	**Hydrocarbons[a]**	**Hazardous chemicals from accidental spills**	**Pesticides**	**De-icing[b]**
Roads	●	●	●	●	●
Railway	●	●	●	●	●
Air traffic	●	●	●	●	●
Inland waterways	●	●	●	●	
Pipelines	●	●	●		

[a] From leakages as well as from refuelling, washing and workshop activities; may also include other chemicals potentially.
[b] Only in countries with corresponding climate conditions.

The most severe impact from traffic to surface water is through direct discharges; for example, accidents and wash-off from sealed areas such as roads. Contamination may also occur during construction of traffic settings, from oil and gas from construction machines, chemicals used during the construction work, the use of hazardous construction materials, and faecal matter from workers' temporary premises. Maintenance of roads, railway lines and airports is a further activity that has the potential to introduce specific hazards.

The volume of traffic has a significant influence on the quantity and type of traffic-related pollution. Average daily traffic volume is an appropriate criterion for classifying roads in categories with different levels of potential pollution risk. For road traffic, Golwer (1991) proposes a classification of risk ranging from fewer than 2000 vehicles to more than 15 000 vehicles per day. Similar classification or risk ranges may be estimated for railway, boat and air traffic.

3.7.1 Traffic activities that may affect surface-water quality

Sanitary facilities

Sanitary facilities on trains are generally operated as either open defaecation latrines or holding tanks. In many countries, open defaecation latrines are still used, and no precaution is taken except prohibiting the use of open defaecation facilities while the train is stopped at a railway station. Thus, surface water can readily be contaminated from this source, with pathogens being the most dangerous component if the railway tracks are close to or actually cross rivers and streams.

Roads with heavy traffic often do not have sanitary facilities at parking lots, resulting in uncontrolled open defaecation with the potential consequences for rivers and creeks in the vicinity as those described above. Where holiday travel with camping vehicles is widespread and facilities for emptying wastewater tanks are lacking, illicit emptying as well as open defaecation may be a significant source of faecal pollution where parking is close to waterbodies.

Inland waterways and lakes are subject to traffic, with both sport boats (e.g. sailing boats and motor boats) and commercial boats. If commercial boats do not have sufficiently well-managed holding tanks for sewage, or harbours do not provide readily accessible facilities to empty them, illicit emptying into harbour areas may be a further source of contamination. More details on recreational motor boats are given in Section 3.8. Hazards from wastewater and stormwater are addressed in more detail in Section 3.5. Guidance on safe sanitation on ships, including on risks to health related to waste management and disposal, and possible measures for safe management is available from WHO (2011a), as is information on the inspection of ships, including sanitation aspects (WHO, 2011b).

Emissions from vehicles and transport routes

Many minor and dispersed leakages and releases from vehicles (e.g. fuels, oil and hydraulic fluids [oils] from hydraulic systems such as brakes) to surface water may accumulate to cause substantial pollution in surface run-off. Hydraulic fluids may contain PCBs that have a carcinogenic potential. Tyres and brakes are abraded with use, releasing, for example, rubber and metals to the environment. These hazardous substances can be transported to surface waterbodies directly via precipitation run-off, or they may be sorbed to asphalt on roads and runways, and to gravel and sleepers in railway tracks. In particular, sleepers made of wood have high sorption capacities and may contain wood preservatives (e.g. pentachlorophenol) and tar (i.e. PAHs). When roads, runways and railway lines are demolished, the dismantled construction materials contain significant amounts of toxic substances, threatening surface waterbodies if the materials are not properly disposed of.

Agrochemicals are used for maintaining roads, railway tracks, airfields and, to some extent, inland waterways. The quantity of herbicides used to keep traffic lines free from vegetation may be higher than in agriculture. Thus, herbicides can easily enter surface water through the drainage systems (Schweinsberg et al., 1999) – a situation that is frequently unrecognized due to a lack of investigations.

The most frequent traffic-related contaminants are oil and gasoline, including additives such as lead (dimethyllead) and methyl tertiary-butyl ether (MTBE). The contaminants released to air include combustion compounds such as carbon dioxide, sulfur dioxide, nitrogen oxides (NO_x), PAHs, dioxines and other hazardous constituents (e.g. lead and MTBE). These contaminants may be washed via rainwater from the air into soil and surface waterbodies. Flood flows, which frequently occur in the vicinity of rivers, may wash contaminants from roads and railway lines into surface waterbodies. Also, where roads are unpaved, erosion can be a significant pathway for hazards sorbed to particles to reach waterbodies. Vehicle traffic directly through fords in shallow river sections introduces oil, gasoline and the above-mentioned contaminants directly into the water.

The coatings used for both sport boats and cargo ships may contain highly toxic substances. Tributyltin (TBT) and other organotins have been added to ship paints since the 1970s, because their toxicity prevents algae and other aquatic organisms from attaching to the surfaces, and they are still widely used. For more details on motor-boating, refer to Section 3.8.

Refuelling, repair workshops, washing facilities

Fuel stations for vehicles and kerosene storage at airports represent a hazard because large amounts of fuels are stored and refilled at these sites. These substances may be released due to insufficient integrity of tanks (e.g. corrosion) and surfaces on which fuelling takes place, as well as improper handling during refilling of tanks, vehicles and planes. Spills may happen during refilling operations on land and in marinas. Leakages from fuelling operations on land may reach receiving surface waterbodies through migration from soil and groundwater, or directly when washed off by rainwater.

Workshops where vehicles are maintained and repaired handle large amounts of oil, lubricants, organic solvents (for cleaning purposes) and, sometimes, varnish. Workshops are often present in the vicinity of fuel stations. The risks are similar to those from washing facilities for vehicles (e.g. cars, trucks, railway coaches, locomotives and aircrafts). Effluent water from car-washing facilities contains significant amounts of fuel and oil, particularly if engines are washed and treatment (at least by an oil separator) is poor or lacking. Washing with organic solvents (which is common for aircraft) may release substantial amounts of solvents if there is poor management of the waste. Washing of cars and trucks in rivers and streams introduces contaminants directly, without any possibility of contaminants being retained in the ground. Spills during oil-changing for cars and trucks are a further source of potential surface-water contamination. Flooding of fuel depots, refuelling stations and workshops may result in severe contamination of stormwater.

Accidental spills of hazardous chemicals

Spills of hazardous chemicals may also occur during transport accidents. The contamination risk then depends on the location of the accident, the drainage system in place, the geological setting, the robustness of the containment of the chemicals in the vehicle, the type and amount of substances spilled, and the emergency response planning in place. Even though illegal in many countries, discharge of liquid and solid waste from trucks into rivers and streams may still be a frequent practice. Transportation of hazardous substances by boat via waterways may lead to direct surface-water contamination in case of accidents or leakages.

De-icing

Thawing agents are used to de-ice roads, runways and airport taxiways, and vehicles (mainly aircraft). Sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) or calcium chloride ($CaCl_2$) are used for different ranges of temperatures to de-ice roads. These chlorides are not significant for human health at the concentrations that de-icing may cause in affected waterbodies, but may have an impact on aquatic ecosystems. Hence, alternatives to the chlorides are increasingly sought; possible alternatives include the use of sand or, where possible, geothermal heating of roads and bridges. Long-term observations of chloride from human activities in some surface waterbodies indicate that, over time, levels of 250 mg/L were reached. Such high levels would exclude or impede these waterbodies from being used as raw water for drinking-water production (because the water would corrode pipes), and may be an upper precautionary limit for individuals at risk of coronary heart disease.

Common de-icing chemicals for aircraft are ethylene glycol, propylene glycol, calcium magnesium acetate, potassium acetate and urea. All are very hydrophilic and, if not contained, they may easily enter groundwater and drinking-water sources. Once there, they support either salinization or undesired microbial growth (by acting as an easily exploitable source of carbon). However, glycols are readily biodegradable and can be disposed of in municipal treatment plants in sludge digesters to produce methane (Zitomer et al., 2008).

Nitrogenous de-icing agents (e.g. urea) have been used in airports since the mid-1970s, potentially leading to contamination with ammonia, nitrite, nitrate or ammonium as degradation products, and in some cases increasing eutrophication of surface water. Therefore, in the 1990s, sodium and potassium acetates and formates began to replace nitrogenous agents.

3.7.2 Checklist for assessing potential pollution from traffic activities

Checklist 8 provides guidance on factors to consider when evaluating issues related to traffic in the catchment, in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

In addition, parts of the Checklist 6 (in Section 3.5.2) regarding sanitation and stormwater run-off and treatment are relevant to run-off from sealed traffic areas.

Checklist 8 Assessing pollution risk from traffic activities

What information is available about traffic?

☑ Compile an inventory of main types of traffic and location of main traffic routes

☑ Compile an inventory of substances, potentially hazardous products and wastes, and wastewater – including their amounts – currently transported via these traffic routes

☑ Evaluate siting, design, construction and technical condition of individual traffic routes in relation to physical, topographic and geological conditions in the surface-water drainage basin

☑ Check data about past accidents (e.g. fires, explosions and spillages) that may have left potential "hot spots" of contamination that can migrate to surface waters

☑ Check potentially conducted environmental impact assessment (EIA) documentation for traffic routes

☑ Check inventory of hazardous paints allowed on boats (e.g. mono-, di- and tributyltin)

☑ Check whether a transport risk information system (TRIS) is in place, including geological and hydrological issues; release prevention and remediation measures in combination with classification of hazardous chemicals

☑ Check whether wooden sleepers containing preservatives are present on railway tracks

☑ Check whether agrochemicals are used for maintaining roads, railway tracks, airfields and inland waterways

☑ Check whether mechanical maintenance measures are used alternatively

☑ Identify location and ownership of pipelines (e.g. substances hazardous to water such as oil, and wastewater).

How well are the traffic routes maintained?

☑ Evaluate age, construction and technical condition of traffic routes with respect to potential surface-water impacts (e.g. integrity of road surfaces, integrity of vehicles and tankers, collection of surface drainage)

☑ Identify existence and applicability of written maintenance plans for the facilities

☑ Check whether surface run-off from the traffic routes is collected and treated before release to surface waterbodies

☑ Check whether standard operating procedures (SOPs) are in place for transportation of substances hazardous to water

☑ Check location, extent, condition and integrity of storage facilities (e.g. fuel storages, storages of de-icing agents and oil storages)

☑ Check condition of maintenance workshops with respect to release of hazards with surface run-off

☑ Check existence and condition of containment structures and monitoring of their integrity for storage, tanks, pipelines, and production and transportation of materials and substances hazardous to water and human health

☑ Check whether there are records of the technical and environmental safety of vehicles, particularly those transporting substances hazardous to water

☑ Assess whether the number of disposal stations of septic tanks of boats navigating on inland watercourses is sufficient, and whether the management of these excreta-receiving stations is appropriate.

Are good management practices implemented to protect surface-water resources?

☑ Check whether there are audits for verification of best management practices and operational precautions for transportation and storage of hazardous substances

☑ Check whether safe handling procedures are in place for fuel storages, storages of de-icing agents, and oil storages

☑ Evaluate whether there is a clear definition of responsibility in written form for dealing with emergency releases

☑ Identify whether direct accidental spills have been reported

☑ Check whether septic tanks are required and in place for trains and boats

☑ Check what type of accident prevention measures are in place (e.g. speed limits on roads in drinking-water protection areas or catchments, regulation of working and rest times for truck drivers).

Checklist 8 **Assessing pollution risk from traffic activities** (continued)

Which maintenance and fuelling processes are relevant?

☑ Check whether de-icing of surfaces and planes is conducted

☑ Assess management of drainage and treatment systems to avoid spills of de-icing agents into surface waterbodies

☑ Identify current vehicle cleaning, fuelling and grounds maintenance characteristics in the catchment

☑ Check for former vehicle cleaning and fuelling sites in the catchment that may still be leaching hazards to the waterbody

☑ Check type of grounds maintenance, use and storage of chemicals

☑ Identify construction activities for traffic routes that may physically affect conduits to surface water or cause contaminant emissions.

3.7.3 Examples of hazardous events and control measures for traffic activities

The hazards typically reaching surface waterbodies from traffic are introduced through hazardous events such as:

- direct discharge to surface waterbodies – for example, from open defaecation latrines in transportation crossing rivers or from biocidal coatings on boats;
- leakages and accidental spills – particularly in the case of improper storage and handling of fuel and the application of pesticides to traffic lines; and
- traffic accidents – these can introduce major amounts of fuel or hazardous goods (if these are being transported) into the surface waterbody.

Heavy rainfall can exacerbate transport of hazards into surface waterbodies, particularly through wash-off from sealed areas such as roads or erosion from unpaved roads.

Table 30 provides examples of hazardous events related to traffic, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

Table 30 **Examples of hazardous events for traffic, control measures and options for their monitoring**

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Traffic-related developments in vulnerable zone in proximity to waterbody (e.g. contaminated run-off from vehicle emissions to waterbody) (M, C)	Planning siting of new or expansion of existing traffic lines and facilities in relation to vulnerability of drinking-water catchments including, for example, choice of materials and mode of construction, run-off collection, restriction of substances used in maintenance	Review plans with respect to the vulnerability and protection of drinking-water catchments
	Chemical spill to waterbody (C)	Develop accident response plans in drinking-water catchments for releases of fuel or hazardous substances including lines of communication, immediate and subsequent measures	Require approval, and possibly audit, of accident response plans by public authority responsible
		Require that substances hazardous to water are only transported by vehicles with the appropriate containment and safety measures	Require regular testing of integrity of vehicles transporting substances hazardous to water

Table 30 Examples of hazardous events for traffic, control measures and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Design and construction	Contamination of waterbody from hazardous substances and inappropriate waste management practices during road construction (M, C, P)	Collect and adequately dispose wastes and wastewater during construction Require appropriate storage of hazardous substances, including during construction phase	Review adequacy of design and compliance with plans and regulations Inspect sites regularly during construction
	Contaminated run-off from vehicle emissions to waterbody (C)	Install protective structures that minimize surface-water pollution through routine traffic and accidents; for example, run-off collection, impermeable surface barriers, bunding of fuel tanks (i.e. constructing retaining wall around tanks), crash barriers, retention and settling ponds, oil separators, treatment facilities for run-off, treatment of wastewater from washing or cleaning facilities for vehicles Install specific protective structures for refuelling and vehicle maintenance stations (e.g. containment, drainage, oil separators)	Review adequacy of design and compliance with plans and regulations Inspect sites regularly during construction Assess integrity of containments
	Improper sewage disposal from transportation users (e.g. from trains, busses, boats, ships, camping vehicles and individual vehicles) (M, C, P)	Install terminal reception facilities for sewage collection Provide sufficient sanitary facilities according to the traffic density to avoid open defaecation	Review adequacy of design and compliance with plans and regulations Assess integrity of collection facilities Check whether indications of open defaecation are present
Operation and maintenance	Chemical contamination from lack of infrastructure maintenance (e.g. drainage channels, retention/settling ponds, road surfaces) (C)	Maintain protective structures that minimize surface-water pollution from traffic; for example, keep run-off drainage clear of obstacles, remove sludge from retention/settling ponds, repair sealed surfaces when damaged	Inspect integrity of structures and test functioning at regular intervals
	Improper sewage disposal from transportation users (M, C, P)	Collect and adequately dispose wastewater from vehicles, terminal reception facilities, toilets; provide and maintain sanitary facilities	Inspect records for maintenance activities Regularly inspect integrity of containments (leak monitoring systems) Regularly monitor fuel amounts delivered, stored and supplied; action plan to follow up discrepancies indicating losses
	Leak from fuel storage facility (C)	Maintain tanks and pipelines for fuel (e.g. kerosene, diesel, gasoline) and have secondary containment in place	Inspect records for maintenance activities Regularly inspect integrity of containments (leak monitoring systems) Regularly monitor fuel amounts delivered, stored and supplied; action plan to follow up discrepancies indicating losses
		Devise and conduct regular staff training programmes in monitoring and maintenance procedures, such as to ensure early detection of leaks	Audit the number of staff trained and the frequency of that training Conduct regular checks of the efficacy of the training by testing staff response to a range of simulated scenarios Review staff performance during both simulated and real situations and modify the training if necessary

Table 30 Examples of hazardous events for traffic, control measures and options for their monitoring (continued)

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Operation and maintenance	Run-off following application of hazardous compound for traffic line maintenance (C)	Control amounts and types of chemicals used for maintenance of traffic lines (e.g. de-icing agents, herbicides)	Inspect records of chemical consumption, devices for use, storage of chemicals
	Chemical spill following traffic accident adjacent to waterbody (C)	Control traffic through protected drinking-water catchments to implement restrictions on the transport of substances hazardous to water as well as speed limits and bans on overtaking	Inspect loads on lorries; inspect records for traffic controls; inspect presence of related street signs

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

3.8 Recreational activities

Recreational activities may range from low-impact ones such as walking or hiking in the catchment or along a shoreline, to high-impact activities such as powerboating or jet-skiing. For other activities, the impact will depend on the number of people and animals in relation to the size and vulnerability of the waterbody; such activities include swimming, dog walking, rowing, canoeing, sailboarding or sailing. Waterborne disease outbreaks known to be explicitly associated with recreation in drinking-water sources are relatively rare, and recreational activities are often not a major source of contamination. Nevertheless, the impact of recreational activities through both direct and indirect mechanisms may be relevant in some settings, and such activities may be banned from drinking-water reservoirs as a matter of principle. A ban on activities may be challenged by pressures for opening the waterbodies to at least some recreational use; for example, to increase tourism. Where forbidden, activities may occur despite the ban, raising the question of how much effort is required for enforcement.

Policies on permitting recreation in drinking-water catchments and reservoirs vary widely. They are rarely based on risk assessments; rather, they tend to be based on attitudes developed historically in relation to other established land uses. It is therefore useful to include recreational activities in a risk assessment. The aim is not necessarily to identify yet another major problem, but rather to achieve a justified assessment, possibly with the result of accepting certain recreational uses.

The major direct impact of recreational access in drinking-water catchments is likely to be the contamination of water supplies with human pathogens – particularly with infectious, enteric faecal–oral pathogens. People conducting recreational activities may in turn also accidentally drink water, and thereby ingest pathogens, or be exposed to pathogens through dermal contact. Poor hygiene (e.g. inadequate disposal of faeces) or faecal accidents (particularly from people infected with diarrhoea) can lead to a range of viral, bacterial and protozoan pathogens entering the drinking-water resource. Many epidemiological studies show that there is an increase in the incidence of viral infections in immunocompromised individuals or people participating in recreational activities in both marine water and freshwater. These infections include gastrointestinal, respiratory, ear, eye and skin infections, and other more serious infections with high morbidity and mortality, such as meningitis, encephalitis and paralysis (Okoh, Sibanda & Gusha, 2010, cited in Sabino et al. 2014; Sinclair, Jones & Gerba, 2009). Humans may also contribute to the amplification of zoonotic pathogens, because some of the pathogens they introduce to the environment may infect wildlife, amplify and spread. Thus, for example, the presence of faecal pathogens from terrestrial animals in marine waters and filter-feeding shellfish has been documented (Shapiro et al., 2010). There have been reports of infections and deaths in aquatic wildlife and humans who became exposed to these parasites, either through recreational activities or consumption of seafood (Sabino et al., 2014).

The number of pathogens introduced per person immersed during water-sports depends greatly on the health status of those using the waterbody; that is, on the pathogens they carry, as well as on their immune status. For microorganisms on the body surface (the skin), an estimate of about 600 million microorganisms per person may be used (Tiefenbrunner, 2002); however, these include all microorganisms, and most of these will be nonpathogenic. People swimming with open wounds will introduce larger numbers of pathogens. Saliva introduces about 20–400 million microorganisms, and the amount of intestinal microorganisms introduced from people's anal regions depends to a large extent on personal hygiene – an estimate of 100 billion microorganisms/g faecal matter is frequently used (Tiefenbrunner, 2002). Again, the actual proportion of pathogens will depend on infections carried by bathers. Other direct effects include chemical pollution, most frequently hydrocarbons from motor boats.

Indirect effects include damage to the vegetation cover around the water as well as to emerging and submersed aquatic plants, all of which act as natural filters. The erosion of shorelines facilitates contaminant transport from the surrounding terrain into the water. Increased turbidity as well as elevated nutrient concentrations (often a consequence of erosion rather than being directly from human faeces) increase the risk of nuisance algae or cyanotoxins. If activity occurs throughout the year, the waterbody and shoreline have less time to recover from polluting and damaging effects, making them more vulnerable. Considerations necessary for the analysis of hazards and hazardous events from recreational activities and to inform management decisions include:

- accessibility of the waterbody, intensity of its use, types of activities, and their respective extent, frequency and seasonal patterns;
- the sites of physical structures supporting recreational activities (e.g. designated beach areas, cabins for changing clothes, booths and restaurants);
- the combined effects of all the activities in relation to the capacity of the environment to absorb their impacts or to remediate them between seasons; and
- specific monitoring of microbiological and physico-chemical parameters, chosen in relation to the type and intensity of activities being undertaken.

3.8.1 Recreational activities that may affect surface-water quality

Contamination from land-based activities and activities with humans' direct contact with the waterbody

The presence of humans near reservoirs can lead to occasional faecal deposition at locations where rain would transport the faeces into the reservoir. Human faeces can contaminate drinking-water sources from direct defaecation into raw water for drinking-water supplies, whether the event be accidental, deliberate, ignorant, negligent or malicious. Accidental faecal releases from flatulence or diarrhoea occur particularly from children. Microbial contamination through bathing and swimming may include:

- *Salmonella* spp.
- *Shigella* spp.
- *E. coli* O157:H7
- *Campylobacter* spp.
- *Staphylococcus aureus*
- hepatitis A
- hepatitis E
- adenovirus
- norovirus
- echo virus
- *Giardia duodenalis* (ex *lamblia*)
- *Cryptosporidium parvum.*

Many recreational activities disturb soils and sediments at the shorelines, leading to erosion, abrasion, reduction of vegetation cover and a change in the gradient of the shore. In addition, increased fire frequency (e.g. from camping) may affect waterbodies through subsequent run-off.

The health risk to other site users as well as to downstream consumers will depend on transport and attenuation between the bathing site and drinking-water offtake, as well as on drinking-water treatment. Microbial contamination from recreational users of waterbodies may be roughly estimated from the number of site users (particularly for bathing), the degree of dilution and the distance of the bathing site from the drinking-water offtake. Dilution is often low in lakes and lagoons.

Motor-boating

Motor-boating, waterskiing, personal watercraft and other boating activities may affect water quality through contamination with PAHs; discharge of oil and fuel near a drinking-water offtake can render the water unpotable. Boating-related activities such as washing-down, sanding and painting, draining bilge water and refuelling can cause pollution from detergents (which contain phosphate and thus fuel algal growth), new paint, old paint scrapings, anti-foulants, solvents, oil and grease, fuels, increased turbidity, greater loading of organic matter and cleaning agents. Ship traffic in freshwater rivers may affect water quality by resuspending contaminated bottom sediment. Boat traffic and marinas with high densities of moored boats contribute considerable sources of hazards (e.g. trace metals, TBT, PCBs and PAHs) and bacteria. The coating of boats may contain highly toxic organotins that have been added to ship paints since the 1970s and are still widely used. Portable toilet effluent and some holding tank systems contain chemical additives used to disinfect, breakdown and deodorize waste. The most commonly used substances for this purpose are chlorine, formaldehyde, ammonium and zinc compounds. Vessels that do not have holding tanks, and instead discharge effluent directly to the waterbody, may pose a microbiological risk to the water quality.

Boating activities cause physical damage to emergent and floating plants and benthic organisms, with the density of aquatic macrophytes being inversely related to the amount of boating in some areas. This is indirectly relevant to drinking-water quality, because macrophytes enhance water clarity and quality. Physical impacts of boating include wave action from powerboating, which damages banks and shorelines, increasing erosion. In shallow waterbodies, the movement of boats through water can disturb the bed of the waterbody, either through direct contact or through the effect of turbulence created by the vessel's passage, the propeller or water jet. This resuspends fine sediments from the bottom of the waterbody, causing turbidity and potentially mobilization of contaminants in the sediments.

Physical infrastructures to facilitate water-based recreation include formal and informal parking areas and boat launch sites, mooring provisions, marinas, boatyards and yacht clubs. Water-quality changes mainly arise from the development of facilities that require extensive in-water infrastructure, particularly in the form of artificial fixed breakwaters. Boat-launching facilities also introduce road grime and other contaminants to the water column from trailers. The repeated backing up of towing vehicles into the water has the potential to introduce grease and oil to water supplies. Bilges are often drained before towing, typically at ramp sites, and sewage and other materials associated with boat and shipyard maintenance may be discharged into the water. For further details on hazards from traffic, see Section 3.7.

Fishing

Anglers may cause bank erosion and water pollution. Shoreline fishing may affect water quality as a result of:

- line dragging and wading, which promote increased sediment resuspension and possibly nutrient flux to the water column;
- organic bait, which adds a nutrient load to the surface waterbody and thus attracts water fowl that potentially carry pathogens;
- live bait (e.g. carp), which could destroy macrophyte beds and increase wave-induced sediment resuspension and nutrient flux;
- litter and rubbish on foreshore and in the water; and
- walking on the shoreline, which causes erosion.

3.8.2 Checklist for assessing pollution risk from recreational activities

Checklist 9 provides guidance on factors to consider when evaluating issues related to recreation in the catchment in order to collect information as a basis for risk assessment. The checklist contains aspects to look for when inspecting the catchment; data to collect before, during and after the inspection; and suggestions for assessing the information obtained. The introductory pages of Section 3.2 explain how to use this checklist in the context of a system assessment.

Checklist 9 Assessing pollution risk from recreational activities

What recreational activities are currently taking place?

- ☑ Is recreational use of the waterbody or surrounding land permitted?
- ☑ What activities are encouraged and formally recognised?
- ☑ What activities are tolerated (i.e. informal activities)?
- ☑ What activities are illegal but happening anyway?
- ☑ Are permitted activities limited to certain areas, or to a maximum number of people or extent?
- ☑ During which season do activities typically take place?

Where are land-based recreational activities taking place?

- ☑ Which catchments and subcatchments are affected?
- ☑ Are the catchments directly feeding water-supply offtakes?
- ☑ Are the catchments feeder streams or headwaters rather than directly feeding offtakes?

Where are water-based activities taking place?

- ☑ Are direct supply reservoirs or weirs affected?
- ☑ Are only indirect supply reservoirs or weirs affected?
- ☑ Are rivers or streams used for drinking-water purposes affected upstream of the offtake?

What infrastructure is in place for recreation and how is it operated and maintained?

- ☑ Develop an inventory of picnic sites, tracks for walking, biking, horse riding, beaches, sanitation facilities, boat launches, marinas, restaurants, hotels and holiday houses and so on.
- ☑ Assess whether their structure and maintenance indicates a likelihood of contamination of the raw water.

How does user pressure relate to the capability of the system to withstand water-quality impacts from recreation?

- ☑ What is the extent of activity; that is, how many visitors (and their pets, boats and so on) use the facility, what are peak times of their presence, how long do they stay (e.g. to be counted at bottle-necks for site access, such as train stations or parking lots, or at typical beaches)?
- ☑ Are quantitative indicators available, such as traffic counts on routes to a specific area (e.g. number of train tickets sold and parking lot use)?
- ☑ Are facilities, particularly for sanitation, in place and sufficiently well maintained and designed to meet the demand placed upon them?
- ☑ What is the size of restaurants and amount of garbage removed from recreational areas?
- ☑ What are the numbers for holiday houses and hotel beds, and boats available for rent or moored at marinas; and how many kilometres of walking tracks are present along the shoreline and in the catchment?
- ☑ What is the level of information for site users about protection of the waterbody, and how do users behave?

3.8.3 Examples of hazardous events and control measures for recreational activities

The hazards typically reaching surface waterbodies from recreational activities are introduced through hazardous events such as direct discharge (when there is recreational activity within the waterbody) or from open defaecation (when there are insufficient facilities), leading to contamination through surface-water run-off. Discharges from sanitation facilities for recreational activities close to the waterbody may occur where these are not adequately designed and connected to treatment. Recreational activities can also cause erosion of shorelines, in turn facilitating hazard transport from the surrounding terrain into the water, and increasing turbidity and nutrient concentrations.

Table 31 provides examples of hazardous events related to recreation, and potential measures to control their impact on surface waterbodies. It also provides options for monitoring to confirm that control measures are in place and working as they should. The list is not exhaustive; rather, it gives examples of approaches that are potentially applicable and feasible.

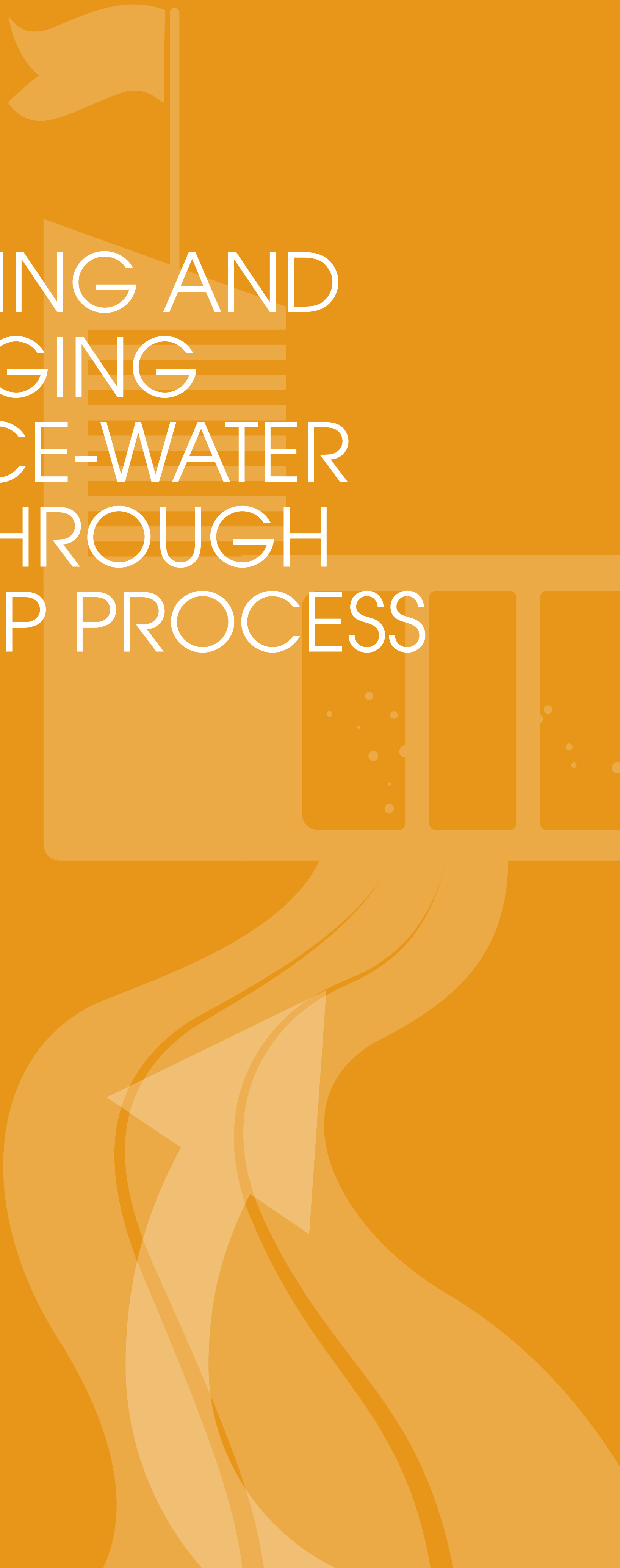
Table 31 Examples of hazardous events for recreation, control measures and options for their monitoring

Process step	Hazardous event, source of hazard(s), hazards[a]	Examples of control measures	Options for monitoring their functioning
Planning	Recreational developments in proximity to waterbody and activities in and on the waterbody (C)	Identify and designate sites for recreation to take pressure off the rest of the water-supply catchment and make managed sites attractive Locate recreational sites in relation to expected impacts on the terrain (e.g. erosion and disruption of vegetation cover), expected usage rates and ensuing contamination, transport and attenuation of contaminants to the drinking-water source Require permits for different types of recreational activity (e.g. boating, or even powerboating) and issue them in relation to the criteria outlined above or ban such activities partially/completely If marinas are (to be) allowed, consider specific water-quality protection requirements for their construction and operation Develop user information and education programmes (e.g. flyers, organized catchment tours, wildlife watching, visitors' centre, signs)	Review plans Review (applications for) permits for site use Inspect catchment and raw water Perform site inspections to identify potentially non-permitted uses/ uses outside permitted locations Perform random interviews with users to identify their level of risk awareness Record and evaluate participation at education programmes
Design and construction	Erosion of embankments from motor-boating at excessive speeds in sensitive areas (P)	Install signs on entry and exit points clearly setting out what is and is not allowed Construct fences and security infrastructure to discourage restricted activities	Monitor legibility of signs Monitor integrity of fences and other security infrastructure
	Sewage contamination of waterbody from run-off due to lack of adequate sanitary facilities and accumulating garbage (M, P)	Where recreational use is permitted, install sanitary facilities and garbage bins in sufficient amounts and quality for acceptance by users	Inspect presence and adequacy of sanitary facilities and garbage bins Inspect recreation areas for signs of open defaecation and littering
Operation and maintenance	Lack of facility maintenance resulting in pollution from site run-off (M, C)	Maintain sanitary facilities in good condition and encourage use Empty garbage bins at sufficiently tight intervals Conduct visitors' information, awareness and education programmes on caring for the recreational site	Inspect facilities and records of maintenance regularly Record and evaluate participation at information and education events

[a] Hazard classification: microbial (M), chemical (C) or physical (P).

CHAPTER 4

ASSESSING AND MANAGING SURFACE-WATER RISKS THROUGH THE WSP PROCESS



This chapter discusses how actions within the WSP steps can be applied to the management of risks to public health in surface-water catchments and waterbodies. It integrates the information presented in Chapters 2 and 3 on hazard identification and risk assessment. It also discusses the particularities to consider when developing a WSP for a surface-water catchment that is used for producing drinking-water (Section 1.1.1 provides a general overview of WSPs, with Fig. 3 showing how the sections of this publication align with actions within the WSP steps).

This chapter first focuses on how catchment information can be used to assess the risks to the safety of raw water up to the offtake point for drinking-water supplies. It then discusses the identification of measures to control the hazards and hazardous events associated with these risks. Box 4.1 lists the key WHO resources that support the development and implementation of WSPs.

Box 4.1 WHO resources that support water safety planning

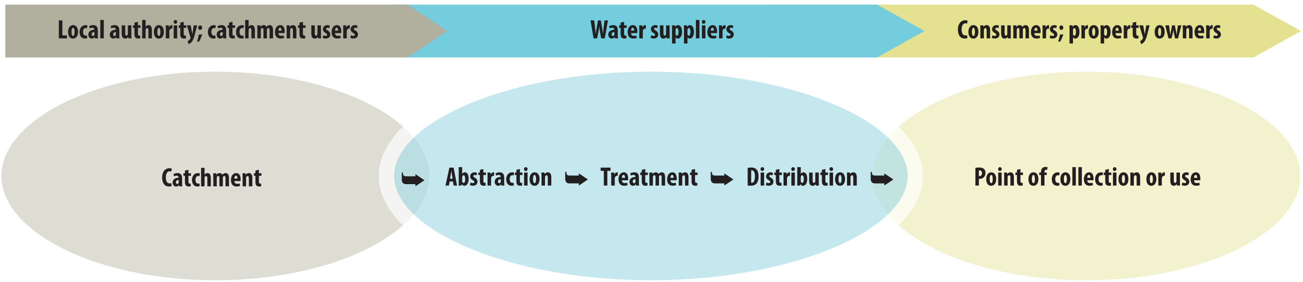
- *Water safety plan manual: step-by-step risk management for drinking-water suppliers* (Bartram et al., 2009)
- *Water safety planning for small community water supplies: step-by-step risk management guidance for drinking-water supplies in small communities* (WHO, 2012c)
- *Water safety plan: a field guide to improving drinking-water safety in small communities* (WHO, 2014d)

4.1 Assemble the WSP team for the catchment and waterbody and engage with stakeholders

Assessing risks from the catchment requires a range of expertise, and implementing measures to control those risks involves a range of competent authorities and other stakeholders. A WSP team integrates these skills, authorities and interests to jointly minimize the risks from raw water to human health. The team is responsible for the overall development and implementation of the WSP. It should meet regularly, first to develop the WSP, and then to keep it up to date (Section 4.9).

Typically, WSPs are developed by drinking-water suppliers, and they address the whole system for the supply of drinking-water, from catchment to consumer. However, the water supplier often has limited influence at the two endpoints of the drinking-water supply chain – the source water in the catchment and the distribution systems in buildings (see, for example, WHO, 2011c) – because often these areas are not owned or controlled by the supplier (Fig. 11). Thus, developing and implementing the parts of a WSP that pertain to these areas requires a strong role, input, engagement and commitment from other stakeholders.

Figure 11 Stakeholder areas of influence and typical responsibilities within water-supply systems



The catchment aspects of a WSP can be managed by the authority responsible for public health or for management and protection of surface water. Such an authority may already have a leading role in catchment management. For example, they may have already developed an environmental risk assessment and risk management system for the catchment. This can form a sound basis for developing the WSP. A leading role for such an authority may be advantageous where input and support by those having influence on the catchment and activities in it (e.g. the respective authorities) is crucial for protecting drinking-water resources and thus contributing to drinking-water safety. For example, catchments that are not fully owned by water suppliers usually require collaboration with, and support from, influential stakeholders such as local authorities responsible for catchment-management aspects including land-use planning, urban development, water management, agriculture and other catchment users. However, the influence of these stakeholders may be limited by prevailing legislation and regulations (e.g. by legislation governing behaviour related to activities in catchments, and governing who can enforce this behaviour). No matter which stakeholder leads the development and implementation of a risk-management plan for the catchment, the principal stakeholders (especially the relevant authority and the water-supplying entity) need to have a common understanding of risk assessment and risk management, and need to ensure that actions to manage risks are coordinated.

The core disciplines and competencies likely to be needed in developing WSPs involving the catchment and waterbody (either as team members or as external expertise) are presented in Box 4.2.

Box 4.2 The core competencies needed in developing WSPs involving the catchment

Development of WSPs requires the following people, either as team members or as providers of external expertise:
- *hydrologists and hydrogeologists*, to provide an understanding of the flow paths for water and contaminants;
- *microbiologists and chemists*, to provide an understanding of the most relevant hazards originating in the catchment;
- *engineers, planners and authority representatives*, to understand the control measures that can be applied;
- *one or more water suppliers*, to provide an understanding of processes in the drinking-water supply chain; and
- *key stakeholders in activities in the catchment* – owners and operators as well as authorities responsible for licensing them.

Depending on the particular circumstances (e.g. the complexity of the system and the availability of resources), stakeholders may form part of the WSP team, be engaged to contribute to a broader process, or be engaged on an ad hoc basis to provide specific input.

Beyond the core competencies outlined in Box 4.2, additional disciplines are likely to be necessary for more complex catchments. Depending on the composition of the permanent team, additional external support may be required on a sporadic or a permanent basis. Such support may include field inspectors, agricultural experts, environmental engineers, limnologists, experts in geographical information systems (GIS), social scientists and – for specific aspects of the assessment – potentially also toxicologists and epidemiologists. The specific expertise required will depend on the nature of the catchment, the activities in it and the scope of the water-safety problems that need to be addressed.

Beyond the members of the WSP team, both the risk assessment and the control of the risks identified can benefit greatly from extensive communication with those who can provide important information for the risk assessment. Such people range from observant citizens (e.g. with knowledge of algal blooms, manure application on sensitive slopes or illegally operated wastewater discharges) to institutions that have both an interest in the risks identified and the authority to control those risks. Involving the local population and stakeholders helps in balancing drinking-water against other priorities; it also increases the acceptability of the measures decided on and implemented.

Where stakeholders are not a part of the WSP team, it is particularly important to involve them in the overall process, at a minimum by informing them about the process and their possible contribution to it. Such stakeholders include, for example:
- those with direct access to the waterbody;
- those most affected by decisions about the waterbody;
- those who hold claims (e.g. customary rights and legal jurisdiction) over the area;
- women who collect the water and use it at the household level; and
- vulnerable groups who may have particular needs with respect to water quality of access to water.

Authorities have varying opportunities to influence activities and catchment users. Such authorities range from national policy-makers to those at regional and local level, and include those dealing with different disciplines and interests (e.g. health, environment and agriculture). Through the WSP implementation process, authorities can identify information held by other authorities, and can inform each other about the needs of the system from both an environmental and a health point of view. This is particularly beneficial for catchments for small-scale water supplies, because typically authorities have only limited influence on the protection of raw water for such supplies. In such cases, identifying relevant information is a crucial step, because drinking-water treatment is often limited or absent as a barrier towards the end of the water-supply chain in small supplies. Box 4.3 explains the considerations that need to be taken into account when establishing a WSP for small water supplies.

Box 4.3 Considerations for WSP teams in small water supplies

Compared with residents of large urban centres, people who live in small communities typically have considerable knowledge about their environment. For example, indigenous people may have extensive anecdotal information relating to local conditions within the catchment, and this information should be considered in a WSP. Also, in such settings, it is often the consumers who use and potentially contaminate the catchment. Hence, the involvement of local communities in protecting waterbodies used by small supplies is important. Ideally, WSP team members in small communities will come from different backgrounds and will include, for example, those with knowledge of the catchment area (e.g. community elders and those working in local industries such as fishing and fisheries), and those who can influence land uses and activities (e.g. community leaders).

When setting up the WSP team for a small water supply, the participation of external "experts" may be particularly helpful. Thus, regardless of the level of sophistication of policy, programme and institutional supports, experts from local government or NGOs should assist with and guide the decision-making processes, even if only on an advisory or an ad hoc basis. These experts may include water-resource specialists, inspectors and public health professionals. Experts can also help community members to recognize and take advantage of education and funding programmes, by drawing attention to tools and resources, and by highlighting critical regulatory or other requirements that may not be obvious to non-experts. Being able to draw on networks of expertise will provide a community with greater capacity for protection of raw water for drinking-water supplies.

In many small water supplies, the required expertise, including external support, may not be readily available. However, even without this specific expertise, it is helpful to start developing a WSP using common sense and the joint capacity of the community. For example, farm animals grazing and defaecating next to the water offtake on a flat surface clearly pose a greater risk than animals further away from the waterbody. This will be obvious even if the WSP does not have the expertise to estimate the pathogen load resulting from such activities. Peer-to-peer support (e.g. on challenges and success factors when developing a WSP) between community water supplies is useful and can often be achieved without significant resources.

Stakeholder engagement can help to inform stakeholders about their possible contribution to water safety in the catchment, improve their understanding of the complete water-supply chain and related risks, and promote understanding among different interest groups. In turn, this supports coordinated development and management of water, land and related resources, taking into consideration not only environmental but also public health aspects. Box 4.4 outlines different ways in which utilities and catchment stakeholders can collaborate.

Local communities are seldom homogenous; they usually comprise various stakeholder groups with different and sometimes conflicting interests. Consequently, decisions about water-resource management made with the participation of local and neighbouring communities tend to require complex negotiations that are sometimes lengthy and often involve conflict. Also, decisions usually require compromise and trade-offs between various stakeholders. Decisions made in this way can generate "winners" and "losers". Negotiated outcomes are usually more sustainable than decisions imposed by external authorities. Stakeholders' communication of their issues and concerns to each other is, in and of itself, a successful outcome that is likely to contribute to a sense of ownership and responsibility, particularly in smaller water supplies.
Developing catchment elements of a WSP is often a challenging process, given the complex ownerships in catchments.

Local circumstances will affect who can contribute to each part of the WSP. It is best to start at whatever point in the WSP is most feasible, and then make incremental improvements. For example, it may be possible to start by implementing better control of discharges to waterbodies from an enterprise in the catchment, more adequate management of the flow regime to a reservoir, or fencing of the surface waterbody near the point of abstraction. Such contributions are an important step towards safer raw-water quality for drinking-water supplies.

Box 4.4 Examples of how utilities and catchment stakeholders can collaborate

Informal collaboration – this can be through workshops, meetings or agreements. For example, in regional **Victoria (Australia)**, informal agreements were in place with landholders to notify the water utility of intended stock movements within the catchment, upstream of raw-water offtake points.

Memoranda of understanding (MOU) – an MOU is a bilateral or multilateral agreement formalizing the arrangements between collaborating parties. In a German example, a bilateral agreement between the police authority and the water supplier stipulated that the water supplier would be immediately informed of any accidents involving substances hazardous to water.

Contracts and cooperation agreements – such agreements may include contracts with farmers stipulating what practices they can apply, and any potential compensation. For example, the water law of the **German federal state of North Rhine-Westphalia** includes the option for water suppliers and farmers to create local cooperation agreements that are voluntary but are nevertheless formalized and binding. Thus, in the **Rhine district of Neuss**, such agreements have been established between water utilities and farmers with the main goal of preventing the introduction of pesticides, and reducing nitrate levels. The topics covered under the agreements include consultations on water-protective application of fertilizers, financial support for intercropping and adapting manure storage capacities. Of the approximately 520 businesses with business premises in the district, 320 (agriculture and horticulture) are participating in these agreements, which cover 95% of the surface areas that are used for agriculture in drinking-water protection zones.

In regional **Victoria (Australia)**, communication agreements were in place between a water utility and the catchment management authority responsible for herbicide application. The aim was to coordinate selective harvesting of raw water for drinking-water supplies during periods of herbicide application within the catchment, and to document emergency communication protocols in the event of accidental chemical release.

4.2 Describe the catchment and waterbody

Development of the WSP builds on the information obtained about the catchment and the potentially polluting activities present in that catchment. Information on catchment conditions can be obtained from a range of sources, examples of which are presented in Box 4.5.

Box 4.5 Examples of information sources for catchment and waterbody conditions

For slope or topography – visual inspection during a site visit; for more detailed information, topographical maps, digital geodata, aerial photographs (e.g. from a regional or national ordnance survey, or from a geological survey) or, if the relevant skills and software are available, digital elevation models.

For groundwater–surface water interactions – local and regional environmental authorities, and geological or hydrogeological surveys to determine, for example, whether a stream gains water from groundwater inflow or loses water through infiltration into groundwater.

For flows of rivers or streams, and water levels – direct measurements, or historical data on flow (including flood events) from the relevant local and regional environmental authorities (including information from people familiar with the local situation); maps and digital geodata on hydrometry (watercourses).

For constructed water offtakes – site inspections; for more detailed information, local and regional environmental authorities that grant abstraction permit, and water suppliers.

For evaporation, precipitation and groundwater recharge – meteorological data, and data on hydrological balance from a meteorological service.

For infiltration capacity of the ground – soil maps; for more detailed information, direct measurements or drillings, aerial photographs (e.g. for proportion of sealed surfaces), online sources and site inspections.

For run-off from slopes – estimations based on the conditions listed above (particularly slope, level of precipitation and infiltration capacity), data and models.

For erosion rates – site inspection (with experts in geography), particularly during and shortly after heavy rainfall, to identify recent or historical signs of erosion (e.g. rills and larger gullies washed into the slope by rainfall); interviews with local farmers about their experience; estimation from slope, soil type and vegetation cover; for more detailed information, test plots in the field (e.g. soil analyses for specific isotopes where relevant expertise is available).

See Novotny (2003) for further information.

Before starting the assessment, it is useful to complete the general checklists provided in Section 3.2 – *Checklist 1: General checklist for activities in the catchment* and *Checklist 2: General checklist for characterizing the catchment and waterbody* – to gain an overview of the situation in the catchment. Section 3.2 also has more information on preparing for, and performing, a catchment inspection.

Typical sources of existing data on activities that may be reviewed for the WSP include:

- inventories of commercial activities and enterprises permitted (e.g. those inventoried for tax collection);
- permits authorized for discharges into tributaries or the waterbody itself;
- storage capacities;
- wastewater discharge parameters;
- statistical data;
- recorded data from ongoing or past monitoring programmes; and
- published studies.

Usually, such data have been established with a different focus or in a different setting (e.g. studies from another water catchment). Even so, they can serve as a starting point, and may reveal requirements for additional information. Data may be obtained from, for example:

- public authorities (local, regional and national) responsible for:
  - health, environment and water management;
  - planning, permitting and licensing of potentially contaminating activities; and
- entities responsible for water supply and wastewater discharge.

Further sources of information include health-care facilities, universities and other research institutions, NGOs, community initiatives, local leaders and government officials, statistical bureaus, literature, aid and development organizations, professional associations and people living in an area who observe activities in the catchment or waterbody. In communicating with these people or organizations, as well as with those operating activities in the catchment, it is useful to ask about obstacles for the implementation or improvement of control measures. Understanding such obstacles is crucial for overcoming them. Typical information sources for developing an inventory of activities are given in Box 4.6.

Box 4.6 Examples of information sources for catchment activities

Information for an inventory of catchment activities (and for hazard analysis) can be derived from a variety of sources, including:

- field trips and site observations; experiences from people with local knowledge (e.g. water company staff or local residents);
- hydrochemical and microbiological monitoring by the waterworks operator and environmental authorities;
- maps or registers kept by local and regional environmental authorities of contaminated sites and industrial facilities that handle or store hazardous substances;
- topographic or historical maps, enquiries to geological authorities for actual or former open-pit or underground mining activities, and quarries;
- local wastewater utilities and the competent authorities (e.g. for sewage treatment plants and stormwater overflow tanks);
- agricultural cooperatives, local farmers and authorities (e.g. for agricultural land use);
- fisheries unions, and authorities for aquacultures and fisheries;
- operators and competent local water authorities for urban drainage systems in the catchment area (e.g. for decentralized and small sewage treatment plants);
- foresters, local forestry authority (e.g. for the type and intensity of forest management);
- aerial photographs (e.g. for location of main traffic routes); and
- counts to determine the number of recreational visitors (e.g. at bottle-necks for site access, such as train stations, parking lots at typical beaches) or traffic counts on routes to a specific area (e.g. number of train tickets sold, and parking lot use).

In many settings, only a limited number of these data sources may be available. Nevertheless, it is important to get started by describing the system, and undertaking hazard analysis and risk assessment. Section 4.3.7 shows possible ways of dealing with data gaps.

For waterbodies with small catchments, land uses and other human activities in the catchment may be easier to identify, assess, influence and control than is the case for larger catchments (e.g. the lower stretches of many rivers). Knowing the size and delineation of the catchment is a precondition for defining the extent of the catchment that will be considered for the WSP. For example, for a small catchment (e.g. a mountain reservoir) it is likely that a comprehensive assessment and control of all the risks will be possible. In contrast, for a large catchment (e.g. the lower regions of large streams and rivers), it will not be feasible to consider the entire area of the watershed and the activities within it. Hence, it will be necessary to decide how much of the catchment (e.g. how far upstream) to consider in detail, and which hazards and hazardous events to simply address in a generalized way through water-quality monitoring, and emergency-response and early-warning systems.

Typically, information for the system description, and for the hazard analysis and risk assessment, will be collected at the same time; this is particularly feasible when conducting catchment inspections (see also Section 3.2). Describing catchments and waterbodies involves:

- describing processes that may influence water quality up to the offtake point; and
- checking the potential impacts of, for example, sanitation, stormwater, wastewater reuse, agriculture, aquaculture and fisheries, commerce, industry, mining, traffic, and recreational and other activities in the catchment.

Information is gathered about the design, condition and operation of individual activities in the catchment. This information is then used as the basis for estimating the extent to which these activities are likely to release hazards into the catchment, and how tightly the risks of such releases can be controlled. The inventory should include, as far as possible, the hazards, hazardous events and control measures that apply to the activities. The inventory will be most useful if it includes details of who is primarily responsible for the construction and operation of each activity, for issuing the relevant permits and for executing surveillance. Often, it is hard to access and compile this information. This is particularly the case for water suppliers who, in many settings, do not have a legal basis to request such information; hence, the contribution of local authorities to this step is crucial. Chapter 3 provides complementary checklists that can be used in identifying potential polluting activities in the catchment; it includes a generic template checklist and specific ones for individual activities. The description of the catchment area also comprises:

- the water quantity provided by the water source in relation to demand (including anticipated future demand);
- future activities and developments in the catchment that may affect the quality and quantity of the raw water; and
- an overview of known water quality, including possible problems.

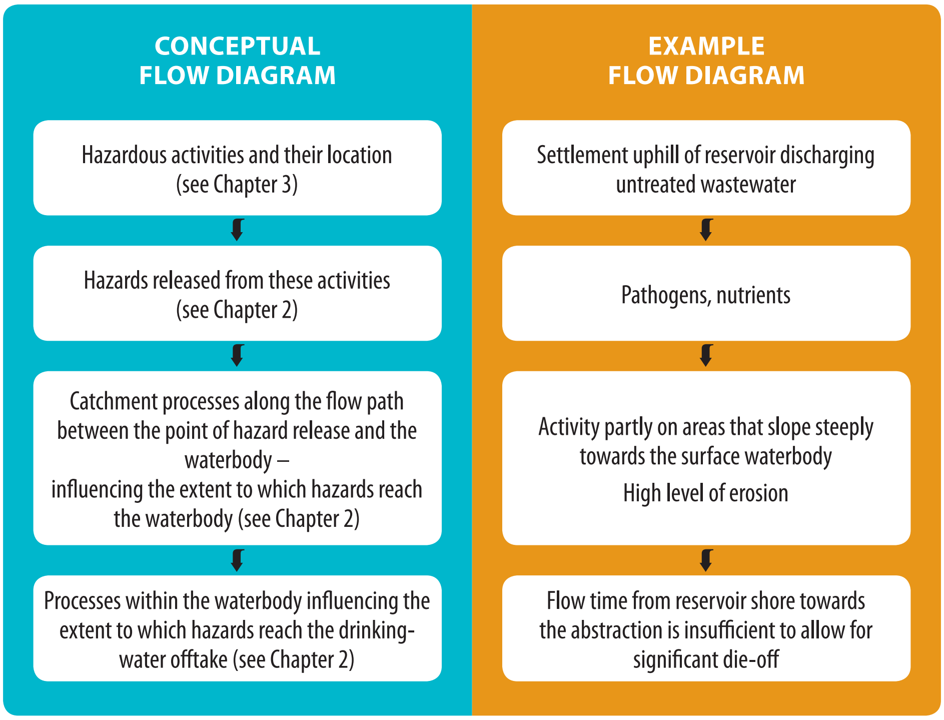
Development of a system description must be informed by a site visit, the results of which are recorded as part of the WSP documentation (i.e. as flow diagrams or tables with a textual description). When developing flow diagrams for catchments, the levels of detail may vary, and more than one flow diagram may be required, depending on the spatial extent of the catchment. Examples of possible levels of detail are given in Table 32.

Table 32 Three levels of detail for flow diagrams and tables for describing catchments

Level	What is it?	Which form is used?	Who does it?
Summarizing	Conceptual process overview	Process flow diagram (Fig. 12) Illustrative representation (Fig. 13)	Water supplier and/or catchment management, preferably together
Spatially explicit (i.e. refers to the larger catchment area)	Spatial inventory of potentially polluting activities and their controls	Map GIS	Water supplier and/or catchment management, preferably together
Site-specific (i.e. refers to the specific site of a potentially contaminating activity)	Detailed description of processes and control measures for specific pollution sources	Flow diagram Diagram of engineered process Tables listing site and outlining key features relevant to hazard release and attenuation	Polluters and/or the permitting authority

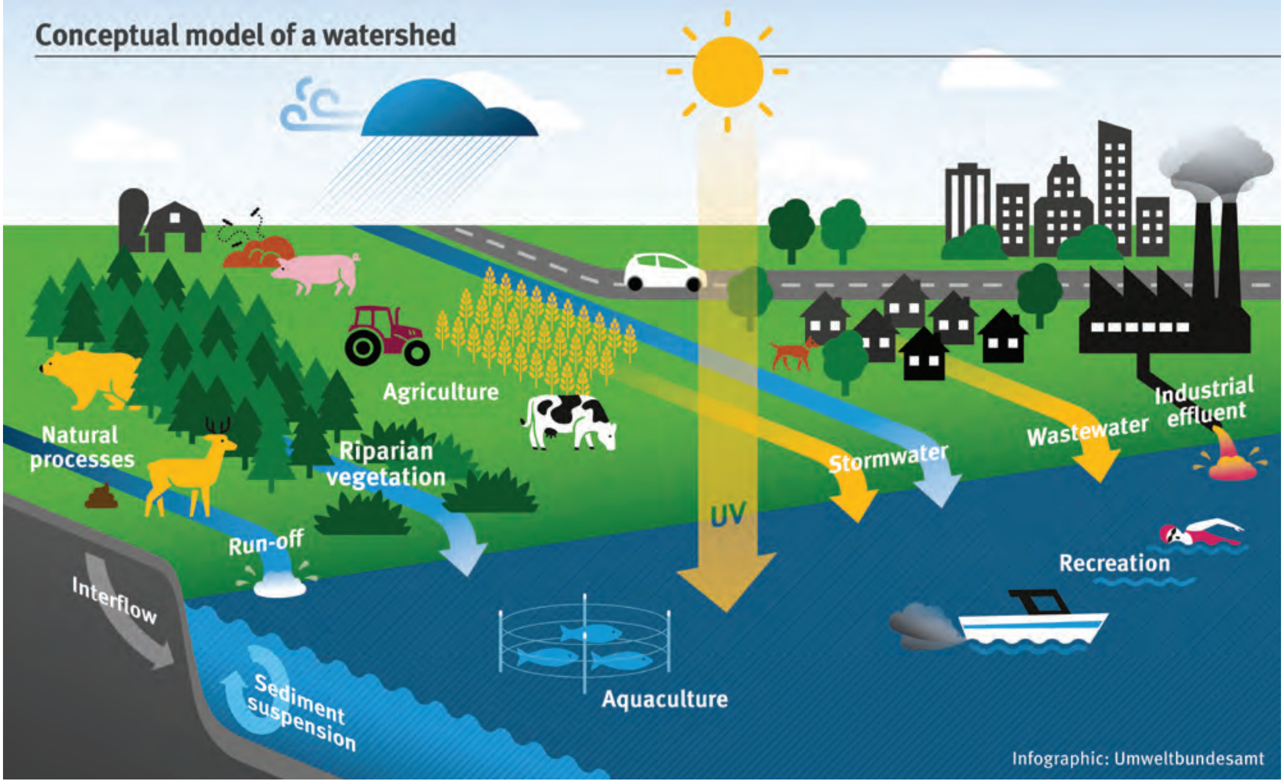
Many examples of conceptual-level flow diagrams for catchments are available, such as those given in Fig. 12 and Fig. 13. Illustrative flow diagrams such as that shown in Ferguson et al. (2003) are ideal for community-based and non-technical working groups, where they can be used to illustrate knowledge gaps.

Figure 12 Conceptual flow diagram for a catchment (blue) alongside an example flow diagram (orange)



CONCEPTUAL FLOW DIAGRAM	EXAMPLE FLOW DIAGRAM
Hazardous activities and their location (see Chapter 3)	Settlement uphill of reservoir discharging untreated wastewater
Hazards released from these activities (see Chapter 2)	Pathogens, nutrients
Catchment processes along the flow path between the point of hazard release and the waterbody – influencing the extent to which hazards reach the waterbody (see Chapter 2)	Activity partly on areas that slope steeply towards the surface waterbody High level of erosion
Processes within the waterbody influencing the extent to which hazards reach the drinking-water offtake (see Chapter 2)	Flow time from reservoir shore towards the abstraction is insufficient to allow for significant die-off

Figure 13 Illustration of an example process flow



Source: based on the illustration in Ferguson et al. (2003) that originates from the Sydney Catchment Authority.

Data available on water quality and possibly also on water-related disease in the population are not a prerequisite for assessment, but are a valuable support. Pathogens or harmful chemicals found in raw water for drinking-water supplies indicate that events taking place in the catchment are releasing these hazards. Although the data do not necessarily reveal the specific enterprise or activity responsible for the release, they do highlight parameters of concern (see also Table 13 in Section 3.1, which gives an overview of a selection of potential hazards found in surface waterbodies, together with the contaminating activities that typically introduce them into watercourses).

4.3 Hazard analysis, control measures and risk assessment

4.3.1 Compile an inventory of hazards and potentially hazardous events

The hazard analysis step in a WSP includes analysis of all relevant land-use patterns, actions and facilities within the catchment area. The aim is not only to create an inventory of potentially hazardous activities, but also to characterize the respective hazards and events causing their release as potential contaminant loads to the catchment. Hazardous events for surface-water quality within the catchment may be attributed to various anthropogenic activities; for example, industry and commerce; human settlements; traffic and transportation; agriculture; forestry; horticulture; aquaculture; and the generation, disposal and treatment of waste and wastewater. They may also be related to natural events (e.g. heavy rainfall, snowmelt and flooding), and the release of hazards from natural sources (e.g. wildlife accessing the surface waterbody) and geogenic sources (e.g. heavy metals in rocks and sediment reaching the waterbody via groundwater).

Chapters 2 and 3 describe the relevant factors to identify and analyse in relation to hazards and hazardous events. Chapter 3 provides a general checklist for activities in the catchment (Checklist 1), several activity-specific checklists to facilitate this analysis (Checklists 4–9) and a detailed discussion of potential sources of pollution, many of which are listed in Table 13 (Section 3.1) and Table 14a and Table 14b (Section 3.2.1).

To provide the basis for subsequent risk assessment, it is useful to characterize the hazards and related hazardous events with respect to:

- the hazards' chemical, physical or biological properties that determine mobility and persistence in the catchment (Section 2.1 describes the various hazard classes); if availability of raw water in sufficient quantity is an issue, this may also be included in the assessment of the risk;
- their health relevance – hazards with high health significance are indicated in the GDWQ (WHO, In preparation-a) and discussed in Section 2.1;
- possible maximum loads of pollution (e.g. caused by extreme events);
- the type and time pattern of pollution; that is:
  - point sources with direct discharge into the surface waterbody versus diffuse sources;
  - continuous ongoing release on land or drainage from land to waterbody versus temporary periodic release; and
- relevant pathways of potential pollution transport to the raw-water offtake (see Fig. 14).

Options for documenting the results of this characterization range from simple spreadsheets to sophisticated databases. Maps – supplemented with hand-written sketches or, on a more complex level, GIS – facilitate the documenting of spatial information. The risk assessment should also document information gaps that require further investigation or more data, assumptions made and uncertainty estimates. Section 4.3.5 discusses approaches to risk assessment, and Section 4.3.7 discusses how to deal with uncertainties and information gaps.

4.3.2 Conceptual model for risk assessment in the catchment

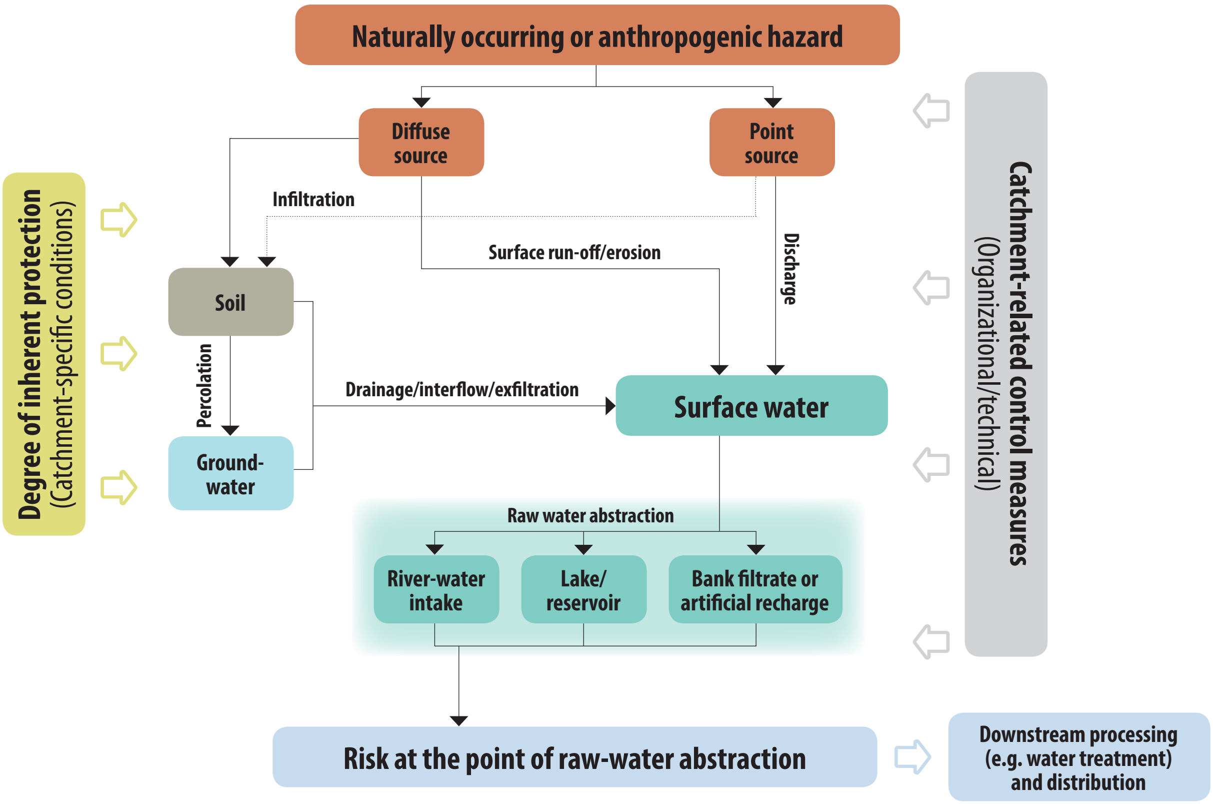
An assessment of the system-specific risks in a catchment should include consideration of the following:

- the "degree of inherent protection" of the raw water (see Section 4.3.3); this involves determining the risk-reduction capacity of:
  - hazard transport along the overland flow path between an activity and the waterbody or tributary (e.g. absorption of surface run-off after rainfall); and
  - the surface-water system (i.e. conditions in the waterbody used for raw-water abstraction and its tributaries that reduce hazard concentrations before the water reaches the raw-water offtake);

- the effectiveness of existing control measures applied:
  - at the point where the hazards occur (i.e. upstream hazard mitigation);
  - within the catchment to restrain the transport of hazards along the flow path to the waterbody; and
  - at the offtake point for drinking-water supplies (see Section 4.3.4); and
- the likelihood that a hazardous event will occur within the catchment or waterbody, and the severity of its consequences (the likelihood will be influenced by the degree of inherent protection and the effectiveness of existing control measures; see Section 4.3.5).

A conceptual model for a catchment risk assessment is presented in Fig. 14.

Figure 14 **Conceptual model for a risk assessment of surface-water catchments (line strength indicates typical pathway relevance)**



In certain circumstances, a two-stage risk-assessment approach may be considered (Bartram et al., 2009). As explained in Box 4.7, this more sophisticated approach can determine the risk-reduction contribution of the control measures, by assessing the level of risk both in the absence and presence of the identified control measures.

Box 4.7 Adopting a two-stage approach to risk assessment in a catchment setting

A two-stage risk assessment provides a comprehensive way to identify how much control measures contribute to controlling the risk. The first stage (the "initial" risk assessment) assesses the risks that hazardous events would pose to drinking-water safety if no control measures are in place. The second stage (the "residual" risk assessment) assesses the risk that remains when control measures are taken into consideration. The two-stage process demonstrates the importance of control measures; it is often performed for drinking-water treatment and may be applied to a catchment as follows:

- the *initial* risk assessment considers:
  - the naturally present hazard attenuation capacity of the catchment (i.e. the degree of inherent protection) along flow paths between the points of contaminant release and the waterbody, and within the waterbody itself to the offtake point;
  - the likelihood of a hazardous event introducing a hazard into the catchment or waterbody; and
  - the severity of public health impacts;
- the *residual* risk assessment considers all of the above, as well as the effectiveness of existing engineered control measures applied, to obtain water with the least hazards and risks for use as drinking-water. It considers control measures:
  - at the point where the hazards occur (e.g. containments for chemicals and fences for animals);
  - within the catchment that act as barriers along the potential flow path of hazards between the point of their release and the waterbody (e.g. vegetated buffer strips); and
  - at the offtake point for raw-water abstraction (e.g. siting of offtakes and riverbank filtration).

The resulting residual level of risk provides an assessment of the effectiveness of existing control measures, and may highlight where controls are inadequate and improvement planning is required.

In some catchment settings, resources may not permit such a comprehensive approach, and a one-stage risk assessment may be more appropriate where resources are limited. For example, if complex modelling is used to inform the risk assessment, the two-stage approach would require modelling to be performed both in the absence and presence of the identified control measures, which might not be feasible.

4.3.3 Assess the degree of inherent protection of the raw water

Most catchments and waterbodies have a capacity to reduce risks after hazards have been released; thus, the risk-reduction capacity of the overland flow path and of the waterbody are key considerations for the risk assessment. Such capacity is important because, in most cases, it is not possible to implement effective control measures for all hazards from human activities in the catchment at the point of their origin, or for naturally occurring pathogens.

The risk of a hazard reaching the point of raw-water offtake is determined not only by the type and by properties of the hazard itself, but also by the naturally present hazard attenuation capacity; that is, the type and length of the pathway between the point of entry of a hazard into the surface-water system and the offtake point. In most cases, biological or physico-chemical processes will attenuate the level of risk to some extent, as illustrated by the conceptual model in Fig. 14.

Determining how well raw water is inherently protected against contaminants – that is, its "degree of inherent protection" or protectedness – means estimating the extent to which the pathway between the point of the hazard's entry into the catchment or waterbody can reduce the hazard before it reaches the raw-water offtake (i.e. the natural attenuation or risk-reduction capacity). This process, often referred to in the literature as a "vulnerability assessment", is common in groundwater protection (EC, 2004; Vrba & Zaporozec, 1994) and has been applied to risk management in groundwater catchments (e.g. in Schmoll et al., 2006). Transferring this concept to surface waters means that the degree of inherent protection now comprises the intrinsic properties of the surface-water catchment from the land surface to the waterbodies, and within the waterbodies themselves. These properties determine the extent to which a hazard reaches the watercourse and, ultimately, the offtake point.

The first step in assessing or mapping the degree of inherent protection in a system is to identify general principles relevant to transport and risk-reduction capacity in that system. These principles can be derived from the conceptual model for catchment risk assessment of surface-water systems (Fig. 14). In most cases, two main pathways are relevant:

- *Pathway A* (risk-reduction capacity of the catchment) – diffuse hazard source on land → surface or subsurface transport → entry into surface waterbody; and
- *Pathway B* (risk-reduction capacity of the river and waterbody) – point-source hazard release into surface waterbody or diffuse sources after having passed pathway A → transport within the surface-water system → point of raw-water offtake.

Pathway A is relevant for on-land activities such as farming, forestry and traffic; it links diffuse types of pollution with the water system. Pathway B is relevant for all hazards that have passed pathway A, and for point sources with direct discharge into the surface waterbody (e.g. discharge of municipal or industrial sewage, or aquaculture in the waterbody used for raw-water abstraction). Another example of possible direct contamination of the surface waterbody is the direct deposition of faecal material into streams draining pastoral land, in cases where livestock have access to the watercourse.

The following sections list characteristics of the catchment area and the water system that influence contaminant transport and attenuation, and which indicate the risk-reduction capacity of the considered catchment area.

Hazard transport and attenuation on land

The main catchment characteristics influencing contaminant transport and attenuation on land are listed in Table 33. These characteristics are relevant in the process of assessing hazards that are continuously or temporarily released on land, predominantly reaching the waterbody or its tributaries via surface run-off or erosion (i.e. diffuse sources).

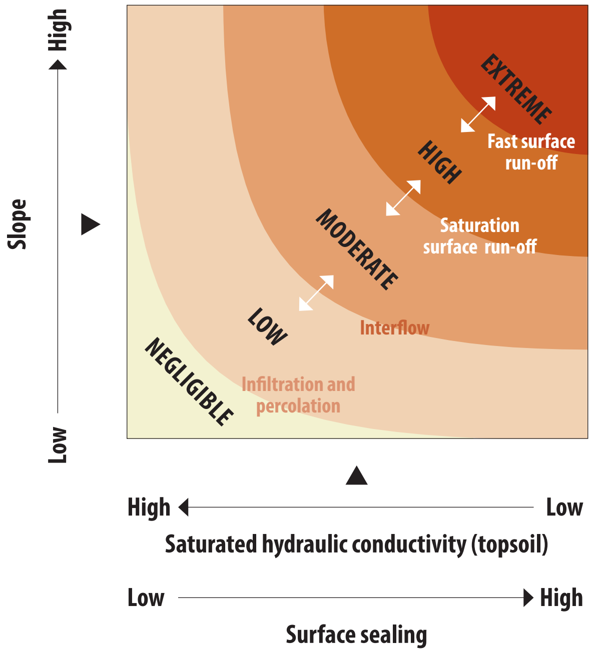
Table 33 Catchment risk-reduction capacity (width of arrows indicates increases or risk-reduction capacity from low to high)

Characteristics	Low risk-reduction capacity (i.e. higher risk)		High risk-reduction capacity (i.e. lower risk)
Slope	Steep	◀	Flat
Topsoil infiltration capacity	Low permeability	◀	High permeability
Degree of surface sealing	Sealed	◀	Unsealed
Interflow or drainages	Scarcely permeable layers near surface; drained	◀	No layers with low permeability; not drained
Vegetation cover	Poor	◀	Dense
Saturated hydraulic conductivity (i.e. topsoil)	Low	◀	High
Proximity of contaminating activity to surface-water system	Close	◀	Far

Rapid surface run-off from rainfall and the possible resulting erosion processes are the main pathways by which hazards from diffuse sources reach surface waters, as indicated in Fig. 15. Run-off formation is a complex process that involves many hydrological factors. As indicated by the diagonal double arrows, the actual type of run-off is strongly dependent on meteorological dynamics such as precipitation intensity. An assessment of the degree of inherent protection of the surface-water resource needs to combine the relevant factors contributing to formation of run-off. The manner in which surface run-off is produced in a catchment (see "Run-off and slope" in Section 2.2.1) will determine the extent to which a hazard will be transported via overland flow to a surface waterbody, and the extent to which it will infiltrate groundwater (which may eventually reach the surface waterbody, after being subject to subsurface contaminant attenuation mechanisms).

Fig. 15 illustrates the relationship between land slope and saturated hydraulic conductivity of the topsoil. It indicates how the characteristics of surface run-off change as these factors vary. Steep slopes combined with soil of low infiltration capacity promote fast surface run-off, whereas highly permeable (e.g. sandy) soils in flat terrain allow infiltration and percolation of rainwater. Surface sealing of the land can reduce the infiltration capacity to almost zero. Therefore, paved or sealed surfaces will generate intensive overland flow, increasing the rate at which contaminants are transported to the surface-water system. The influence of slope and topsoil permeability on run-off formation is highly variable, depending on meteorological dynamics such as the intensity and duration of precipitation, as indicated with double arrows in Fig. 15.

Figure 15 **Run-off formation resulting from slope, surface sealing and hydraulic conductivity**



For example, simulation experiments carried out by Collins, Elliott and Adams (2005) on steep pastoral land in New Zealand showed that, under heavy rainfall, overland flow can transport substantial levels of faecal bacteria to streams.

The formation of run-off also depends on the density of the vegetation cover. Forest and meadow, for example, favour rainfall interception and a higher rate of infiltration. Consequently, the formation of overland run-off over such vegetation may be negligible, even if slope and topsoil permeability indicate a significant potential for formation of run-off. In contrast, surfaces that are only partially vegetated or are fallow do not increase infiltration; hence, the actual formation of run-off is the same as the potential formation derived from slope and topsoil characteristics.

The extent to which hazards mobilized by surface-water run-off and erosion reach a waterbody depends on the distance the run-off covers before entering the nearest tributary. Increasing the distance to the watercourse significantly reduces the range of hazard transport to surface watercourses. This has been investigated, for example, by Ferguson et al. (2007) for microbial hazards, with results implying that "while vegetated riparian buffers of the order of 10 m distance will be successful in reducing *Cryptosporidium* oocyst transport to waterways, vegetation buffers to retard bacterial and viral pathogens may need to be significantly wider".

In a simplified approach to assessing the risk-reduction capacity of the catchment, the distance may be classified using buffers with fixed widths around the watercourse network. In a more complex modelling approach, the exact distance of each plot to the nearest ditch or river may be calculated using data from digital elevation models. (Box 4.8 in Section 4.3.4 provides an example of the delineation of riparian protection zones as a control measure.)

Hazard transport and attenuation in water

Table 34 lists characteristics influencing hazard transport and attenuation in the surface waterbody. These characteristics are relevant to the assessment of hazards that are continuously or temporarily discharged into a waterbody, including into tributaries (i.e. point sources, as indicated in Fig. 14). They are also relevant to the assessment of hazards from diffuse sources that have reached the waterway. If, for example, the hazard source is located in the outer catchment, with connection to the river system only via small ditches or subordinate smaller tributaries, even an extreme input of contaminated surface-water run-off might result in negligible effects in the distant water resource, because of dilution and sedimentation during transportation. On the other hand, the same hazard load released directly upstream of the raw-water offtake or into the reservoir is likely to have significant consequences.

Distance (and therefore travel time) can be used as a generic substitute for and approximation of the many possible characteristics from Table 34, all of which contribute to hazard attenuation in the river system. The advantages of this approach are that the information required is usually evident in the field or readily available from maps, and that the individual contributing processes do not have to be known in detail. However, if the processes subsumed under the criterion "distance" are not sufficiently well understood, it is possible to overlook potentially opposing processes. For example, high flow velocity may favour fast transport of particle-bound or microbial hazards in mountain streams, but may also cause turbulent flow patterns, increasing the oxygen content in the water and thus the attenuation capacity for organic contaminants such as certain pesticides.

Due to the often complex hydrological settings, many of the factors mentioned in Table 34 are interwoven and in some cases mutually dependent.

Table 34 Risk-reduction capacity of the surface waterbody (width of arrows indicates increases or risk-reduction capacity from low to high)

Characteristics	Low risk-reduction capacity (i.e. higher risk)		High risk-reduction capacity (i.e. lower risk)
Location of hazard point of entry in water system	Close to offtake point	◀	Large distance to offtake point
Flow velocity	High (e.g. mountain streams)	◀	Low (e.g. lowland river impoundment)
Dilution of hazard load by mixing with uncontaminated water	Low (small waterbody or few uncontaminated inflows)	◀	High (large waterbody or high inflow without hazard)
Potential for sedimentation of particles carrying hazards, depending on:	Poor	◀	High
• residence time in water system	Short (e.g. small reservoir)	◀	Long (e.g. bank filtrate, very large lakes)
• specific hydraulic circumstances increasing risk-reduction capacity	None (e.g. "polymictic" lakes with less stable thermal stratification)	◀	Effective (e.g. "monomictic" lakes with more stable thermal stratification)
Additional technical barriers (e.g. allowing reduction by means of sedimentation, degradation, inactivation)	None established	◀	Highly effective (e.g. pre-dam, variable depth of raw-water offtake)

Different types of raw-water sources may differ significantly in their capacity for risk reduction. The system's natural attenuation capacity includes processes such as filtration, sorption, biological degradation, "die-off" or dilution, and processes that counteract attenuation, such as resuspension of sediment. Riverbank filtration, artificial groundwater recharge – for example, via soil aquifer treatment, or aquifer storage and recovery (ASR) – make particular use of this attenuation capacity, as explained in Sections 2.2.2 and 2.2.3. The residence time within the raw-water resource before it reaches the raw-water offtake may vary from years (e.g. in large, deep lakes or in stratified, monomictic reservoirs; i.e. those that mix from top to bottom during one mixing period each year) to a few hours when abstracting water directly from rivers with high flow velocities.

Additional aspects to be considered include flow velocity, in combination with level of meandering or coarseness of the riverbed and ecological status of the river (see Sections 2.2.2 and 2.2.3). All of these factors can vary widely, depending on the local situation, and may be subject to considerably high temporal variations (especially seasonal variations), depending on the meteorological and hydrological dynamics.

Influence of short-term events

The characteristics affecting risk-reduction capacity discussed so far rarely represent a steady state in the catchment. Rather, they vary over time under natural conditions. For example, torrential rain, high water levels and flood events may increase flow velocities of watercourses dramatically and lead to decreasing residence times (e.g. in bank filtration sites). Similarly, storms or snowmelt may suddenly lead to disturbance of the thermal stratification within lakes or reservoirs. The assumption that hydrological and geomorphological conditions will be reasonably constant (or seasonal patterns predictable) may be valid in many cases for most of the year, but short-term events can drastically and rapidly alter conditions, inducing or increasing hazard mobility and transport.

Possible natural events inducing or increasing hazard mobility and transport on land include, for example:

- frozen ground;
- torrential rainfall and floods;
- snowmelt;
- drought periods that reduce the permeability of the soil surface and increase overland or interflow pathways;
- stormwater events that connect the ephemeral waterbodies that occasionally contribute to the catchment; and
- seasonally changing patterns of vegetation cover.

Events and conditions inducing or increasing hazard transport within the surface waterbody to the raw-water offtake include, for example:

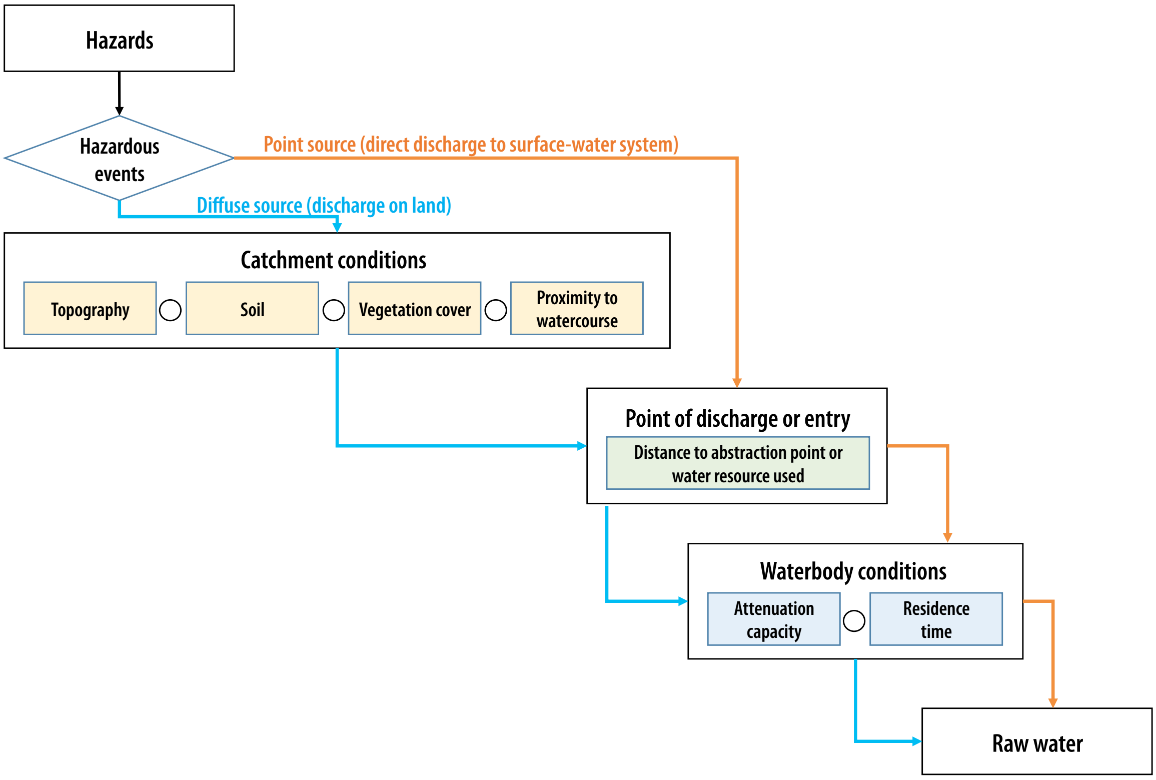
- seasonal patterns of thermal stratification and vertical mixing in lakes and reservoirs;
- occasional storms or density-induced currents disrupting seasonal stratification patterns;
- seasonal discharge patterns (e.g. related to occasional flood events);
- shifts in the relationship between river discharge and contaminant loading; and
- drought-induced extreme reductions in water levels that minimize dilution in rivers or decrease residence time in lakes and reservoirs.

In general, it is difficult to appropriately incorporate the dynamic factors listed above into an evaluation of the degree of inherent protection of a catchment without using highly complex time-variable simulation models. The assessment will therefore start with the conditions that are static or follow known seasonal patterns, assuming that such a description is valid and representative for a mean situation of the hydrological system. However, worst-case scenarios are important for risk assessment. Therefore, it is necessary to attempt to identify times and periods when the degree of inherent protection is reduced, by capturing the potential influence of extreme scenarios (e.g. from climate change predictions). This can be done by making assumptions about how the conditions listed in Tables 33 and 34 could change as a consequence of, for example, snowmelt, storms or extended dry periods. Experiences from the past are particularly valuable in such assessments. The uncertainties of such assumptions can be evaluated using sensitivity analysis; for example, by varying assumptions from worst to best case (see Section 4.3.7). Sampling programmes targeting extreme events are sometimes logistically challenging, but they can provide valuable data for risk assessment.

Practical illustration of a qualitative assessment of the degree of inherent protection of surface water

The practical procedure of classifying, ranking, and possibly weighting and combining the influencing factors specifically depends on the chosen method, the available database and the specific conditions of the given setting. Fig. 16 illustrates the processes of assessing risk-reduction capacity. The process used will depend on the type of hazard release – point source or diffuse source – as indicated in Fig. 16.

Figure 16 Assessment scheme of risk reduction for point sources and diffuse sources



The junctions in Fig. 16 can be processed by means of a set of two-dimensional matrices or by calculating combinations, as in scoring or index-type systems.

Table 35 illustrates a stepwise assessment of the degree of inherent protection of raw water, as depicted in the flow chart in Fig. 16 for diffuse (on-land) sources using a table or spreadsheet. The approach can be applied for a wide range of settings; it is based on the assumption that the spatial variability can be reduced to a limited number of sub-area types that have similar geographical and hydrological conditions. More complex settings and detailed approaches may require the use of cartographic techniques (e.g. map overlay) or the application of GIS.

In the example shown in Table 35, an ordinally scaled classification of the selected input characteristics was applied, with five categories of effect on risk reduction, ranging from zero for the lowest to four for the highest. Each criterion was ranked according to this scale, and all single scores were summed to give a total score that describes five categories of the degree of inherent protection of raw water, ranging from negligible (0–6) to extreme (26–32). A similar approach was used by Foster (1998) to derive a “run-off potential index” from several catchment characteristics. When using such an approach, it is important to be aware that a simplified calculatory combination may imply a (non-existing) “mathematical” accuracy, and that all input variables are of equal relevance.

The example in Table 35 illustrates the principles of assessing the degree of inherent raw-water protection. However, it has been greatly simplified, with the influencing factors limited to a few and obvious predictors (and therefore should not be used as an assessment template). The example uses the same number of criteria for processes on land and in water in order to balance the impact of both main pathways. Sensitivity studies in a particular case may show that some factors are insignificant whereas others bear a lot of weight. This can be reflected by introducing weighting factors or differently ranked numbers. Other factors may be important in the production of run-off in a rainfall event; for example, soil moisture conditions at a particular time, and distribution of low-permeability horizons in the subsoil. Including these factors may improve the overall assessment of run-off potential, but the assessment may still be limited by the lack of reliable data or of the resources needed to obtain and assess the necessary data.

Table 35 Example of a simplified assessment of the degree of raw-water protection using a spreadsheet for the catchment of a smaller lake

	Examples for generalized sub-areas with similar topographical and hydrological conditions				
	A	**B**	**C**	**D**	**E**
		Hillsides of tributaries		**Outer catchment**	
Qualitative assessment criteria	**100 m buffer around lakeshore (100 m)**	**(Forested, <1 km upstream offtake)**	**(Not forested, >1 km upstream offtake)**	**(Hilly terrain)**	**(Flat terrain)**
Processes on land					
Slope	Very steep (score: 0)	Steep (score: 1)	Steep (score: 1)	Undulating (score: 2)	Flat (score: 4)
Infiltration capacity (topsoil)	Low (loam) (score: 1)	Extreme (grit/debris) (score: 4)	Low (loam) (score: 1)	Very low (loam/silt) (score: 0)	Moderate (sandy loam) (score: 2)
Density of vegetation cover	Dense (meadow) (score: 3)	Very dense (forest) (score: 4)	Moderate (heathland, only partially vegetated) (score: 2)	Low (arable land, fallow in winter) (score: 1)	Low (arable land, fallow in winter) (score: 1)
Location in catchment	Very close to watercourse (score: 0)	Near watercourse (score: 1)	Near watercourse (score: 1)	Moderate distance to watercourse (score: 2)	Very far to watercourse (score: 4)
Processes in water					
Distance of sub-area to raw-water offtake	Very close (score: 0)	Near (<1 km) (score: 1)	Moderate (>1–5 km) (score: 2)	Very far (>10 km) (score: 4)	Very far (>10 km) (score: 4)
Residence time in waterbody	Low, mostly <1 month (due to small size relative to discharge of tributaries) (score: 1)				
Specific hydraulic circumstances	No stable stratification; thus, only limited potential for sedimentation of particles carrying contaminants (score: 0)				
Overall risk-reduction capacity of waterbody	Low (smaller lake: no filtration, moderate dilution of contaminant loading, limited potential for biological degradation) (score: 1)				
Degree of inherent protection (considering processes on land and in water) for each sub-area					
Total score (sum)[a]	6	13	9	11	17
Degree of inherent raw-water protection[a]	Negligible	Moderate	Low	Low	Moderate

[a] Degree of inherent raw-water protection: classification of the total score (considering processes on land and in water): negligible (0–6), low (7–12), moderate (13–19), high (20–25), extreme (26–32).

Note: this table is for information purposes only, and is not intended to be used as an assessment template; for further information, consult the explanation provided below.

4.3.4 Identify and validate existing control measures

In general, control measures are activities and processes that prevent occurrence or re-occurrence of hazards, and thus reduce or mitigate the resulting risks. The control measures applied should be suitable for operational monitoring (see Section 4.5). Detailed guidance on control measures for human activities in a catchment, covering measures related to planning, design and construction, and operation and maintenance, is given in Sections 3.2 to 3.8.

The processes of requiring, establishing and operating control measures at the point of occurrence of a hazard may involve several stakeholders, and significant risk control (and thus risk reduction) may take place at this stage.

Natural attenuation can be enhanced by engineered structures in the catchment or management strategies for the waterbody, as highlighted by the examples in Table 15 (Section 3.2.2). Engineered structures may take several forms, including:

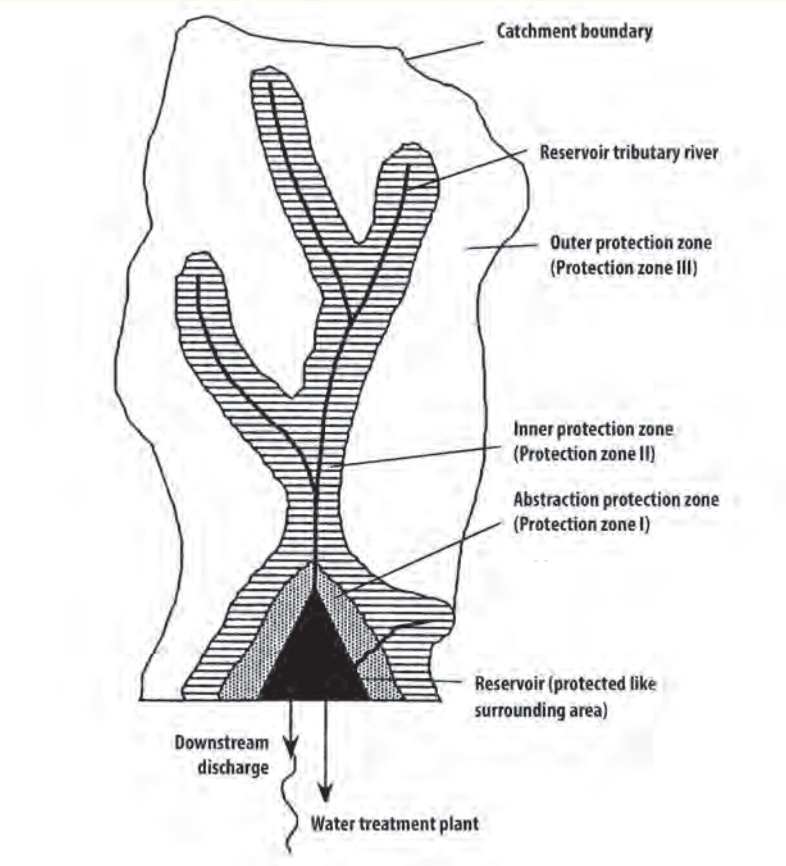
- *control measures applied where the activities potentially release hazards* – includes measures to mitigate or reduce either the likelihood that a hazardous event will occur (e.g. physical measures, such as double-walled containments for hazardous chemicals or manure, or keeping livestock in fenced corrals away from the watercourses) or the severity of its consequences (e.g. reducing the hazard load in wastewater discharges);
- *control measures applied in the catchment* – includes measures to restrain the transport of hazards along the flow path to the waterbody (e.g. diversion ditches, fences to keep animals away from the waterbody and constructed riparian buffer strips); and
- *control measures at the offtake point* – includes structures designed to obtain water with the least hazards and risks for use as drinking-water (e.g. multi-depth raw-water offtake structure, see Section 2.2.4).

Box 4.8 gives an example of protection measures applied in drinking-water protection zones for drinking-water reservoirs.

Box 4.8 Managing surface-water run-off and erosion hazards through drinking-water protection zones

Buffer zones around watercourses play an important role in mitigating the impacts of surface-water run-off by increasing the distance to the watercourse and by intercepting hazards such as pathogens, sediment and nutrients.

Raw-water protection schemes sometimes define tiered protection measures and restrictions of land use depending on the position and location of the land use within the catchment. Such schemes often draw on risk-reduction capacity by delineating protection zones and buffer strips around watercourses. The figure below shows an example of such a control measure applying an integrative approach, based on the delineation principles of protection areas according to the guideline W 102 for drinking-water reservoirs in **Germany**.



Delineation principles for surface-water protection zones according to guideline W 102 in Germany (adapted from DVGW, 2002).

As discussed in Section 3.2, activities in the catchment can be planned, designed, constructed and operated with control measures that are subject to effective operational monitoring, and that could be integrated into a WSP. Therefore, it is useful to collect information on the condition of the infrastructure and the quality of the day-to-day operation of the control measures (including monitoring for potential release of hazards into the catchment) as the basis for the risk assessment.

Such information is essential for assessing whether the barriers implemented within each activity (as outlined in the control measure tables at the end of each activity-specific section in Chapter 3) serve the purpose for which they were put in place, and hence whether they can be considered effective.

Having effective control measures in place for the activities in the catchment depends on having legal requirements that are sufficient and enforceable, or on having operators who are willing to collaborate even when there is no legal obligation to do so. Therefore, when analysing the hazards from the activities in the catchment, it is useful to explore both the legal requirements and the willingness of the respective operators to cooperate, including the terms under which they would and could cooperate. Such terms may include financial support for upgrading infrastructure, improving operations or limiting an activity (e.g. spreading of slurry or stock density) to control hazard release and thus protect the drinking-water source.

Usually, the operation and monitoring of such control measures are not within the responsibility of water suppliers, and even surveillance authorities may have limited influence over enterprises or agriculture. Hence, the efficacy of such control measures tends to be subject to some uncertainty. Where such measures are outside the control of the water supplier, the ideal situation is for the supplier to liaise with the responsible catchment authorities and other catchment stakeholders through the WSP process (e.g. through the establishment of a multiagency WSP team), to ensure that adequate measures are in place and continue to be effective. For example, the water supplier may contribute to controlling the risk through providing financial incentives to those who have direct influence on the activity, as outlined above.

Validation of existing control measures (i.e. obtaining evidence that the control measures are capable of effectively controlling the risks) is necessary because control measures may be unsuitable or not working as initially planned. For example, a fence intended to keep animals away from a waterbody may be too low, so that access is still possible. In essence, validation determines whether the control measure in the catchment works effectively to reduce or mitigate the risk or hazardous event to which it is assigned. For further information on validation of control measures, see Bartram et al. (2009).

4.3.5 Assess the risks

Risk-assessment approaches

The principles of risk assessment are the same in considering both the likelihood that a hazardous event will occur and the severity of its consequences. However, a number of approaches are available for the assessment, with varying degrees of complexity, and associated strengths and limitations. Approaches to risk assessment can be qualitative, semiquantitative or quantitative; they range from simple to detailed, and from expert judgment to evidence-based assessment of the risks (WHO, 2016). Table 36 illustrates the range of possible risk-assessment approaches and their different levels of sophistication. In general, risk assessments should be as simple as possible for the given purpose; thus, for a small water supply, a simplified or qualitative evaluation scheme is probably sufficient (e.g. WHO, 2012c).

Table 36 Catchment risk-assessment methods (width of triangles indicates increase or decrease)

Effort, resources, data requirements	Risk-assessment methods relying on varying levels of sophistication	Informative value	Uncertainty
▲	Site inspection of observable features potentially introducing, reducing or removing hazards (without any further in-depth assessment of risk) Qualitative assessment of the risk of hazards to reach the raw-water offtake (as the example given in "Practical illustration of a qualitative assessment of the degree of inherent protection of surface water" in Section 4.3.3) Quantification of factors determining loads and/or factors influencing transport and attenuation along the relevant pathways, and of contaminant concentrations Semiquantitative risk assessment using GIS-supported index or scoring methods Quantitative modelling of transport and attenuation in the catchment and in the waterbody	▲	▼

To choose an approach that provides acceptable results but is both reasonable and feasible under the given local conditions, the following aspects need to be taken into account:

- What resources are available for performing the assessment and filling data gaps?
- How complex is the system?
- What information is available, or can be readily obtained or easily generated?
- How accurate is the information available?
- What technical and methodological expertise is available within the WSP team?
- Is it possible to acquire external expertise?

Simple and qualitative risk assessment

One of the most basic forms of risk assessment is the "descriptive" risk assessment approach – whereby hazards and hazardous events can be assessed and prioritized (e.g. assigned a significant, medium or low ranking) based on the judgement of the WSP team. This approach should include consideration of how likely the hazardous event is to occur, and how serious the consequences may be and what control measures are in place to prevent the event from happening. This approach allows the WSP team to document the issues that are of greatest concern, and that should be addressed as a priority. Box 4.9 describes how sanitary inspection forms can support the risk assessment process.

Box 4.9 Sanitary inspection forms to support WSP implementation

Sanitary inspection is a powerful on-site fact-finding activity that can strongly support WSP implementation, in particular to identify potential hazards and hazardous events, and thus inform the risk assessment process. Sanitary inspections are particularly useful for simple systems – for example, smaller communities, households or non-piped systems using surface water as a source of drinking-water. Sanitary inspections typically make use of standardized sanitary inspection forms. The sanitary inspection forms are Yes/No questionnaires with a limited number of questions that focus on frequently encountered sources of microbial hazards, and on obvious possible deficiencies in design and operation of a water supply. The number of positively answered questions is called the "total risk score", and it is subsequently classified according to its proportion of the total number of questions. A detailed discussion on the design, evaluation and refinement of sanitary inspection forms is given in WHO (1997).

Semiquantitative risk assessment

Semiquantitative approaches use scoring or index methods (as exemplified in Table 35), sometimes carried out with GIS (Foster & McDonald, 2000; Macary et al., 2014; Romanelli et al., 2013). In such an assessment, the "risk index" derived is based on easily measurable and available parameters such as land cover, terrain slope and soil characteristics. Foster and McDonald (2000) present several examples of the use of GIS in risk assessment on a catchment scale; these include *Cryptosporidium* hazard mapping and assessment of the risk of road tanker spills. Use of a semiquantitative risk assessment on a catchment scale is discussed in more detail below.

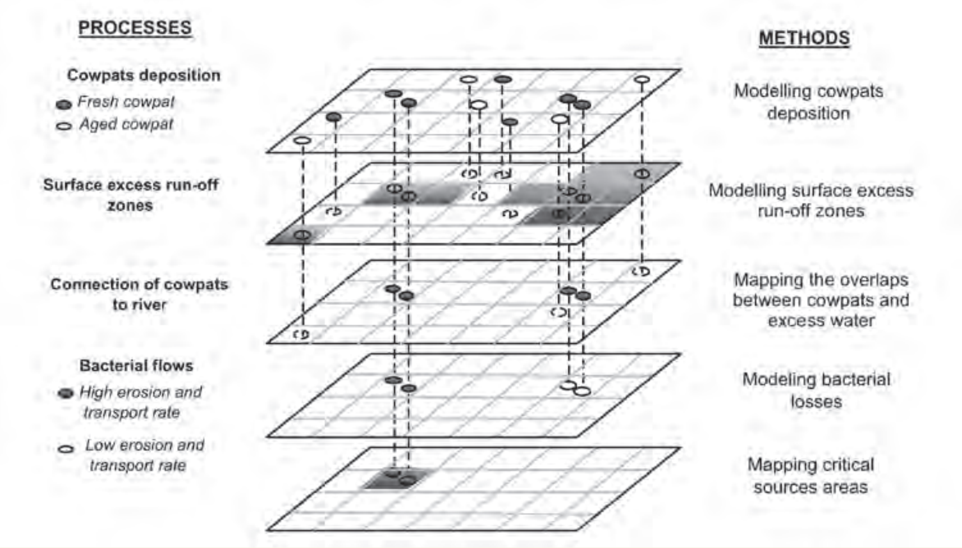
Quantitative risk assessment

A more sophisticated quantitative approach might use simulation models (e.g. Collins & Rutherford, 2004; Trevisan et al., 2010) and require measurement results as input data. Such data can range from established parameters that are easy to measure such as nitrate or faecal bacteria, to more complex parameters such as molecular-biological analytical methods; for example, microbial source tracking based on quantitative polymerase chain reaction (qPCR) techniques (e.g. Astrom et al., 2013). Complex modelling approaches may rely on hydraulic modelling; for example, models of precipitation run-off, or of particle and solute transport and water quality (e.g. Chapra, 1997). An example of a modelling approach to calculate the outflow of faecal bacteria in a catchment is presented in Box 4.10. (For information on quantitative microbial risk assessment (QMRA), see "Risk-assessment considerations for pathogens" within this section).

Box 4.10 Example of a modelling approach to calculate faecal bacteria outflow of a catchment

The figure below shows an example of a modelling approach to calculate the flow of faecal bacteria from cowpats to the outflow from the processes on land in a catchment (Trevisan et al., 2010). The figure highlights the level of sophistication possible with modelling. The approach includes:

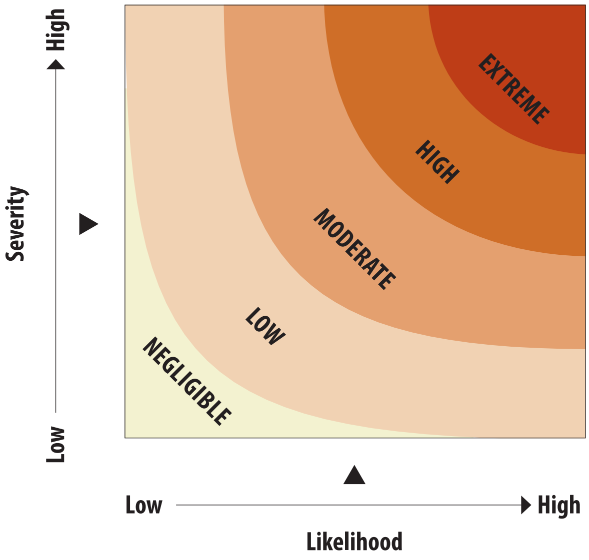
- modelling the distribution of cowpats;
- modelling variable sources of surface run-off; and
- parameterization of deterministic and stochastic functions for modelling bacterial emission from cowpats and retention of bacteria during transport to the catchment outflow.



Semiquantitative risk assessment on a catchment scale

The semiquantitative approach for risk assessment in a catchment setting uses a risk matrix to schematically express the relationship between the likelihood that a hazardous event will occur, and the severity of its consequences. This relationship is illustrated in Fig. 17.

Figure 17 Schematic illustration of the relationship between likelihood, severity and resulting risk and examples of risk categories



Risk matrices typically show the likelihood of occurrence and the severity of consequences of hazards and hazardous events assessed, and the resulting risks. In developing a risk matrix in the context of a catchment risk assessment, the likelihood of occurrence and the severity of the consequence will be influenced by consideration of the degree of inherent protection and the effectiveness of the control measures at the point of hazard release, both in the catchment or waterbody, and at the offtake point (see Sections 4.3.2 to 4.3.4).

Examples of semiquantitative risk matrices are given in:

- *Water safety planning for small community water supplies* (WHO, 2012c), which describes a risk matrix for simple qualitative and descriptive risk ranking; and
- Deere et al. (2001) which describes a risk matrix for a more complex semiquantitative risk ranking using scoring or index methods; this matrix is also presented in Bartram et al. (2009).

Textual descriptions of the likelihood and severity categories (Table 37) and risk categories (Table 39) complement the matrix. The consistent use of terminology in the textual description ensures that the evaluation is transparent and easy to understand.

Classification of the likelihood of a risk occurring may be quite different for different subprocesses in the water supply. For example, an event that happens once in a year in a water treatment plant may be categorized as "unlikely", whereas an event that happens once a year in the catchment (e.g. a thaw) may be categorized as "almost certain".

Table 37 Example of textual descriptions when using a semiquantitative risk matrix

Severity categories	
Insignificant	Insignificant or no impact on public health
Minor	Short term, not health-related non-compliance, or aesthetic impact
Moderate	Significant aesthetic issues, long-term non-compliance, but not health related; occasional interruption of supply
Major	Potential long-term health effect, acute health effect of minor impact; frequent or regular interruption of supply
Catastrophic	Acute public health impact; that is, with potential for severe health effects; no water available
Likelihood categories	
Most unlikely	Less frequently than once every 10 years
Unlikely	Once every 6–10 years
Foreseeable	Once every 2–5 years
Likely	Between every 1 and 2 years
Almost certain	Once per year or more frequently

Source: adapted from WHO (2012c) and Schmoll et al. (2014).

In a catchment area where annual and therefore "regular" snowmelt releases turbidity to the adjacent river, this hazard is categorized as "almost certain" to happen. In contrast, road accidents with spills of hazardous chemicals are significantly less likely, and thus may be categorized as "most unlikely" to happen. Although such classifications are subject to some personal bias, they have the advantages of making judgments explicit and transparent, particularly when the rationale for the classification is documented (see Section 4.3.8). Moreover, undertaking the assessments in a team and subjecting them to discussion is likely to increase their accuracy and to help identify uncertainties that are relevant to the decisions that build on the assessment. In some settings, example matrices are defined by regulatory requirements. This is particularly the case where the matrices are used both by the water supplier (in its internal assessment), and by the surveillance authority (to identify settings that are a priority for action).

Severity categories

Severity can be evaluated by expert judgment, guidelines or other sources of information. Rough assumptions can generally be used as a starting point.

The severity of a hazard depends on its potential impact on human health, the duration of its occurrence and the related impact, and the proportion of consumers affected. Severity categories are most easily estimated for pathogens and for chemicals in the water source, in cases where maximum expected concentrations have been determined (e.g. from raw-water monitoring, including during extreme events such as snowmelt, or strong rainfall after an extended dry period) and the toxicity or infection rate is known. For pathogens, the subsection "Risk-assessment considerations for pathogens" (below) outlines the approach to QMRA, which can be used for this purpose. For chemicals, regulatory limits or guideline values are derived in two different ways: for carcinogens on the basis of a toxicological risk assessment, and for chemicals with a threshold mechanism on the basis of a tolerable daily intake. For the former, lifetime exposure to a concentration of a carcinogen in drinking-water can be related to the likelihood of cancer cases in the population. For the latter, consulting the toxicological derivation (e.g. the steepness of the dose–response curve) for the respective substance is useful in assessing the potential public health impact of exposure to concentrations above the guideline value.

It will not always be possible to express the severity of the consequences as the quantifiable health impact of a given hazardous event (e.g. "leaching of 150 tonnes of substance A with toxicity B"). For example, the severity cannot be expressed in this way unless there is information on how much of the hazard will reach the raw water and hence the consumers, or the harm that is likely to be caused by a given dose. Semiquantitative assessment by means of a classified ranking scale allows a relative evaluation even when specific details are missing; also, it provides an opportunity to make underlying assumptions transparent. The evaluation must take into account characteristics of the hazards that indicate their significance for public health (see Section 2.1).

Likelihood categories

Often, neither measurements nor reliable statistical data are available for estimating the likelihood of hazards and hazardous events occurring in catchments. Therefore, in most cases, it will not be possible to apply the ideal scenario of using a metric scale showing, for example, the statistical return period of a certain event. Adopting values from the literature or from statistical data will often lead to considerable uncertainty.

In practice, a practical, rapid and reproducible evaluation can be achieved by applying classified ranking scales based on expert judgment and the past experience of the operators or responsible authorities (e.g. "turbidity has always increased to the point of filter breakthrough when we've had this much rain in 24 hours"). Preliminary rough but plausible assumptions may be used as a starting point. WSPs also provide a platform for considering future changes; for example, the increased likelihood of the occurrence of certain hazardous events as a result of climate change.

Characteristics of different hazards lead to different behaviour during transport, affecting the likelihood that a hazard will reach the raw-water offtake. For example:

- real solutes are transported more easily and over greater distances than substances that are colloidally dissolved or particle bound;
- a highly biodegradable substance is less critical than a highly persistent contaminant (see "Degradation of chemical hazards" in Section 2.2.3); and
- water-associated pathogens that die off rapidly in the environment or that can easily be inactivated (e.g. by sunlight) are less critical than microorganisms that propagate in the environment or can form stable spores or cysts (see "Occurrence in surface water" in Section 2.1.1).

Risk categories

Table 38 presents an example risk-assessment matrix that describes how the severity and likelihood categories can be combined to yield risk categories. Following the risk assessment, the resulting risk categories (e.g. "negligible" to "extreme", as indicated in Table 38) define the priority or necessity for additional control measures to eliminate or mitigate risks. Table 39 shows an example of possible descriptions of the risk categories. A sixth category ("uncertain") is needed because risk assessment should always include the documenting of information gaps that require further investigation or data (see Section 4.3.7).

Table 38 Example risk-assessment matrix

		LIKELIHOOD				
		Most unlikely	**Unlikely**	**Foreseeable**	**Likely**	**Almost certain**
SEVERITY	**Catastrophic**	High	High	High	Extreme	Extreme
	Major	Moderate	Moderate	High	High	Extreme
	Moderate	Low	Low	Moderate	Moderate	High
	Minor	Negligible	Low	Low	Moderate	Moderate
	Insignificant	Negligible	Negligible	Low	Low	Low

Table 39 Example of textual descriptions of risk categories and resulting prioritization of action

Risk categories and resulting priority for taking action	
Negligible	***Clearly not a priority*** No action is needed at this time, or actions may be taken but not with priority. No special attention is required, but the risk should be revisited in the future as part of the WSP review process.
Low	***Not a priority*** Actions may be taken as part of routine operation. Both the risk and the measures in place to control it should be described in documentation in order to maintain the controls implemented and to manage them well, and they should be considered in the future, especially when changes in the catchment take place, or as part of the WSP review process.
Moderate	***Medium priority*** Currently there is no impact on drinking-water safety, but attention is required in operation and/or possible improvements in the medium and long term to continue minimizing risks.
High	***Priority*** Actions need to be taken to minimize the risk. Possible options (short-, medium- and long-term options) should be documented (as part of the improvement plan) and implemented based on priorities and available resources.
Extreme	***Clearly a priority*** Serious negative impacts on drinking-water safety and even interruption of the supply cannot be excluded. Check short-term options to mitigate acute consequences; examine alternative water resources.
Uncertain	***Clarification needed*** Further data collection or studies are required to better understand the significance of the risk. Some action can be taken in the meantime as deemed necessary to reduce risk based on existing information, community priorities and available resources.

WSP, water safety plan

Source: adapted from WHO (2012c) and Schmoll et al. (2014).

Risk-assessment considerations for pathogens

Some pathogens occur naturally, even in pristine environments, and thus should always be expected in untreated surface water, even in the absence of human settlements and animal husbandry. The variety and concentration of pathogens may range from very low in a completely pristine area where access by wild and domestic animals and humans are restricted, to very high in an area strongly affected by human or animal faeces. For guiding assessments of public health risks and for setting priorities when deciding on control measures, it is useful to estimate the pathogen concentrations expected – on average and at maximum – following specific short-term or continuous hazardous events. As a first step, such an estimation may identify major sources of pathogen pollution and options for controlling these sources, thus reducing the maximum pathogen concentrations likely to occur in the raw water.

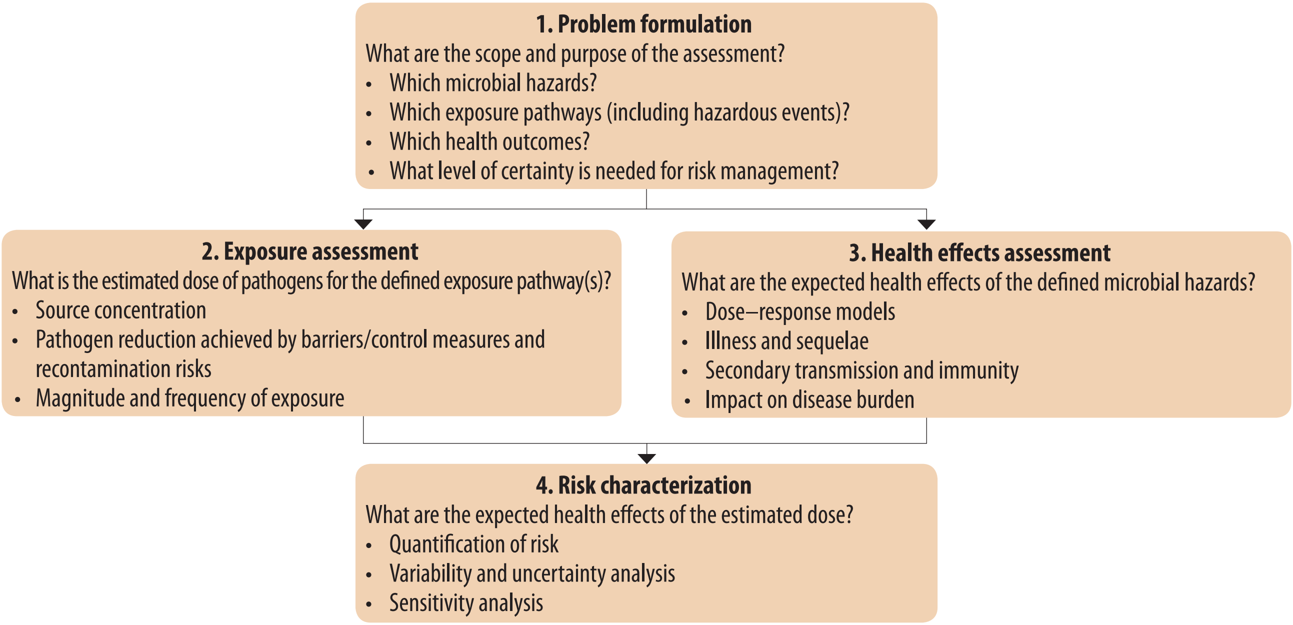
At one end of the spectrum are drinking-water utilities in metropolitan areas that need to use surface water into which wastewater has been discharged. Such utilities face the challenge of demonstrating that their treatment chains are sufficiently effective to remove pathogens, including highly infectious viruses and parasites that are resistant to disinfection. At the other end of the spectrum are small communities that need to prioritize interventions such as providing or improving safe sanitation to protect the raw water, or treating the drinking-water.

An estimate can be based on pathogen characteristics (e.g. infectivity, severity of disease and survival time outside a host), combined with an assessment of concentrations likely to be released into a waterbody and of attenuation within it. Such estimates may serve to prioritize risks of infection from different sources; for example, parasites shed by livestock on pastures close to the drinking-water reservoir compared to viruses or Vibrio shed by an infected population living in a town a certain distance upstream.

A number of risk-assessment approaches are available for estimating both the overall risks to the safety of surface water used for drinking-water (see "Risk-assessment approaches" in Section 4.3.5) and the risk of pathogens in surface water, with varying degrees of complexity and associated strengths and limitations. Where simplified risk assessments are sufficient to support risk-management decisions, it may not be necessary to undertake more complex and resource-intensive risk assessments (WHO, 2016).

QMRA is a more complex risk-assessment approach that may be adopted for assessing the infectious risks from pathogens in a specific waterbody. The framework for water-related QMRA is presented in Fig. 18; it includes four essential activities related specifically to microbial risk assessment.

Figure 18 Framework for water-related quantitative microbial risk assessment



1. Problem formulation
What are the scope and purpose of the assessment?
- Which microbial hazards?
- Which exposure pathways (including hazardous events)?
- Which health outcomes?
- What level of certainty is needed for risk management?

2. Exposure assessment
What is the estimated dose of pathogens for the defined exposure pathway(s)?
- Source concentration
- Pathogen reduction achieved by barriers/control measures and recontamination risks
- Magnitude and frequency of exposure

3. Health effects assessment
What are the expected health effects of the defined microbial hazards?
- Dose–response models
- Illness and sequelae
- Secondary transmission and immunity
- Impact on disease burden

4. Risk characterization
What are the expected health effects of the estimated dose?
- Quantification of risk
- Variability and uncertainty analysis
- Sensitivity analysis

Source: adapted from *Quantitative microbial risk assessment: application for water safety management* (WHO, 2016).

QMRA is an effective method for estimating public health risks for high priority microbial hazards and for evaluating control measures. It is a valuable tool in the development of a WSP. Typically, WSPs rely on simpler risk assessments, such as qualitative or semiquantitative estimates of the likelihood of occurrence and the severity of the consequence. However, QMRA can provide specific quantitative input (e.g. quantitative treatment targets) where necessary (see WHO, 2016).

Box 4.11 shows an example of how QMRA can be used to estimate a risk. Although the concept is termed "quantitative", QMRA can also use qualitative estimates, particularly as a first step; quantitative measurements can then follow, if they are available and if the uncertainty from the qualitative estimate proves relevant to the decision. QMRA is an iterative process that needs to be repeated when new information becomes available or when health-based targets are redefined.

For further information on dose–response data for selected pathogens, see *Quantitative microbial risk assessment: application for water safety management* (2016).

Box 4.11 Example calculation of the risk of infection from consuming drinking-water contaminated with enterovirus

1. Enterovirus concentration in raw wastewater is between 1 and 1000 virus particles per litre.
2. Conventional wastewater treatment leads to a 1 Log reduction, to give a concentration of between 0.1 and 100 virus particles per litre in effluent.
3. Dilution in the river water leads to a 44 times reduction, to give a concentration of between 0.0022 and 2.2 virus particles per litre at the point of wastewater discharge.
4. Travel time of the river water from the wastewater discharge point to the offtake point for drinking-water consumption is 2 days. The river water temperature is 20 °C. The respective inactivation rate coefficient (Equation 1; Section 2.1.1) is $10^{-(1.8-0.035 \times 20)} = 0.079$ Log_{10} per day. Thus, after 2 days, 69% (i.e. $10^{2 \times 0.79} \times 100\%$) of the virus particles are still infectious.

Hence, the concentration in the river water at the offtake point is between 0.0016 and 1.6 virus particles per litre.

5. Assuming a 4 Log_{10} reduction in concentration by drinking-water treatment processes (e.g. filtration and disinfection), the concentration in the final treated drinking-water will be between 1.6×10^{-7} and 1.6×10^{-4} virus particles per litre.
6. Assuming consumption of 2 L of unboiled drinking-water per person per day, and that every enterovirus is infectious, the probability of exposure is then equal to the infection risk per person per day: $1\text{-}e^{(-\text{virus concentration} \times \text{volume})} = 3.2 \times 10^{-7}$ and 3.2×10^{-4}. Applying the dose–response relationship to rotavirus, which is the most infectious enterovirus – describing its infectivity, about 50% is infectious (Teunis & Havelaar, 2000) – then this risk would be halved.
7. The infection risk per person per year can be approximated by $1\text{-}(1\text{-risk per day})^{365}$, which varies between 5.8×10^{-5} and 5.4×10^{-2}.
8. This risk level may be compared to the health-based target level as specified in national standards or as suggested in the GDWQ (e.g. 10^{-4} to 10^{-6}). If the target is exceeded, measures need to be taken. In a full risk assessment, use of a 95-percentile of the risk should be considered.

Note that this is a simple point estimation based on a low and a high virus concentration in wastewater. In a full risk assessment, variability (at least) and uncertainty should be taken into account in all steps of the assessment.

A number of computational tools support QMRA, particularly for steps 5–7. One such tool is QMRAspot, in which the virus concentration in the water at the offtake point can be given in the form of a mean and a 95-percentile value (Schijven et al., 2014).

Measuring pathogen concentrations in a waterbody used as a source of drinking-water is a complementary approach to estimating concentrations from loads and attenuation processes. Such measurement does not necessarily require continuous monitoring; rather, it can be done using targeted sampling campaigns under specific conditions, ideally reflecting both typical (seasonal) situations and extreme events. An investigative programme can be run for a year, for example, with specific sampling to be repeated when a risk assessment (e.g. a WSP) is reviewed and revised. Raw-water data on the range of pathogen concentrations to expect are a valuable basis for developing control measures in the catchment and waterbody, and in drinking-water treatment where necessary.

Risk-assessment considerations for chemicals

Depending on the geological circumstances, some chemicals may occur naturally in surface waters at concentrations relevant to public health (see “Inorganic chemicals” in Section 2.1.2). However, most chemicals of concern in surface waterbodies reach the water from human activities, with those activities being the source of the substance or creating a pathway for it to reach the waterbody, or both. Therefore, as for pathogens, the variety and concentration of chemicals may range from very low in a completely pristine area with little human activity in the catchment, to very high in a heavily used catchment with few or inadequate measures to contain chemicals and to protect land surfaces from loss of their attenuation capacity. The chemical legacy of historically poor management practices can mean that chemicals used decades earlier may continue to impair surface-water quality, particularly where transport pathways are slow (e.g. via groundwater), or where chemicals are persistent and accumulate in waterbody sediments.

For guiding assessments of public health risks and for setting priorities when deciding on priorities for the risks, a useful approach is to estimate which chemicals might be expected in the surface waterbody used to abstract drinking-water at concentrations close to or above regulatory limits or guideline values in the GDWQ. (For considerations for trace chemicals for which there are no regulatory limits or drinking-water guideline values, see Section 2.1.2.) The estimation is an important first step to:

- support identification of major chemical pollutants and options for their control;

- identify chemicals to analyse, provided there is an option to design a screening programme for assessing maximal concentrations to expect in the waterbody and at the drinking-water offtake; and
- assess whether treatment steps to mitigate the concentrations of chemicals are likely to be needed (potentially after a screening programme to identify their maximum concentrations in the waterbody), or – vice versa – to demonstrate that this is unlikely to be necessary.

In addition to the likelihood of occurrence, the risk assessment needs to consider the severity of potential health impacts of the chemical in question. The characteristics of chemicals outlined in Section 2.1.2 (summarized in Table 40) can be used in combination with information about the catchment and waterbody to estimate the risk of chemicals reaching a given surface waterbody at concentrations relevant to public health. Such first estimates may serve to identify priorities for interventions at the source of their release to the waterbody.

Table 40 Characteristics of chemicals relevant for risk assessment (width of arrows indicates extent of severity or likelihood from high to low)

Characteristics and information	High severity or likelihood		Low severity or likelihood
Toxicity	Pronounced	▶	Unlikely or non-toxic
Persistence versus biodegradability	Persistent	▶	Rapidly degraded
Volatility	Low	▶	High
Solubility	High	▶	Low
Adsorption to suspended solids	Low	▶	Pronounced
Concentration estimated or measured in samples	High	▶	Low
Mode of release or formulation and physical state	Readily available for transport, or released as solution or suspension (e.g. liquid manure or slurry)	▶	Slowly or gradually available for transport/released as solid (e.g. dung)

More accurate estimates may be achieved by scientific approaches using modelling techniques and physico-chemical properties of the respective substance (as outlined in Table 6, Section 2.1.2) together with information on the chemical's pathway over land and in water (Section 2.2).

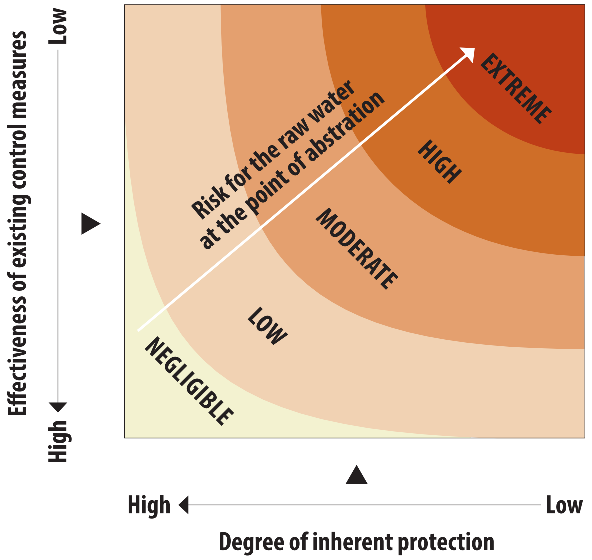
4.3.6 Prioritize the risks of raw-water contamination at the offtake point

The risk to raw-water quality at the offtake point is different for each hazard and hazardous event assessed. It is based on assessment of the system-specific risks within the catchment, and includes consideration of:

- the degree of inherent protection of the raw water (see Section 4.3.3);
- the effectiveness of the control measures applied (see Section 4.3.4); and
- the likelihood that a hazardous event will occur and the severity of its consequences (see Section 4.3.5).

The risk categories resulting from this assessment (Fig. 19) can be used to prioritize control measures to eliminate or mitigate the identified risks. They can also inform the drinking-water treatment required, based on the level of attenuation that needs to occur during treatment and disinfection. Table 39 provides an example of possible descriptions of the risk categories.

Figure 19 **Risk for the raw water at the offtake point resulting from the degree of inherent protection and the effectiveness of existing control measures**



4.3.7 Risk assessment data gaps and uncertainties

The risk assessment needs to take into account uncertainties at all levels of the process. Uncertainties may result from knowledge gaps in input information, or inaccuracies in measurement data. In most assessment processes, the WSP team can expect to encounter gaps in knowledge. At first this may seem to make the risk assessment difficult or impossible. However, if significant knowledge gaps are identified, this supports and prioritizes activities for gathering or generating the missing information. Therefore, knowledge deficits should not stop the WSP team from beginning and proceeding with the risk-assessment process, while keeping a record of the uncertainties.

Some gaps in essential input information can be addressed using proxy assumptions or simulations, the outcome of which can show whether specific data gaps are relevant to the resulting assessment. The effect of proxy assumptions can be tested by considering the extreme ends of the likely range for a given parameter; the use of worst-case assumptions as defaults leads to conservative results.

An adequate raw-water monitoring programme complements the assessment of the degree of inherent protection and provides data that help to reduce uncertainties. In addition to inaccuracies in measurement data and knowledge gaps, especially for spatial issues, it may be useful to check whether the topographic scale of information in maps, aerial photographs and digital geodata provides sufficient resolution for the assessment.

The varying levels of sophistication for risk-assessment approaches are discussed in “Risk-assessment approaches” in Section 4.3.5. Uncertainties are undoubtedly large when using simple approaches, the informative value of which may therefore be limited (Table 36). However, complex approaches require detailed data to produce robust results, and in practice such data are often not available or can only be obtained through unreasonable effort. Therefore, even complex approaches involve making assumptions for some uncertainties, which in turn leads to uncertainties in the output. It is thus crucial to document and include uncertainties in the reports of the outcomes (see Section 4.3.8). A critical assessment of the input information is also important, to avoid a pretence of accuracy that is not borne out in reality.

4.3.8 Document the risk assessment

During development of a WSP, details of the following should be clearly documented:

- the *hazard analysis*, including identification of hazards and hazardous events, and the basis for the analysis;
- the *control measures* identified, including any upstream mitigation measures that have been established in the catchment, and who is responsible for the implementation and operational monitoring of such measures;
- *validation* of all identified control measures, including information relating to their effectiveness; and
- the *risk assessment,* including any uncertainties or lack of information that lead to preliminary assumptions (Section 4.3.7); these assumptions should be identified clearly and described in detail.

Documentation is required to guarantee the transparency of the assessment.

In relation to hazard analysis, it is best to differentiate between deliberate hazard release (e.g. permitted, in accordance with regulations or established operational practices), and accidental or illicit hazard release (e.g. assuming improper handling or unintended spills). Such differentiated analysis will often lead to different estimations of the likelihood of such events. Risk profiles for a given combination of hazard and hazardous event are useful for the analysis. As shown in Table 41, they include a description of the hazard identification, the assessment criteria and the results. The profiles also provide space for additional information, references and notes for follow-up actions required.

The "Fact sheet code no." can be used as a reference in subsequent documentation and assessment steps; for example, as a generic identification when linking risk-assessment results with spreadsheets, maps or GIS data. The risk fact sheet will provide all basic attributes of the objects stored in the GIS database.

4.4 Develop, implement and maintain an improvement and upgrade plan

The risk assessment leads to a ranking of the hazards and hazardous events needing urgent attention. It should also lead to recommendations for further action; for example, the introduction of new control measures if the existing ones are found to be insufficient. The assessment usually also identifies information gaps and uncertainties that may need to be resolved before it is possible to make a decision on implementing additional control measures.

It is not feasible to address every possible risk to the surface-water source. Rather, a stepwise approach is useful that deals first with the highest risks and takes into account what can be achieved with the resources available, and with the stakeholders who are willing to take action. The risk assessment should, therefore, lead to a documented, step-by-step improvement and action plan that prioritizes further action based on the assessment, and the resources that are available or can be mobilized. This plan should include information on what should be done and why, by when, by whom and with what resources. It should also document the status of implementation of these actions (see examples in Table 42).

Input and support from multiple stakeholders is often required, to fully implement an improvement in a catchment setting. For example, a water supplier may identify that stock exclusion from a waterbody is required through the provision of fencing; however, fencing programmes (and their associated budgets) may be controlled by a separate entity, such as a catchment management authority (Box 3.1, Section 3.3.3).

Table 41 Example of a risk fact sheet for catchment risk assessment

Surface-water WSP – Risk profile	
Fact sheet code no.	11
Version (last modified)	01/12/2015
Hazard analysis (Section 4.3.1)	
Hazardous event	Agriculture: Spreading of slurry on grassland even early in spring on waterlogged or frozen soils, exceeding the absorption capacity of the soil, leads to introduction of slurry to surface waterbody (direct run-off).
Hazard	Microbial hazards such as faecal bacteria or parasites (e.g. *Cryptosporidium* or *Giardia*), and chemical hazards (e.g. nitrate or veterinary pharmaceuticals). (Risk assessment focuses on microbial aspects because severity of impacts from chemical hazards are considered secondary to those from pathogens.)
Basis or evidence for hazard analysis	Observations frequently reported by local inhabitants; evidence seen during site inspections; increased faecal bacteria levels detected in tributaries draining the intensively used grassland.
Degree of inherent protection (Section 4.3.3)	
Risk-reduction capacity in the catchment	Activity takes place at a large distance from the water offtake point on flat terrain; steeply sloped areas towards the waterbody are mostly forested. Overall risk-reduction capacity of the catchment is considered high.
Risk-reduction capacity in the waterbody	Natural UV-disinfection in the rather shallow reservoir and retention time in the range of 4–8 weeks reduce the likelihood of occurrence of pathogens in the drinking-water. Overall risk-reduction capacity of the waterbody is considered high.
Existing control measures (Section 4.3.4)	
Description of existing control measures	Legal framework and guidance document on good practice in slurry application exist (i.e. control measure at the point of activity/hazard release).
Validation for existing control measures	The legal framework and guidance document for slurry application are based on scientific literature; limitations, if implemented, should be sufficient to prevent direct run-off.
Risk assessment (Section 4.3.5)	
Considering: • risk-reduction capacity in the catchment and waterbody (i.e. degree of inherent protection) • effectiveness of existing control measures at the point of hazard release, in the catchment or waterbody and at the offtake point	**Event likelihood:** Medium (possible) **Severity:** High (major) **Risk:** High Basis for classifications: *Risk reduction*: The area with land use as described above is situated in the outer catchment; spreading is common only in flat terrain; steep slopes towards the adjacent watercourse are mostly forested; discharge from grassland to watercourse occurs only in extreme situations after torrential rainfall, with the riparian strip acting as quite effective buffer; activity occurs at a distance from the offtake point. *Effectiveness of existing controls*: Spreading takes place several times a year under inadequate conditions, and has been observed during site inspections; local awareness of requirements and implementation appears limited or unclear. *Likelihood*: Although spreading takes place regularly under suboptimal conditions, the high risk-reduction capacity of the catchment reduces the likelihood to medium. *Severity*: High concentration of pathogens present in slurry, alongside the potential for health effects if pathogens are insufficiently removed by rapid filtration and are resistant to disinfection, resulting in a high severity.
Consequences of the risk assessment (Sections 4.3.7 and 4.4)	
Summary of current uncertainties and information gaps to clarify	Implementation of restrictions on spreading of slurry – why have they been so poorly enforced in this area of the catchment? Load to the reservoir and concentration in raw water at the point of offtake during peak precipitation events: do concentrations of faecal indicators and selected pathogens (*Cryptosporidium*, *Giardia*) increase; if so, to what extent? Water retention time in reservoir during peak precipitation events – how long does it take inflow peaks to reach the offtake point?
Description of control measures to implement or upgrade, and of other improvement needs	Additional control measures in treatment (e.g. rapid filtration, UV disinfection) are required as sufficient raw-water quality cannot be continuously ensured. Respective requirements should be coordinated with staff at drinking-water treatment plant. Initiate information, training and communication programme with farmers to implement the existing legal framework and good practice guideline; that is, develop an understanding of the consequences of spreading in times with critical conditions (e.g. waterlogged or frozen soils, high rainfall intensity expected from weather forecast) and find out their needs for enabling better compliance to good practice. Explore options for legal enforcement of requirements. Focus future site inspections on situation of riparian buffers (width, distance of vegetated area to grassland used for grazing and slurry spreading); document outcomes.

Table 42 Example improvement plan for a catchment and waterbody

Action	Arising from	Improvement	Responsibility	Due	Status
Rehabilitation of embankments of a waste storage dam from an upstream mining facility	Risk of dam embankment breach with subsequent contamination of adjacent stream (raw water for township) Occurrence would result in significant acidification and metal contamination of the waterbody	Dam integrity to be assessed and necessary rehabilitation works are to be implemented (including relining of the dam)	Operator of facility under surveillance of environmental authority (primary) Catchment management authority (secondary)	Within 1 year	Not started
Septic tank inspection programme	Catchment inspection has identified a number of ageing septic tank systems for domestic wastewater treatment High probability that these systems are leaking/ releasing inadequately treated effluent to adjacent waterbody (raw water for township)	Provision of a septic tank inspection programme; to include issuing of enforcement notices for refurbishment/ replacement of non-complying systems Clarify options for connecting to central sewerage system and wastewater treatment	Local council (primary)	To be completed within 3 years	Ongoing
Develop communication protocol for the management of pesticide application	Risk of raw-water contamination during and after pesticide application works (e.g. from accidental spill)	Communication protocol to be developed documenting: (i) staff contact details (ii) roles and responsibilities for coordinating the programme (and during an incident) (iii) procedures for notification of other relevant stakeholders	Catchment management authority Agricultural authority and farmers' associations	Within 3 months	Deferred (needs input from agricultural authority that is awaiting new staff)

The point at which measures for risk management and related investments are most effective depends on the specific situation of each catchment, the policy setting and the stakeholders involved. A pristine catchment may be an ideal, but is rarely achievable in practice because of pre-existing land use. Implementing restrictions on activities in the catchment for the sake of protecting the drinking-water resource may prove challenging, particularly where legal requirements are not sufficiently strong and stakeholders are reluctant to cooperate (e.g. because of concerns about the consequences for their livelihoods). In some settings, it may be most feasible to take action at the level of the activities potentially causing hazardous events (i.e. release of hazards) or through land-use planning measures (e.g. by ensuring that a large new industrial facility will be placed far away from the water offtake point, thus avoiding the need for major water treatment at a later step). However, this will only be possible where the relevant authorities can take action and are willing to do so, and where stakeholders in the catchment are aware of the needs of drinking-water supplies. The challenge is bigger where activities already exist, particularly where a large number of small-scale activities are scattered across the catchment. In such cases, engineered control measures in the catchment to intercept hazards along the flow path between the activity and the waterbody will be the more feasible (or even the only) options for risk reduction. The GDWQ contains guidance on assessing the efficacy of treatment in relation to the expected types of hazards and their concentrations (WHO, In preparation-a).

A range of control measures may be applied at the points of hazard release, to reduce and control related risks. A particularly effective measure is to improve the current practices of existing activities. Current practices can be improved if:

- those operating the activities are motivated to contribute to the WSP; and
- there are regulations that could be enforced more tightly (where those operating the activities are not willing to cooperate).

Such measures are especially important where control measures in treatment alone would not be feasible or even possible. A further option may be financial support for upgrading control measures. This could be as simple as funding the material costs for building a fence around a waterbody. There could also be models of formal collaboration between a water supplier and farmers, whereby the water supplier refunds the farmers' lack of income due to measures taken to improve water quality (e.g. reducing stock density or use of fertilizers).

Developing an improvement plan to reduce risks therefore requires consideration of:

- whether it is achievable to take upstream action towards implementing or improving control measures within the polluting activity;
- whether it is effective and feasible to implement control measures in the catchment (i.e. along the flow path between the activity and the waterbody) or within the waterbody;
- whether downstream action (e.g. in upgrading water treatment) is to be targeted;
- which stakeholders can take action, whether they are motivated to do so and whether they have the required resources; and
- whether reallocation of resources is an option; for example, using financial resources gained from drinking-water fees to reimburse farmers for water-protective farming practices that reduce initial contamination.

Decisions also depend on how quickly the risk needs to be reduced further. Sometimes, intermediate measures need to be taken before comprehensive risk management can be achieved. For example, for reducing health risks from occasional short-term occurrences of chemicals, it may be best to apply a precautionary principle and negotiate upstream controls with the emitting enterprises even without previously assessing the risk in detail. This approach may avoid the need to invest in expensive and energy-demanding treatment technology.

In contrast, downstream barriers in treatment (e.g. filtration and disinfection) are important, particularly for risks from pathogens that could have major and immediate impacts on public health upon exposure. Even in a catchment with little introduction of human pathogens or with excellent attenuation along the flow paths to the waterbody, the risk of pathogen introduction from wild animals and water fowl remains. Furthermore, particularly in the case of pathogens, redundancy of barriers is desirable to ensure safety at all times (i.e. the multiple-barrier approach).

To finalize the risk assessment for a drinking-water supply system, the presence and validation of all control measures – both in the catchment and throughout the entire drinking-water supply system – is necessary to ascertain that, together, they are sufficiently effective to achieve the target of protecting public health from waterborne disease (Section 4.3.4). If the outcome shows that further actions, improvements or interventions are necessary, management actions need to be developed, taking into account the setting and particularities of each single system.

4.5 Define monitoring of the control measures

Operational monitoring as part of a WSP aims to demonstrate the performance of control measures. It comprises ongoing observations or measurements (e.g. visual checks of the integrity of a fence in the catchment), selection of process parameters that are easy to monitor, and the setting of limits that the parameters should not exceed. Where operational monitoring shows a parameter to be outside the predefined limit, this should trigger corrective action. Operational monitoring should not be confused with end-product testing, which can only confirm that a hazard is present in or absent from the sample tested. For engineered components of the catchment (e.g. stormwater and wastewater treatment systems) operational monitoring can be conducted in much the same way as for drinking-water treatment plants or any other engineered system specifically designed to control hazards.

The spatially extensive nature of catchments affects the type of monitoring that is feasible. Automated in situ, online or real-time monitoring is common at treatment level, and increasingly so at distribution level. Such monitoring is not as prevalent for catchment monitoring, although its use is increasing and it does have an important role. Instead, monitoring in catchments tends to be largely observational, long term and relatively infrequent, in line with the frequency with which a control measure may fail. For example, inspection of fencing may occur annually by observation, because deterioration of the material typically does not happen within minutes; however, electronic systems signalling interruption of a fence are feasible in some cases and can be set up where appropriate. Monitoring of amounts of slurry or fertilizer applied may rely on inspection of farmers' records (if available) and may occur only seasonally. Similarly, monitoring of stock density by counting heads of stock is only feasible periodically in very small catchments.

Monitoring may include surveys of community attitudes, beliefs and behaviours where control measures depend on these. Such surveys might only be possible every 5 years, for example. Nonetheless, in principle, the concepts that apply to monitoring in catchments are the same as those for any other stage in the water supply; that is, process monitoring should focus on ensuring that control measures are working as intended. The monitoring should have the capacity and should be frequent enough to detect and trigger a response to deviations, so that corrective actions are initiated in time to prevent unsafe water being supplied.

An operational monitoring plan should summarize what will be monitored, where, how, by whom (e.g. depending on legal duties and competences) and when. Monitoring will require collaboration and cooperation between different stakeholders in the catchment; for example, when implementing routines of information exchange and reporting between local authorities and the water utility.

The tables in the activity-specific sections of Chapter 3 include examples of activity-specific control measures, as well as options for their operational monitoring.

Corrective actions

Corrective actions are planned responses to be taken when the results of operational monitoring of a control measure indicate a loss of control during standard operation. Examples include:

- repairing a fence if operational monitoring has shown that it is damaged and can therefore no longer properly prevent animal access;
- reducing the size of a cattle herd if monitoring shows that it exceeds the numbers agreed as acceptable for a given piece of pasture; and
- balancing excessive application of fertilizer or slurry by imposing a strict limitation, including tighter surveillance, in the subsequent season.

Examples of control measures, their operational monitoring and corrective actions are given in Table 43.

Table 43 Examples of operational monitoring requirements and corrective actions for a catchment and waterbody

Process step and control measure	Critical limit	What?	Where?	When?	How?	Who?	Corrective action
Protection of raw water for drinking-water supplies Stock exclusion agreement with landholder	Exclusion of calves and lambs from source-water shoreline	Presence of juvenile animals at shoreline	Site inspection of shoreline	Annually during birthing season	Visual inspection	Catchment officer	Meet with landholder and examine stock exclusion options
Protection of raw water for drinking-water supplies Dam integrity at upstream mining facility	Visible damage to dam integrity	Dam integrity (including lining of the dam)	Dam (entire length) and lining	Twice per year	Visual inspection	Mine operator	Repair of damaged parts of dam

In catchments, many of the control measures and monitoring activities are likely to be outside the control of the water supplier or catchment management organization. For example, if a sewage treatment system is malfunctioning or a stock animal exclusion fence has been breached, the water supplier can call attention to the problem and start the process of giving it attention, but it is likely that the matter will need to be resolved by the stakeholder concerned (e.g. the sewage treatment plant owner or the landowner, respectively). It may not be possible to enforce actions quickly. Therefore, given that a second barrier increases safety of the water-supply system, it may be necessary to consider downstream corrective actions in addition to actions at source. This is why it is crucial to include local health and catchment authorities in the WSP process, as well as other stakeholders who may be able to take or enforce action, or to mediate in such processes.

4.6 Verify the effectiveness of the WSP

Verification involves obtaining evidence that the WSP is working effectively to meet health-based targets. This includes traditional end-product testing to confirm compliance with drinking-water targets or standards, as well as WSP auditing and monitoring of consumer satisfaction. Verification confirms the effectiveness of the entire WSP, including the elements addressing catchment protection. Specific monitoring of raw-water quality at the offtake point provides valuable information on both the efficacy of the control measures taken with respect to activities in the catchment, and the risk-reduction capacity of the catchment. Such data provide useful information about what treatment is required to meet the quality targets for finished drinking-water. Box 4.12 provides guidance on auditing catchment elements of a WSP.

Box 4.12 Considerations for auditing a WSP for a catchment

Auditing supports the continuous improvement of WSPs, and is essential to the success and sustainability of a WSP. The audit is an independent and systematic check of a WSP to confirm its completeness, adequate implementation and effectiveness at managing risks along the complete water-supply system, from catchment to consumer. Thus, the thorough audit should confirm that catchment-level risks are being appropriately addressed. A WSP audit may check that, for example:

- the catchment is appropriately delineated and described in the WSP;
- all relevant hazards and hazardous events within the catchment have been identified, associated risks have been appropriately assessed and controls are effective (as evidenced by validation and operational monitoring records);
- any catchment-level improvement and upgrade plans needed to reduce risks to acceptable levels are being implemented in practice; and
- standard operating procedures (SOPs) cover key operational activities within the catchment, and emergency response plans consider catchment-level events.

In principle, WSP auditing considers risk management at the catchment level; in practice, the catchment focus may be limited by the expertise of the WSP auditor or by audit time constraints. To ensure due focus on catchment-level risks during WSP auditing, development of customized WSP auditing tools is recommended. Such tools should prompt the auditor to duly consider all elements of the water-supply chain.

A practical guide to auditing water safety plans (WHO, 2015c) provides guidance on developing and implementing WSP auditing schemes. The guide includes practical tools, and examples from more than a dozen low-, middle- and high-income countries. It also provides a list of typical threats to water safety in surface-water catchments, and several examples of audit criteria that can be modified as necessary to reflect audit priorities. The examples in the guide provide a useful starting point for the development of customized auditing tools that focus sufficiently on risk management at the catchment level.

Ideally, the complete WSP should be audited externally, but this is not always feasible for the part of a WSP that concerns the catchment and waterbody. However, WSP auditing is commonly undertaken by an audit team that collectively satisfies requirements for auditor skills and competencies. Therefore, it may be appropriate to include an independent catchment expert on the WSP audit team (e.g. a catchment authority without any direct involvement in developing or implementing the WSP).

4.7 Prepare management procedures

Management procedures should be developed as part of the WSP process. Standard operating procedures (SOPs) should be prepared to cover times when systems are operating under normal conditions, and additional procedures for incident or emergency situations. Management procedures should be:

- clear and easily understood by those responsible for their implementation; and
- reviewed following any incident, emergency or “near-miss” scenarios within the catchment and waterbody, to ensure that the procedures and protocols are adequate.

Authorities working in catchments with several small water supplies may consider drafting generic management procedures to support those supplies that have limited human resources.

4.7.1 Standard operating procedures

Examples of SOPs for normal catchment activities include the following, with the relevant authority or organization shown in brackets:

- routine inspection of the integrity of stock exclusion fencing protecting a waterbody (water utility or water authority);
- best management practices for erosion and sediment control (catchment authority);
- routine monitoring of the integrity of a mining dam or embankment, to avoid spill of mining waste (mine operator);
- biocide application protocols for vegetation management (catchment authority);
- fertilizer and manure application schemes (farmers);
- feeding regimes in aquaculture matched to fish intake and satiation time (aquafarmers);
- protocol on inspecting and cleaning of sewers and drains (wastewater utility);
- sanitary inspection and follow-up action for decentralized sanitation facilities (operators and surveillance agency);
- inspections of industrial operations, including tanks above ground and underground (operators of industrial and commercial facilities, and inspection bodies); and
- selective abstraction protocols for seasonal raw-water harvesting (water utility).

These procedures should specify inspection requirements, and follow-up action and related communication protocols, in case non-compliance with the desired condition or action is identified. They should be reviewed regularly to ensure that they are up to date and accurately reflect the dynamic environment of a catchment and waterbody. Training and assessment of competency of those applying the SOPs should be an integral and ongoing part of operator training programmes of the relevant entities.

4.7.2 Incident and emergency procedures

Of particular relevance to catchments, emergency events should, where possible, be managed through the development of situation-specific procedures (e.g. response to oil spills from fuel depots located upstream). However, given the nature of catchments, planning for specific events may not always be possible. Such unforeseen events may be managed by the development of a generic emergency-response procedure, including:

- roles and responsibilities of stakeholders (e.g. catchment management authorities, local industries, emergency services and water suppliers);
- communication protocols (e.g. notification procedures, and staff contact details for relevant agencies, authorities and water suppliers);
- clear reference to relevant management procedures (e.g. alternative raw-water supply for drinking-water);
- water-quality monitoring and public health surveillance requirements; and
- reporting requirements (e.g. regulatory and licensing obligations).

As with SOPs, these procedures should be reviewed and updated regularly, with training on emergency exercises performed regularly. As for the other steps described in this section, the local authority may take the leading role in developing emergency procedures and coordinating them with the relevant stakeholders.

4.8 Develop supporting programmes

WSP supporting programmes are intended to assist the provision of safe drinking-water through the development of human resources and through furthering knowledge and understanding. Supporting programmes may include training, within both the water supply and the relevant authorities, and for those involved in potentially polluting activities, quality control, and research and development programmes. Examples of supporting programmes relevant to catchment and waterbodies include:

- WSP development and implementation training;
- riparian revegetation programmes (e.g. involving local community groups and schools); and
- chemical tracer studies to determine residence time of a contaminant following accidental release of a chemical to a waterbody.

4.9 Plan and carry out periodic review of the WSP

The WSP should be reviewed regularly, and in response to emergencies (see Section 4.10) or significant changes of circumstances (e.g. changes in potentially polluting activities in the catchment). As conditions in the catchment change, or new information and data become available, risks should be re-assessed. WSPs may require updating as a result of the following changes in catchment conditions:

- changes to land use or industrial practices within a catchment (e.g. commencement of mining activities, or centralization of wastewater collection and treatment);
- expansion of existing land use or industrial activity (e.g. expansion of agricultural activities or development of an industrial zone);
- changes in water use (e.g. new impoundments or changes in water abstraction);
- demographic changes (e.g. urbanization or rural exodus);
- changes to regulatory or policy frameworks (e.g. for drinking-water, activities and resource protection); and
- newly implemented control measures.

4.10 Revise the WSP following an incident

Even with the most robust WSP, unforeseen incidents, emergencies and near misses may occur within the catchment. Examples include:

- a severe weather event or natural disaster (e.g. storm, flood, bushfire or earthquake);
- a change in raw-water quality, of unknown origin; and
- a contamination event (e.g. chemical spill, accidental release of domestic or industrial wastewater, algal bloom or identification of contamination of unknown origin in the abstracted water).

Following any incident or near miss, it is crucial that WSPs be reviewed and revised as necessary, to ensure that all risks are adequately managed and that the frequency or severity of a repeat event is minimized. Checklist 10 outlines important considerations for post-incident review of the WSP.

Checklist 10 Post-incident review process to assist with WSP revision

☑ Determine whether the hazard or source of the hazard within the catchment or waterbody is documented in the existing WSP; if not, revise the WSP accordingly

☑ Determine whether control measures are in place for the hazard and source of the hazard and, if they are adequate, determine whether they are working as planned and are sufficiently monitored

☑ Establish whether there are relevant management procedures and, if so, determine their adequacy and revise as required

☑ Ascertain the adequacy of existing communication protocols for catchment stakeholders, and update as necessary

☑ Determine whether relevant technical expertise or information pertaining to the catchment and waterbody is readily available and up to date

☑ Determine whether the risk-assessment matrices and improvement programmes require updating

☑ Determine whether existing trigger levels for incidents are appropriate, and revise as necessary

☑ Establish whether the existing level of training and supporting programmes are adequate.

Source: adapted from Bartram et al. (2009).

ANNEX A

Case studies

Case study A1: Risk assessment for a drinking-water reservoir in Germany[1]

Following a microbial contamination incident in 1993 with *Cryptosporidium* and *Giardia*, the operators of the Wehebach drinking-water reservoir (Wehebachtalsperre) initiated a risk assessment for the catchment area. As this assessment was performed before the WSP concept was introduced by WHO, it used somewhat different terminology. In the following summary, WSP terms are used wherever they are synonymous with the terms originally used in the study.

This risk assessment encompassed:

- compilation and documentation of existing hazards and risks to raw-water quality;
- timely identification of trends and developments in the catchment (i.e. possible future hazards associated with plans for developing land use in the catchment); and
- recommendations for measures to control risks, to enable sustainable protection of the raw-water resource.

The development of the risk assessment was supported by external expertise and largely followed the modules of WSP development (see Fig. 3 in Section 1.1.1 for information on the WSP modules referred to in parentheses below):

Phase 1) System description and data collection (WSP Module 2):

- established an inventory of past and current land use in the catchment; and
- compiled data on relevant catchment conditions; for example, data on soil cover, run-off and drainage in the catchment, as well as susceptibility to erosion and retention capacity for contaminant loads.

Phase 2) Risk assessment for the drinking-water reservoir (WSP Modules 3 and 4):

- assessed land uses in relation to their potential to release hazards;
- assessed the sensitivity of the raw-water resource (i.e. the inverse of the risk-reduction capacity along the flow path); and
- determined the risk of raw-water contamination, using GIS to combine information on potentially polluting activities and on the catchment conditions (taking into account pollution pathways, but not specific hazardous events).

Phase 3) Developing an improvement plan (WSP Module 5):

- suggested and documented practical and specific planning and technical measures for controlling the risks identified in the catchment, including a plan for monitoring.

A1.1 Phase 1) System description and data collection

The risk assessment covered the area included in the reservoir's drinking-water protection zone. This zone is defined according to the German specifications for defining protection zones around reservoirs (DVGW (2002), English version), and differentiates three zones as follows:

Zone I – Protects reservoir from any contamination from the direct vicinity;
Zone II – Protects reservoir and feeding rivers from contamination through human activities or facilities, and may be subdivided into Zones IIa and IIb; and
Zone III – Protects reservoir and feeding rivers from extensive contamination.

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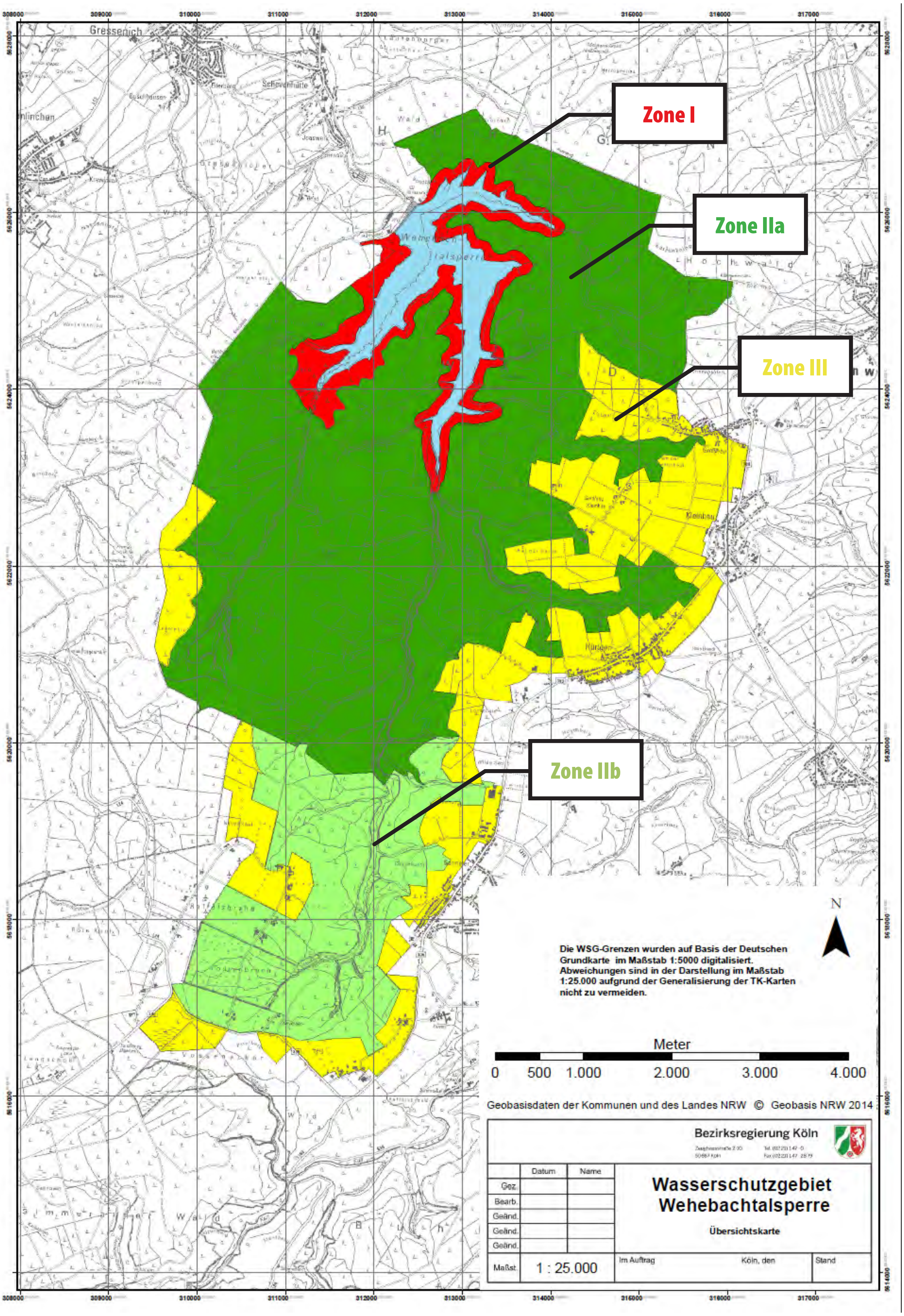
[1] Based on Kirch, Sailer and Coenen (2014).

Figure 20 **Protection zones around the Wehebach drinking-water reservoir**



Zones as established on 1 January 1976 (*Source*: District Government of Cologne).

Catchment information for the risk assessment was collected from a range of sources:

- digital geodata on topography, surface waterbodies and land use from the Land Survey Office;
- information on sites using substances hazardous to water and brownfields, and on potentially contaminated sites, based on information from the pertinent agencies for soil and water protection;
- data on former uses of sites (e.g. mining) from historic maps and information from the operator of the reservoir, the authorities and so on;
- data on wastewater disposal in the area from the responsible water board and the responsible authorities;
- data on forest use from the forest management authorities and on agricultural areas from the board of agriculture;
- digital soil maps and digital geological and hydrogeological maps from the geological service; and
- hydrochemical analytical results from the water supplier, on the raw water and the quality of the tributaries.

The data were entered into digital databases and assessment systems, depicted with help from GIS, and subsequently assessed.

A1.2 Phase 2) Risk assessment for the drinking-water reservoir

In the chosen approach, the risk of raw-water contamination resulted from consideration of both land uses and the sensitivity of the raw-water source.

The assessment was conducted separately for discharges from unsealed surfaces (e.g. agriculture and forestry) and sealed surfaces (e.g. through drainage channels from settlements). For sources from unsealed surfaces, the sensitivity of the raw-water source (i.e. attenuation capacity of the flow path) was predominantly determined by the level of erosion and the likelihood of lateral run-off or interflow. The assessment of sealed surfaces considered the use and the discharge properties of the surface area.

Assessment of land uses

Information on former and current land uses was obtained and assessed. Site inspections were then conducted to verify the data collected during the desk-top phase, particularly data relating to water management. The findings from the site inspections were systematically documented and integrated into the risk assessment.

The national technical rules *DVGW W 101* and *W 102* (DVGW, 2002; DVGW, 2006) provide criteria and principles for bans on activities in catchment areas and how to delineate drinking-water protection areas for groundwater resources for impounded dams. Finally, they provide guidance on a rough risk ranking for certain activities in catchment areas.

This qualitative assessment based on the technical rules was adopted. For example, agricultural uses were assigned a high initial risk, whereas extensive use of grassland was assigned a low initial risk. Unlike the WSP concept, this assessment did not take into account details of severity and likelihood for the risk assessment.

Assessment of the sensitivity of the raw-water source (or the risk-reduction capacity)

The risk assessment for the Wehebachtalsperre waterbody also considered the extent to which soil properties, morphological factors (e.g. slope) and hydrological factors influenced the transportation and attenuation of hazards from their source to the waterbody. That is, the assessment considered the risk-reduction capacity of each of these factors. The factors identified as most relevant were:

- the level of erosion – universal soil loss equation (USLE), according to Wischmeier and Smith (1978); and
- the occurrence of lateral run-off (direct and intermediate run-off, depending on land use, slope, type of soil and soil moisture).

Further aspects that were considered for the risk-reduction capacity were:

- the presence of agricultural areas with artificial drainage;
- the type of drainage from sealed surfaces (e.g. settlements, wastewater discharge); and
- the presence and condition of buffer strips between areas of arable land and flowing waters which serve as protection for input from soil erosion.

Assessment of risk to raw water

The Wehebach reservoir assessment based the risk to the raw-water source on an integrated assessment of the risks for sub-areas of the drinking-water protection zone and the flow path to the surface waterbody; the results were combined using GIS. The risk assessment was subsequently conducted using several matrices that assessed the (potential) hazard input into the relevant tributary to the drinking-water reservoir.

To develop a worst-case scenario (deviating from the prescribed approach in Section 4.3.3), the flow path to the drinking-water reservoir was not considered as a risk-reducing factor. Rather, entering the tributary was considered to be equal to entering the drinking-water reservoir. Further, engineered control measures that were potentially present within the catchment (e.g. erosion protection hedges, riparian strips and sedimentation basins for particles carrying phosphate) were also not quantitatively considered for the assessment. Instead, such measures were considered within the scope of the planning process (see below).

The assessment identified risk areas within the catchment and priorities for action. Risks considered critical were:

- land uses without sufficient distance to surface waterbodies;
- direct discharges via drainages;
- individual tributaries with distinctive features;
- erosion from arable land; and
- levels of heavy metals in main tributaries.

A1.3 Phase 3) Developing an improvement plan

Based on the risk assessment, and taking into account the previously established protective measures (e.g. cooperation with farmers to fence off surface waterbodies adjacent to pastures, avoidance of use of fertilizers on riparian areas, implementation of slurry application measures, adoption of sustainable forestry certification, improvements in wastewater treatment performance and catchment inspections), a concept of measures for the catchment was developed and documented, including:

- continuation and adaptation of the ongoing monitoring processes (e.g. inclusion of additional sampling points at tributaries, and additional sampling to further specify points of entry of contamination at the identified risk areas); and
- safety management and technical discussions: measures for risk reduction and risk avoidance are assigned a priority and discussed with stakeholders from within the water protection zone, including the following agencies and institutions:
  - responsible water authority (that authorize discharge permits);
  - health agency;
  - agencies for water management, soil protection, contaminated sites and waste;
  - chamber of agriculture;
  - cooperative bodies dealing with agriculture and water management;
  - forest management authority;
  - further water suppliers and municipalities which draw water from the reservoir; and
  - operator of the drinking-water reservoir and consultants.

Case study A2: WSP implementation for surface-water protection in Nepal

The Amarapuri water-supply system is located in the Amarapuri Village Development Committee of Nawalparsi District in Western Nepal, serving a population of about 10 000 people in a periurban setting. Raw water for drinking-water supplies is obtained from a local stream (via gravity flow) before treatment (sedimentation, filtration and chlorination), intermediate storage and distribution (through 18 km of distribution pipes, with both public and private taps; Fig. 21). The water-supply system is managed by the community through an elected Water Users and Sanitation Committee (WUSC) which is responsible for the operation and maintenance of the water-supply system.

Figure 21 Amarapuri water-supply system schematic

तालिका नं. १: मुख्य पाइपलाइनको विवरण

मुख्य पाइपलाइन	पाइप साइज	लम्बाइ (मी)	उचाइको फरक (मी) / हेडलस (मी) (डिजाइन फ्लो १० ली.प्र.से.)
मुहान देखि ग्रीट चेम्वर/सेट्लीङ बेसिन सम्म	HDPE १६० मिलिमीटर, ४ के.जी./से.मी.^{2}	५०	०.५ / ०.२
सेट्लीङ बेसिन देखि जङ्गल सम्म	HDPE १६० मिलिमीटर, ४ के.जी./से.मी.^{2}	८००	८.६ / २.८
जङ्गल देखि प्रशोधन केन्द्र सम्म	HDPE १२५ मिलिमीटर, ४ के.जी./से.मी.^{2}	४००	१६.५ / ४.८
प्रशोधन केन्द्र देखि २,००,००० लीटर रिजर्भ टंकी सम्म	HDPE १०० मिलिमीटर, ४ के.जी./से.मी.^{2}	६००	१२.२ / १३.२

प्रशोधन प्रणालीका मुख्य संरचनाहरु

Desilting basin	1 pc
Volume	0.8 m * 11 m^2 = 8.8 m^3
Depth	(0.1 + 0.45 + 0.25) m = 0.8 m
Area	0.6m * 2m + 0.7m * 2m + 2 m * 4.2m = 11 m^2
Surface load, normal	4.5 m/h (deeper flushable area approx. 8 m^2)
Settling tank	1 pc
Area	3.45 m * 13.8 m = 48 m^2
Depth and Volume	2.05 m / 98 m^3
Detention time	2.7 h
Surface load	0.75 m/h
Horizontal flow coarse media filter	3 pc
Area	11.6 m * 14.7 m = 170 m^2
Depth and Volume	1.2 m / 216 m^3
Surface load	2.0 m/h (theoretical against flow direction)
Grain size / length in the filter	1st = 20-12 mm / 2.8 m 2nd = 12-8 mm / 3.0 m 3rd = 8-4 mm / 3.0 m 4th = 4-2 mm / 2.6 m
Slow sand filtration	3 pc.
Area	6.55 m * 12.0 m = 78.6 m^2 /unit Total 236 m^2 (measured: approx. 6.5 m * 11.8 m)
Surface load	0.15 m/h
Size of sand / sandbed	0.2 – 0.35 mm / 1000 – 500 mm
Uniformity coefficient of sand	3.0
Chlorination	1 unit
Solution tank volume	500 l
Solution preparation	Fill the tank daily: 1 kg (1 sachet) / 50 l water
Chlorine dosing	Target: free chlorine 0.2-0.5 mg/l throughout the distribution system, 0.5 (– 1.0) mg/l in reservoir => solution 2 – 3 ml/s / water 10 lps
Reservoir tanks	200 m^3 main area & 36 m^3 remote villages
Detention time (200 m^3)	5.6 h

Source: Amarapuri water safety plan.

The catchment area is predominately forested, with steep slopes, and includes human settlements. Human activities upstream of the offtake point for drinking-water supplies that may influence raw-water quality include forestry, recreational (e.g. swimming and picnicking) and domestic activities (e.g. bathing and washing).

Catchment management within the Amarapuri water-supply system is the joint responsibility of the WUSC and a dedicated forest management community group: the Sundari Community Forest Management Group.

A2.1 WSP team (WSP Module 1)

The WSP concept was adopted by the WUSC in Amarapuri in 2010. The WSP team is composed of 12 members, with a team coordinator nominated by the WUSC. In addition to representatives from the WUSC, members were selected from management and operational staff of the water-supply system, health workers, local teachers, social workers, a local mothers' group and water-supply users. An engineer from the district water-supply office who had experience of WSPs facilitated the process.

For catchment-level risk identification, assessment and management activities, the WSP team was supported by external expertise as required; for example, representatives of the Department of Water Supply and Sewerage, Nepal (the government agency with responsibility for delivery of national water-supply and sanitation programmes); WHO; and expert consultants.

A2.2 Hazard identification and risk assessment (WSP Modules 3 and 4)

Hazard identification within the catchment was undertaken by the WSP team, and was based on a combination of:

- field visits (Fig. 22);
- consultation with catchment stakeholders; and
- anecdotal (i.e. word-of-mouth) reports from operators of the water-supply system, community members and individuals who were familiar with activities within the catchment.

Figure 22 **WSP team undertaking field visits for hazard identification in the Amarapuri catchment**

Following the hazard identification process, several high-risk activities were identified within the catchment, as presented in Table 44. A simple risk assessment approach was adopted, whereby the WSP team considered the risk posed by each activity and assigned a risk score (Table 44).

Table 44 Excerpt from the Amarapuri water-supply system hazard identification and risk assessment for the catchment

Hazardous event, source of hazard(s)	Risk score (1–4)[a]
Domestic use of raw water upstream of the offtake (i.e. bathing and washing of clothes)	4
Recreational activities upstream of the offtake (i.e. swimming and picnicking)	4
Pesticide application close to the raw-water offtake	4
Open defaecation adjacent to raw water	4

[a] A score of 1 represents the lowest risk and 4 represents the highest risk.

Source: adapted from Amarapuri WSP.

A2.3 Improvement planning and operational monitoring (WSP Modules 5 and 6)

Following the process of hazard identification and risk assessment, several system improvements were identified and implemented to manage catchment-related risks for water quality within the Amarapuri water-supply system, as outlined below.

Establishment of a catchment protection zone

A catchment protection zone was established: all activities 2 km upstream of the raw-water offtake are controlled by the WUSC, and any land disturbance or new activity within this zone must be reviewed and approved by the WUSC. The creation of this zone was achieved through consultation and negotiation with the Sundari Community Forest Management Group, the primary land users within the catchment. Because many of the forest management group are also members of the Amarapuri community (and therefore users of the water supply), the benefit of protecting surface water for the health of the community was used to influence stakeholders. A memorandum of understanding was signed by both parties to formalize the agreement. This arrangement is enforced through public notice and regular inspection by a caretaker.

Establishment of a code of conduct within the catchment

A code of conduct was established that controls the domestic and recreational use of the raw-water supply (e.g. bathing, washing, swimming and picnicking) upstream of the raw-water offtake for the Amarapuri drinking-water supply. The code also controls the application of pesticides in proximity to the raw-water supply. A caretaker is responsible for monitoring and enforcement, with penalties in place for individuals found to be in breach of the code. Public consultation and raising of awareness resulted in much support from the community and water users, which may support community-level enforcement of the code.

Sanitation improvements within the catchment

Following the identification of open defaecation practices within the catchment as a threat to surface-water quality, the WSP team established links to sanitation initiatives within the community. Discussions were held with key stakeholders – the district-level government agency with responsibility for water supply and sanitation, and the Village WASH (water, sanitation and hygiene) Coordination Committee – to link the WSP process to the existing "Total Sanitation" programme. A goal of that programme is to eliminate open defaecation practices within the community. In addition, public consultations and meetings were held to raise awareness, supported by household surveys and a reward system. Overall, this approach has led to significant community support, and the programme is community-led under the guidance of the WUSC and the Village WASH Coordination Committee. A monitoring and verification programme is in place to assess the effectiveness of the approach; it includes household visits and is one of six indicators used to assess the effectiveness of the Total Sanitation programme. As a result of this sanitation initiative linked to the WSP process, the community that was located upstream of the source has been declared an "open defaecation free" zone, with appropriate toilet facilities provided for all of the community.

Overall, through the WSP process, several significant water-quality risks within the catchment of the Amarapuri water-supply system have been identified, prioritized and managed. Since the development and implementation of the WSP and the concurrent Total Sanitation programme, the prevalence of waterborne diseases has significantly decreased, with a quarterly statement issued by the relevant health authorities to formally declare Amarapuri "waterborne disease free".

ANNEX B

Lists of boxes, checklists, figures and tables

List of boxes

List of checklists

List of figures

List of tables

ACRONYMS AND ABBREVIATIONS

General

ADI	acceptable daily intake
AN-FO	ammonium nitrate-fuel oil
As	arsenic
As_2S_3	arsenic sulfide
As(III)	arsenate
As(V)	arsenite
BDOC	biodegradable dissolved organic carbon
BOD	biochemical oxygen demand
BTEX	benzene, toluene, ethylbenzene and xylene
CO_2	carbon dioxide
DBP	disinfection by-product
DDT	dichloro-diphenyl-trichloroethane
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DRAPS	double recirculation aquaponics system
E. coli	*Escherichia coli*
EDB	ethylene dibromide
EIA	environmental impact assessment
ERA	environmental risk assessment
F_{OC}	fraction of organic carbon
GDWQ	Guidelines for drinking-water quality
GIS	geographical information systems
HACCP	hazard analysis and critical control point
Hb	haemoglobin
IARC	International Association for Research on Cancer
IWA	International Water Association
IWCP	integrated water cycle planning
IWRM	integrated water resource management
JMP	Joint Monitoring Programme
K_d/K_{OC}	solid-water partition coefficients
K_{OW}	octanol-water partition coefficient
LNAPL	light non-aqueous phase liquid
MDG	Millennium Development Goal
MIB	2-methylisoborneol
MTBE	methyl tertiary-butyl ether

MTD	minimum therapeutic dose
N	nitrogen
N_2	atmospheric nitrogen
NAPL	non-aqueous phase liquid
NGO	nongovernmental organization
NH_3	ammonia
NH_4^+	ammonium
NO_2	nitrite
NO_3	nitrate
NOM	natural organic matter
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	perchloroethene
PFOS	perfluorooctane sulfonate
PhAC	pharmaceutically active compound
POM	particulate organic matter
POP	persistent organic pollutant
QMRA	quantitative microbial risk assessment
RAS	recirculating aquaculture systems
SOP	standard operating procedure
SO_X	sulfur oxides
spp.	species
SRAPS	single recirculation aquaponics system
SSP	sanitation safety plan
SVOC	semi-volatile organic compound
TBT	tributyltin
TCE	trichloroethene
TDS	total dissolved solids
TP	total phosphorus
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children’s Fund
United Kingdom	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
US EPA	United States Environmental Protection Agency
UV	ultraviolet
VC	vinyl chloride
VIP	ventilated improved pit latrine
VOC	volatile organic carbon
WHO	World Health Organization
WSP	water safety plan
WUSC	Water Users and Sanitation Committee

Units of measurement

µg/L	micrograms per litre
µm	micron
g	gram
g/L	grams per litre
km	kilometre
kPa	kilopascal
L	litre
m	metre
m/s	metres/second
m^3	cubic metre
m^3/d	cubic metres per day
mg/L	milligrams per litre
mL	millilitre
mm^3	millimetre cubed
mol	mole
mol/L	moles per litre
mSv	millisievert
ng/L	nanograms per litre
ºC	degree Celsius
Pa	Pascal
PPM	parts per million

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