Chapter 7

Assessing and controlling the risk of cyanobacterial blooms

Nutrient loads from the catchment

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CONTENTS

INTRODUCTION AND GENERAL CONSIDERATIONS

As discussed in Chapter 5, cyanobacterial blooms in surface waters are most effectively and sustainably controlled by limiting nutrient concentrations in the waterbody, and this requires sufficiently limiting the nutrient loads that it receives from its **catchment** (for terminology, see Box 7.1). These loads enter a waterbody from point sources such as discharges and sewage outfalls and from nonpoint sources (also termed "diffuse sources") such as surface run-off or drainage from fields. In some cases, inflow of groundwater may also carry significant nutrient loads. Furthermore, sediments may release nutrients, particularly phosphorus (P), into the waterbody. These releases are termed "internal loads", and they delay the decline of concentrations in the water after the external load has been reduced. However, already Vollenweider and Kerekes (1980) showed that in many cases, sediments are – on an annual scale – a sink rather than a source for phosphorus; thus, if the external load reduction is effective and water exchange rates are sufficiently high, the sediments will become a sink again, typically several years after load reduction. While such time spans may be of concern, particularly if a rapid remediation is necessary or water exchange rates are low, the first step for the target of reducing nutrient concentrations in the waterbody is to reduce the external load; otherwise, measures to reduce the internal load have little chance of being sustainably effective. Assessing the role of sediment nutrient release and

BOX 7.1: TERMINOLOGY

A **catchment** is the entire land area from which rain, snowmelt or groundwater drain into a waterbody, typically delineated by the crests of the hills or mountains that form water divides. Synonyms include “watershed”, “river basin” and “drainage area”. Catchments span a very wide range from fairly small, for example, for the close surroundings of hydrologically isolated ponds, to a continental scale for large rivers.

Point sources release nutrients to a waterbody at a single localised point of discharge, such as a sewage outfall.

Diffuse sources, also termed “nonpoint sources”, are many smaller or scattered sources from which nutrients may be released to a waterbody, for example, from the land surface through rainwater runoff, through groundwater or from scattered rural dwellings. The combined impact of diffuse sources on the waterbody may be significant.

Riverine loads are the mass of a contaminant transported per unit of time, typically expressed as kg or tons per year. The nutrient load in the river reflects the sum of inputs upstream of the monitoring point at which these loads are calculated minus the possible retention in the river sediment. As such, these loads provide a first check: the sum of inputs from individual and separate sources should broadly equate to the total riverine load if retention is neglected for very rough estimation. More detailed investigations include retention.

Riparian buffer strips are the areas around a waterbody of about 10–30 m width or more, covered with dense vegetation which can effectively intercept surface run-off carrying phosphorus-rich soil eroded from arable land and pastures.

Tile drainage is a term used for draining land that would otherwise be too saturated with water for crops to grow. The term derives from installing drainage in a grid pattern covering the otherwise too moist field.

options for controlling it are discussed in section 8.6. This chapter focuses on assessing and managing external nutrient loads to a waterbody.

As outlined in Figure 7.1, the first step for this purpose is to estimate the maximum nutrient concentration in the waterbody that can be tolerated to effectively control (toxic) cyanobacterial blooms (section 7.1) and the corresponding load to the waterbody that may be tolerated to avoid exceedance of this target concentration (section 7.2). The next steps are to identify the main pathways and sources of nutrients (section 7.3) and to estimate the respective loads they contribute (section 7.4). The approach to estimating these loads may range from qualitative expert judgement (including that of local stakeholders) to quantitative load modelling (see tiers in

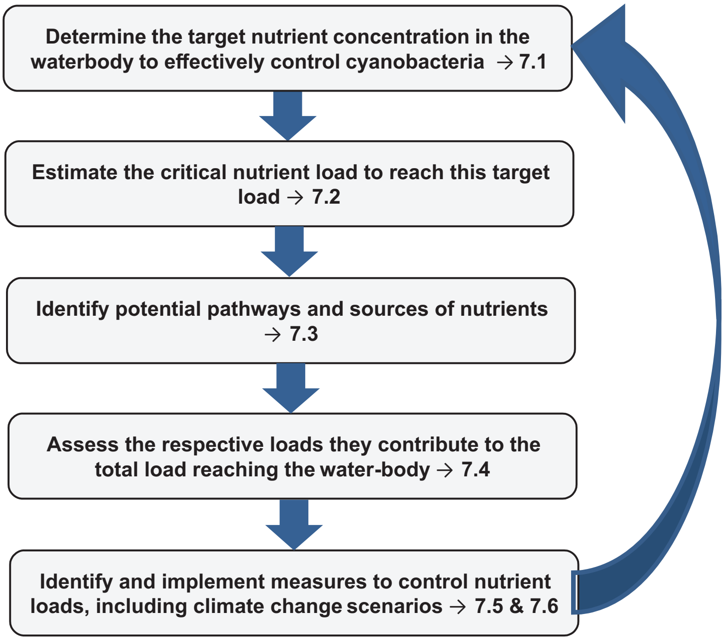


Figure 7.1 Steps in the selection of measures for controlling nutrient loads from the catchment.

section 7.4), depending on the available information. Once the loads from key pathways and sources are clear, the next step is to identify the most promising and most cost-effective measures to control them, to implement these measures, and to ensure they are operating effectively (section 7.5). After the implementation of measures, it is important to monitor whether they are taking effect as planned. This involves going back to assessing the nutrient load in order to validate that it has been sufficiently reduced, and it involves monitoring the nutrient concentration in the waterbody.

Implementing effective measures to control nutrient loads takes time, often several years, and particularly for P, it takes further time for concentrations in the waterbody to decline and for biota to respond to lower concentrations: Jeppesen et al. (2005) reviewed data on the responses to a nutrient load reduction of 35 lakes and found that at least 3 retention times (i.e., exchanges of the lake's volume) were necessary to dilute 95% of the excess P out of the waterbody and <10–15 years for total phosphorus (TP) to reach a new equilibrium between water and sediment; deep lakes tend to take longer. Although time scales of years or even decades may seem prohibitive, in the longer term controlling cyanobacterial blooms through keeping the nutrient load sufficiently low is the most sustainable approach, often rendering further (usually costly and continuously necessary) measures within the waterbody (discussed in Chapter 8) unnecessary.

The guidance given in this chapter for assessing and controlling nutrient loads from catchments to waterbodies is valid independently of the size of the catchment. Estimating nutrient loads from large catchments with a range of possible nutrient sources can be particularly challenging. For rivers crossing municipal, state or national borders, planning and management require collaboration across jurisdictions, and for transnational basins, international commissions have proven useful. For example, the Water Framework Directive of the European Union requires transboundary river basin management plans. Nutrient loads are more readily assessed and controlled for smaller, more readily controllable catchments, for example, those of reservoirs in middle-range mountains.

For further information and guidance on managing waterbodies and their catchments, readers are referred to the WHO guidebook *Protecting Surface Water for Health* (Rickert et al., 2016).

7.1 DETERMINING TARGETS FOR NUTRIENT CONCENTRATIONS IN THE WATERBODY

Which nutrient to address – P or both N and P – is a key question for planning measures to reduce the maximum possible amount of phytoplankton biomass – and thus of cyanobacteria – in a given waterbody. As discussed in Chapter 4, while in theory any nutrient could be limiting, in practice the macronutrients phosphorus (P) and in some cases nitrogen (N) are decisive for the amount of biomass that can occur. Moreover, if the concentration of one nutrient is sufficiently low, reducing those of others will not contribute to controlling cyanobacteria (see section 4.3.2 and Box 4.5). Reducing P loads to waterbodies has been widely successful, provided the measures taken achieved sufficiently low concentrations within the waterbody (Jeppesen et al., 2005; Phillips et al., 2008; Evans et al., 2011; Carvalho et al., 2013; Søndergaard et al., 2017), while there is very little experience with exerting control by reducing N. However, in many eutrophic shallow waterbodies, N limits phytoplankton biomass during the later summer months (Søndergaard et al., 2017). Shatwell and Köhler (2019) show the example of a shallow lake in which phosphorus cycled between water and sediment during summer perpetuated high concentrations of P even after substantial load reduction, and reduced N loads were therefore decisive for controlling summer phytoplankton biomass. Such situations may be particularly relevant for waterbodies with low rates of water exchange in which the gradual dilution of P takes many years (Conley et al., 2009).

In contrast to P, which is removed from a waterbody only by dilution and adsorption to particles with which it is deposited in the sediment, N is lost to the atmosphere through the bacteria-driven process of denitrification. At elevated summertime temperatures, this process can significantly reduce the concentrations of N within days, and in face of this quick response time, N load reduction may quickly render concentrations in the waterbody sufficiently limiting to control blooms during their peak season. As P release from sediments may also be particularly pronounced during later summer, Shatwell and Köhler (2019) propose to assess whether activities causing N loads (fertilisation, spreading of manure) can be timed to avoid loads specifically during the critical summer weeks in which keeping N limiting can control cyanobacterial blooms. In consequence, in situations in which the target concentration for TP cannot readily be reached, it may be effective to also control N loading. This may also serve to protect the macrophyte cover that would otherwise support the improvement of water quality `

N may also be relevant in the wider context of environmental targets for aquatic ecosystem protection. Conley et al. (2009) discuss the negative ecological impacts of reducing only P on some coastal waters and estuaries, such as parts of the Baltic Sea, Wadden Sea, and Gulf of Mexico. In such situations, excessive N may also lead to coastal harmful algal (including cyanobacterial) blooms exposing people during recreational use. Furthermore, N emissions into aquatic environments may be directly relevant to human health where they not only reach surface waterbodies but also reach groundwater, causing elevated nitrate concentrations in drinking-water (WHO, 2017b). As much of the N and P that reach waterbodies originate from the same sources, that is, human and animal excreta and/or fertiliser, some measures for controlling P loads can be readily designed to also reduce N loads, in particular reducing excessive application of fertilisers or manure on land. However, techniques for their removal in sewage treatment tend to be more expensive for N than for P. Also, as discussed below, the transport pathways of N and P to waterbodies are different, and intercepting also those of N may therefore require additional measures to those for intercepting P. Where prioritising investments is necessary, focusing on P is likely to be more effective for the target of controlling cyanobacteria.

The following considerations may serve to assess whether to focus measures on controlling P loads or to also address those of N:

1. Is the waterbody shallow and mixed (with thermal stratification at most lasting for a few days)?
2. Is P clearly too high to be limiting for extended periods during the cyanobacterial growth season, that is, total phosphorus (TP) > 25–50 µg/L (depending on the waterbody) or even soluble P “left over” by the phytoplankton, that is, in concentrations > 5–10 µg/L? Do concentrations of P increase during summer, indicating release from the sediment?
3. How do concentrations of N relate to those that can realistically be achieved by load reduction measures – that is, is a target of 200–500 µg/L of total nitrogen (TN) and < 100 µg/L for dissolved N achievable?

Importantly, because of the possibility of N limitation shifting phytoplankton to N-fixing cyanobacteria, controlling N is not an alternative to measures reducing P loads, but rather an additional approach, focusing on specific summer situations.

Setting target nutrient concentrations: How low must the concentration of phosphorus or nitrogen be to effectively limit cyanobacterial biomass? Sections 4.3 and 4.4 summarise information and references showing that TP scarcely limits the biomass of phytoplankton – including that of cyanobacteria – if concentrations are above 100 µg/L. It can limit biomass to some extent in the concentration range of 50–100 µg/L and more effectively below 20–50 µg/L, while at less than 10 µg/L TP cyanobacteria scarcely occur and if so, health-relevant levels are unlikely in most situations. For nitrogen, section 4.3 shows that the limitation of biomass occurs at 7- to 10-fold higher concentrations as compared to those of TP.

Within this range, the target to set for a specific waterbody depends on both its intended use and specific conditions in it, particularly on its hydrological and morphological features. For example, in some shallow lakes with extensive macrophyte cover, cyanobacteria have only rarely developed blooms even at TP concentrations in the range of 100 µg/L (Jeppesen et al., 2007), and for the purpose of recreational use, this level may be sufficient as target nutrient concentration. At the other extreme, in a large deep lake or reservoir, cyanobacteria may develop and accumulate to scums on leeward shores at 20 µg/L TP, or *Planktothrix rubescens* may form metalimnetic maxima in the depths of the drinking-water offtake, and controlling these cyanobacteria may necessitate a TP target of 10 µg/L or even slightly lower.

For setting a target TP concentration, a general orientation can be gleaned from the experience with lake and reservoir restoration discussed in section 4.4: that is, lower TP concentrations in the range of 20–30 µg/L are typically necessary for thermally stratified waterbodies, yet lower ones closer to 10 µg/L may be needed to control *P. rubescens* in deep reservoirs, whereas shallow lakes with dense macrophyte stands may remain clear at TP concentrations even in the range of 100 µg/L. While much less experience exists for target N concentrations, multiplying these values for P by 7 may serve for a rough estimate. Beyond these rules of thumb, setting nutrient targets for a specific waterbody requires a good understanding of its ecology and the conditions that favour cyanobacterial blooms, and this is best done in collaboration with experts in limnology. It is further important to collaborate with authorities and stakeholders in waterbody and catchment management to identify overlap between targets for human health protection and aquatic ecosystem protection in order to efficiently coordinate measures within this larger context. Models outlined in section 4.4 can support setting target nutrient concentrations.

The following guidance focuses on assessing and controlling phosphorus loads as the nutrient, which is most frequently decisive for controlling cyanobacterial blooms. However, many aspects can likewise be used for developing measures to control nitrogen loads.

7.2 DETERMINING CRITICAL NUTRIENT LOADS TO THE WATERBODY

Once the target for the nutrient concentration is clear, it is possible to estimate the maximum nutrient load that must not be exceeded in order to meet this target. This is termed "critical load". Determining the critical load does not yet differentiate by nutrient sources and pathways but merely focuses on the total amount that should not be exceeded.

The critical load L_{crit} is given in mass per time (e.g., in tons per year). If there were no loss processes removing the nutrient, its critical load could be calculated from the target nutrient concentration (given in mg/m^3, which is equal to µg/L) multiplied by the amount of water flowing through the system. The latter is given in water volume per unit time: for rivers, this is discharge, Q_{river}, (given in m^3/s); for lakes and reservoirs, it is the water exchange rate or flushing rate ρ, given as the number of times the total waterbody volume is exchanged per year. For a river, the critical load of total phosphorus (TP) can be estimated as

$$L_{\text{crit}} = \text{TP}_{\text{target}} \times Q_{\text{river}}$$

- *Example for a river*: If $\text{TP}_{\text{target}}$ is set to 25 mg/m^3 (=25 µg/L) and the average Q_{river} is 2 m^3/s, this gives a critical load L_{crit} of 50 mg/s, which is 1 576 800 000 mg/yr = 1.58 t/yr.

As Q_{river} varies over time, Q_{river} can be defined as mean flow or low flow of the river, with low flow providing the higher level of protection, particularly as cyanobacteria tend to develop during periods of low flow. A more detailed level of emission modelling would include instream retention, as it is presented in section 7.3 as tier 3 approach.

For a lake or reservoir, the critical load of TP would be estimated as

$$L_{\text{crit}} = \text{TP}_{\text{target}} \times \rho \times z_{\text{mean}}$$

which is conceptually the same as the approach for rivers, but it is an established practice to use a different dimension for discharge, that is, the flushing rate ρ multiplied by the waterbody's mean depth (z_{mean}) which together describe the volume of water exchanged under one m^2 of waterbody surface.

- *Example for a lake or reservoir*: If TP_{target} is 25 mg/m³, the flushing rate is twice per year and the mean depth is 15 m (and thus the water volume under 1 m² of surface is 15 m³), this gives a critical load L_{crit} of $10 \times 2 \times 15 = 300$ mg/m² per year.

  Multiplying this critical load by the total lake area then gives the critical load for the entire waterbody – that is, if the lake area were 1 km², L_{crit} would amount to 300 kg/km² or 0.3 t/yr.

However, for lakes and reservoirs, the role of P exchange with the sediments is usually far more significant than for rivers, particularly if the flushing rate is low, that is, less than 2–3 times per year. Sediment influence therefore needs to be included in the calculation of the critical load. For this purpose, Vollenweider (1976) (modified by Cooke et al., 2005) empirically developed a term relating ($\rho^{0.5}$) the interaction of TP with the sediment to the flushing rate. Adding this term to the equation gives

$$L_{Crit} = TP_{target} \times \left(\rho + \rho^{0.5}\right) \times z_{mean}$$

- *Example for a lake or reservoir*: If TP_{target} is 25 mg/m³, the flushing rate is twice per year and the mean depth is 15 m (and thus the water volume under 1 m² of surface is 15 m³), this gives a critical load L_{crit} of $10 \times (2 + 1.41) \times 15 = 512$ mg/m² per year.

  Multiplying this critical load by the total lake area then gives the critical load for the entire waterbody – that is, if the lake area were 1 km², L_{crit} would amount to 512 kg/km² or 0.5 t/yr.

The difference between both approaches highlights that the role of sediments as sink for phosphorus strongly depends on flushing rates: recalculating these two examples with 10-fold higher flushing rates results in a much lower difference between the approach including the term for interaction with the sediment and the approach without ithat term – that is, 3671 mg/m² as compared to 3000 mg/m². The higher the flushing rate, the lower the role of losses of phosphorus via sedimentation.

However, the addition of $\rho^{0.5}$ to ρ introduced by Vollenweider (1976) was empirically derived from the OECD data set and thus is a rough approximation across a range of different waterbodies. A range of factors other than the flushing rate will influence P sedimentation or release, including lake morphometry and patterns of thermal stratification. In particular, if load reduction is pronounced, during the first years after load reduction the sediments are likely to release phosphorus through mineralisation or through desorption of redox sensitively bound P, depending on temperature and redox conditions (see section 8.6). For such situations, the equation will overestimate the acceptable external load or underestimate the time it takes to reach the target TP concentration. For further models that incorporate P release from sediments, including lake-specific approaches, see the discussion in Cooke et al. (2005) or literature therein, for example, Nürnberg (1998). Further complexity results from a substantial variation of loads in time, multiple inflows and/or heterogeneous distribution of the inflow within the waterbody.

The advantage of the loading equation above is its simplicity and reliance on only two terms which tend to be known for reservoirs, that is, flushing rate and mean depth. While it may serve for preliminary orientation, limnological expertise is important when setting a target for the TP load. This includes assessing the quality of the available data for flushing (ρ) and mean depth (z_{mean}) and the applicability of this simple approach to the specific waterbody.

The basic hydrological information needed for determining critical loads with the equation above may be available from authorities responsible for the management of the waterbody and its catchment. If not, mean depth (z_{mean}) and water volume can be determined if topographic maps are available and these maps include bathymetric contour lines showing depths. The rate of flushing (ρ) or its inverse, the water residence time (also termed “retention time”), can be derived from a water budget, which is calculated from flows and water volume – that is, from the balance between inflows (tributaries and in some cases also groundwater), run-off from surfaces and rainfall versus outflow, and – if relevant – amounts lost to seepage and evaporation. Besides outflow (which is often easiest to measure, particularly for reservoirs), further water losses relevant for the budget can include recharge to groundwater as well as evaporation. Measuring inflows requires determining stream flow of tributaries, which can be done by measuring the water level of the tributaries at river gauges (for instance continuously by pressure sensors) and transforming it by a rating curve to flow values. Rating curves quantify the relationship between water level and flow, and they need to be regularly controlled and adapted to changing conditions at the river gauge.

Once a water budget is available, it is further useful to estimate a nutrient budget, that is, the waterbody’s total nutrient content (usually given in tons) compared to the total amounts that flow in and out of it. With sufficient resolution in time and space, a nutrient budget provides a valuable indication of nutrient sources as well as sinks: where it shows imbalances, this implies that there are further sources or sinks, for example, surface run-off not sufficiently well quantified, P losses through sedimentation or gains from sediment release. The nutrient budget can be derived from the water budget, the respective nutrient concentrations of the waterbody and the relevant in- and outflows. The nutrient budget may also vary considerably over time.

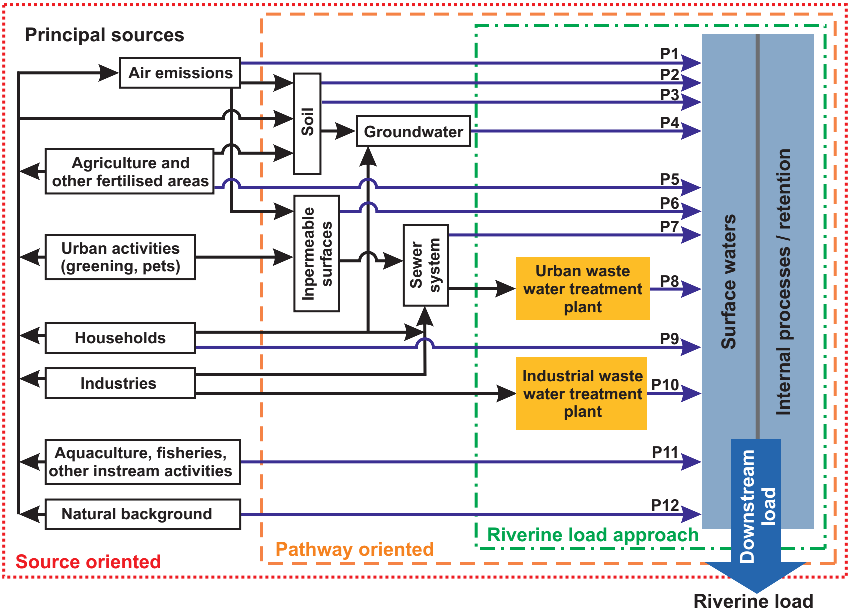
For determining the nutrient content of a thermally stratified waterbody, sampling should include depth profiles because concentrations may show pronounced depth gradients. Nutrient concentrations may also show pronounced seasonal patterns, and therefore, sampling and analysis monthly or even twice per month may be necessary for a sufficiently accurate assessment of the waterbody's nutrient content. Where this is not feasible, in some situations a good first estimate may be possible from one sample obtained during spring overturn, that is, when the waterbody is well mixed, rendering one sample quite representative for the whole lake or reservoir and the growing season (Reynolds & Maberly, 2002). However, this is only meaningful for waterbodies with fairly low water exchange rate and only moderate variation in stream flow of its tributaries, conditions more commonly found in temperate than in tropical climates. For example, tributaries often carry the greatest phosphorus loads during rain-event inflows when tributary streams and rivers are swollen (Zessner et al., 2005; Zoboli et al., 2015). Further challenges to establishing water and nutrient budgets include multiple inflows, for example, with small tributaries that run water only after major precipitation events or snowmelt, or significant groundwater flows which typically are difficult to measure. A comprehensive introduction to approaches to assessing nutrient budgets and critical phosphorus loads is given by Cooke et al. (2005).

7.3 IDENTIFYING KEY NUTRIENT SOURCES AND PATHWAYS CAUSING LOADS

Once the critical load has been determined, this needs to be compared to the current load to the waterbody in order to assess by how much the load needs to be reduced in order to remain below the critical load. The current load then needs to be differentiated according to the locally relevant sources and pathways in order to identify measures for reducing or controlling loads from these sources. This is also useful in situations in which the critical load is not exceeded: this serves to identify situations and measures worth maintaining in order to ensure that a currently good situation does not deteriorate.

7.3.1 Background information

Figure 7.2 shows principal sources, pathways and internal processes of nutrient loads to a waterbody. In this conceptual framework, all processes and activities that are likely to contribute to the input of nutrients are defined as sources. The most important **point sources** for nutrients are settlements which dispose wastewaters to surface waters via sewage without or after treatment and, depending on processes, also industrial facilities (the latter being typical point sources also for specific other pollutants). Relevant **diffuse or nonpoint sources** most frequently originate from agriculture, but they may include other fertilising activities, some urban emissions (including



Pathways

P1	Atmospheric deposition directly to surface water	P7	Stormwater outlets and combines sewer overflows + unconnected sewers
P2	Erosion	P8	Urban wastewater treated
P3	Surface run-off from unsealed areas	P9	Individual – treated and untreated – household discharges
P4	Interflow, drainage and groundwater	P10	Individual wastewater treated
P5	Direct discharges and drifting	P11	Direct discharges from aquaculture, fisheries and other instream activities
P6	Surface run-off from sealed areas	P12	Natural background

Figure 7.2 Sources and pathways of nutrients and different levels (tiers) of their quantitative assessment in the context of emission inventories (Adapted from European Commission (EC), 2012.)

into air and then precipitating on the water surface, contribution to water pollution via atmospheric deposition), and wastewater from rural dwellings not connected to central sewage treatment. Typically, diffuse sources are more variable in space and time than point sources, and quantifying them may be more challenging.

Pathways are the means or routes by which nutrients can migrate or are transported from their various sources to the waterbody. Following release, they may be directly emitted to a waterbody or reach it after being transferred to and stored within environmental media, including soil and impermeable surfaces. Typical pathways of wastewater from industrial or urban sources to a waterbody are sewer systems and wastewater treatment plant effluents or groundwater in unsewered areas. Pathways transporting nutrients from agricultural areas and other surfaces follow the hydrological pathways as surface run-off, interflow (a subsurface run-off component that does not reach the groundwater), **tile drainage** (artificial pipe installations that drain agricultural areas to avoid soil being too wet) and groundwater. While nitrogen in form of nitrate is very soluble and readily reaches waterbodies via drainage, phosphorus supplied to soil in higher amount than needed by the crop is usually adsorbed to a high extent to soil particles. Erosion transports such particles over the land surface to waterbodies. Aerial emission is an important pathway for nitrogen and can result in subsequent direct deposition on the surface of a waterbody or indirect entry via soil or a sewer system.

The differentiation between sources and pathways is useful because measures to reduce nutrient emissions may either directly address the sources of nutrients (e.g., reduced fertilisation or livestock, improvement of industrial production processes, P-free detergents) or intercept the pathways of nutrients to the waterbody (as, for instance, erosion abatement by **riparian buffer strips**), and because, as discussed above, some pathways differ for N and P.

Besides external loads, processes within surface waters determine the nutrient concentrations in the water. These processes include a wide range, for example, sorption onto suspended particles, plant uptake, desorption or – for nitrate and ammonium – denitrification. Retention is a broad term used to describe the outcome if loads entering surface water remain there, without, for example, being discharged to coastal waters or – in case of nitrogen be lost to the atmosphere through denitrification (see section 4.3.2), a process relevant particularly in shallow lakes at elevated temperatures. The fractions that are retained by sedimentation in the river, along riverbanks or in sediments of lakes and reservoirs, can potentially be mobilised in future; however, this is not always the case. The extent of their retention depends on the nutrient (N or P) as well as hydromorphological conditions of the waterbody (Behrendt & Opitz, 1999; EC, 2012).

While nitrogen largely reaches waterbodies as dissolved inorganic N, for phosphorus, loads can occur in different binding forms. As discussed in Chapter 4, for limiting cyanobacterial biomass in the waterbody, it is important to assess not only the concentration of soluble reactive phosphorus (SRP) but rather that of total phosphorus (TP). P binding forms are also relevant for assessing P transport: some of the pathways discussed below transport a high share of P as SRP (groundwater, treated wastewater). Via other pathways, P is transported primarily in particulate forms, that is, P adsorbed to soil particles from erosion or P in organic material from raw wastewater. Whether particulate P may become available for the growth of cyanobacteria and algae depends on P forms in the particulate matter and the physiochemical conditions in the respective waterbody, which determine the fate of the respective P forms: for instance, P in apatite (as part of soil material) will rapidly settle to the sediment and not become available even over long periods of time, while P bound in organic matter will become available as organic matter decomposes, and P bound to iron salts may dissolve in anaerobic zones of the sediment (Psenner et al., 1988). On the other hand, if potential binding partners for phosphorus, such as iron- and aluminium oxides and hydroxides as well as certain clay minerals, are available in a waterbody or reach it together with the P load, dissolved phosphorus may adsorb to these binding partners, and if these complexes settle to the sediments, they will contribute to removing phosphorus from the productive water layers. Consequently, either they may be buried under younger sediment layers and thus be permanently removed from the system, or they may be mobilised again later on by desorption, particularly during events of sediment resuspension, increasing the concentration of dissolved P forms in the water system. Therefore, availability of P is not only a question of its emission pathway but also a question of complex biological and chemical processes of the P cycle within the waterbodies.

Similar processes of interaction between nutrients and soil also apply on land. If agricultural soils with increased P concentrations erode, P is transported together with soil particles and eventually emitted to surface waters. Depending on soil properties and soil saturation with P, P might be transported in soluble form and reach surface waters with surface run-off, tile drainages (i.e., drainage from fields and meadows), interflow or groundwater. In most settings, transport with erosion dominates. Losses of P from agricultural soil are impacted by many factors. Fox et al. (2016) give a review of these processes, including a discussion of “legacy P” accumulated in soils on land with literature indicating that this may be released for years or even centuries after it has been deposited.

7.3.2 Identifying nutrient sources and pathways

A good way to get started is to establish a qualitative overview of potential nutrient sources to the waterbody, that is, to compile an inventory of activities in the catchment, to collect the information available on their potential nutrient discharge and to map where in the catchment they are occurring in relation to the hydrophysical conditions that determine their pathway to the waterbody (for relevant activities, see Figure 7.2). Geographical Information Systems (GIS; see Box 7.2) are highly useful up–to–date tools for organising such spatial data. Such an inventory best begins with a detailed topographical map and with available, documented data, particularly data that can be obtained from public authorities, for example, from permits issued for discharges or for land use. Such data may be spread across a number of authorities, depending on responsibilities for the respective activity in the catchment. Some data may also be available from research institutes in the region.

BOX 7.2: USING GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

GIS is a system designed to capture, store, manipulate, analyse, manage and present spatial or geographic data. GIS applications are tools that allow users to create interactive queries (user-created searches), analyse spatial information, edit data in maps and present the results of all these operations. An example for a typical application is the creation of maps that show the distribution of land–use types in relation to water courses. A more advanced application would be the implementation of the universal soil loss equation (Wischmeier & Smith, 1960) on a regional scale: spatial data on slope (from digital elevation model), slope length, rainfall intensity, soil erosivity and cultivation of crop types are merged to derive data in order to calculate the spatial distribution of erosive soil loss in a catchment. Practically, all advanced methods for modelling emissions rely on more or less comprehensive GIS applications.

For example, in the Action Plan for the Santa Lucia River Basin (see Box 7.4), GIS tools were used at the step of assessing the loads discharged from non-point sources and to develop an environmental information platform of open access ("Observatorio Ambiental Nacional") that centralises and organises the environmental information generated in various areas of the state. This includes a geo-integrator that provides access to georeferenced information and interactive maps, allows territorial analysis of information and makes files available for downloading.

It is useful to include an inventory of control measures that are already in place as well as information on how well they are currently managed (see section 7.5). The WHO guidebook "Protecting Surface Water for Health" (Rickert et al., 2016) gives an introduction into identifying sources and pathways for hazardous contaminants in general, including pathogens, harmful chemicals and also nutrients causing eutrophication and cyanobacterial blooms. This guidebook includes guidance on developing an inventory of activities potentially releasing contaminants hazardous for health and on conducting a catchment inspection, with checklists addressing loads from, for example, wastewater, agriculture, aquaculture and fisheries that can be downloaded and adapted to one's specific situation and needs.

Who should conduct the assessment?

Typically, compiling information on nutrient sources and pathways to the waterbody is a multisectoral exercise for which no one single public authority has the competence and possibility to enforce cooperation or compliance. Success chances therefore increase substantially if good will and motivation can be established among the stakeholders in the catchment. A Water Safety Plan team (see Chapter 6) can be an effective platform for bringing together staff from the public authorities involved; stakeholders from activities in the catchment of the waterbody (e.g., from agricultural or wastewater sector); and technical experts in the fields of, for example, hydrology, catchment management, geography, soil science and wastewater treatment. Together, they can compile information on potential nutrient sources and pathways, and develop proposals for the most effective way of controlling these sources and pathways. The lead for developing the catchment management aspects of a Water Safety Plan may best be taken by those responsible for water or environmental management. However, either the water supplier or the health authority responsible for the quality of drinking-water and/or the safety of recreational water use can take an active role in initiating the assessment and bringing together the key actors.

The relevance of catchment inspection

Regardless of the sources of information thus collated, validating it on site is important as conditions often change without proper notification to authorities. Also, a number of discharges as well as activities relevant to nutrient loading are often not notified, known and documented. Thus, while data available in documents provide a good point of departure for assessing nutrient loads from the catchment, they may not provide a sufficiently comprehensive picture, and visual inspection will reveal which activities relevant to nutrient loading are going on and which pathways for nutrients are evident. In smaller watersheds, catchment inspection is an applicable and valuable tool for the validation of information. In larger ones, inspection may only be partially possible, and it may be necessary to organise a review of the data available through intersectoral collaboration between a range of stakeholders and authorities.

Catchment inspection can be a time-intensive undertaking even in smaller catchments. Good preparation the therefore important, that is, to collect and evaluate as much information as possible prior to the inspection in order to focus on things to look for, which questions to clarify, which experts to ask to participate. Catchment inspection also provides an opportunity to identify owners and operators who may need to be interviewed afterwards (e.g., about discharge amounts, fertiliser application or records of manure application), and contact with them may be established directly during the inspection. It is generally useful to seek contact with locals during catchment inspection, as their information and observations can provide a valuable indication of factors otherwise overlooked. Catchment inspection usually provides a considerable amount of information to follow up afterwards, and this in turn improves and facilitates the next inspection. It is an iterative process, to be well documented and to be repeated at intervals. Rickert et al. (2016) give more guidance on catchment inspection, including checklists for this purpose to download and adapt to local circumstances.

The role of monitoring nutrient loads

Information on the relative contribution of different sources to the total load of a nutrient to the waterbody evidently is valuable for planning measures to control it. Sampling and analysing concentrations of nutrient concentrations may be fairly inexpensive, particularly if a water-quality monitoring programme is in place anyhow. However, capturing events causing peak loads may be more challenging, possibly requiring automated sampling triggered by some signal reflecting changes in discharge or precipitation.

Monitoring nutrient concentrations is valuable to assess the impact of implementing a new control measure if it is done before and after the intervention. For point sources along a water course, this may be quite straightforward. For the overall response of a waterbody to reduced loading, it may take a resolution in space and time (e.g., depth profiles if the waterbody stratifies and monthly or even weekly sampling intervals) for a year before and a few years after implementation and then at larger intervals in the scale of several years. While a cause–effect relationship may well be clouded by other changes in the catchment, such a "try and see" approach may be effective particularly where major loads to control are quite evident. Waterbody data are important for load modelling: they provide the empirical basis to test whether the model correctly depicts developments.

Nutrients and cyanobacteria in the broader context of health hazards

In many cases, it will be effective to assess loads and pathways of nutrients in the broader context of preventing water pollution causing health risks, as one aspect of developing a Water Safety Plan (see Chapter 6). The WHO guidebook "Protecting Surface Water for Health" (Rickert et al., 2016) gives guidance on estimating the health risks caused by the whole range of different hazards from the catchment, based on estimates of their likelihood to occur and their significance for human health. This broader context is important when assessing risks from potentially toxic cyanobacteria, as some sources of nutrients as well as pathways to the waterbody may be identical – for example, pathogens from human excreta – and therefore, one-and-the-same control measure may be significant for both. Recognising and highlighting such combinations may facilitate mobilising funding for implementing control measures.

Events causing loading

The control of chemical pollution is commonly based on monitoring at regular, predefined intervals. This approach to control risks missing major emissions causing peak loads and concentrations that occur during specific events, such as heavy precipitation bypassing wastewater treatment and thus causing sewer overflow directly into the waterbody, spreading of manure on frozen ground, stormwater run-off shortly after the application of fertiliser or manure, or illegal discharges conducted after the sampling team has left the premises. When planning the assessment of loads, it is therefore important to consider which events – from regular continuous emissions to sporadic intermittent extreme ones – are likely to cause relevant emissions and how such loads can be captured in the assessment.

Information to compile about the catchment
Checklist 7.1 (in part adapted from Rickert et al., 2016) outlines the broader information needed as a basis for characterising conditions and activities in the catchment area of the waterbody with respect to their relevance for nutrient loading. More detailed checklists for assessing nutrient loads from individual activities are given in the following sections of this chapter. Important expertise for this initial assessment includes geography, hydrology, local l–nd-use planning as well as wastewater management and agriculture. For later quantification of loads, it is useful to include expertise in catchment modelling when planning the assessment and inspecting the catchment.

CHECKLIST 7.1: ASSESSING WHICH ACTIVITIES IN THE CATCHMENT ARE LIKELY TO CONTRIBUTE MAJOR FRACTIONS OF THE NUTRIENT LOAD TO THE WATERBODY

Which basic information is available for assessing the relevance of different sources?

- Is a detailed topographical (digital) map available? When was it last updated? What topographical data are available on drainage areas, slopes and lengths?
- Which natural conditions in the catchment enhance nutrient pathways from the land to the waterbody, that is, topography (slopes), precipitation patterns, frost and snowmelt, soil types, erosion potential and drainage? Can areas in the catchment be identified which are most vulnerable to nutrient losses from the land to the waterbody?
- Are data available for discharge volumes of key point sources? Which fraction of the total discharge is from such inflows? Are data available for the nutrient loads these carry?

What activities are going on in the catchment of the waterbody and where are they located in relation to it? (See the template for site inspection in Rickert et al. (2016).)

Which areas in the catchment are covered by

- agriculture?
- aquaculture?
- suburban settlements?
- urban housing?
- informal settlements?
- industry?
- paved areas or otherwise impermeable surfaces draining to the waterbody?
- wilderness?
- forest, including use for logging?
- areas for recreational activities?
- other uses which potentially release nutrients to the waterbody or its tributaries?

Based on documentation available, what are the locations, spatial distribution and scale of the activities identified (generate map if possible)?

Are there trends or changes in land use, including population forecast studies?

What is the linear and hydrological distance (i.e., travel time of the run-off or seepage) to the waterbody from these activity points?

How are activities that potentially release nutrients managed, controlled and regulated?

- What national, regional, local or catchment-specific legislation, rules, recommendations, voluntary cooperation agreements or common codes of good practice are in place? How effectively are they enforced?
- Are there regulations for drinking-water protection zones or riparian buffer strips?
- Is land use subject to planning and permission? If so, do criteria for issuing permits include an assessment of the potential nutrient loads to the waterbody? How effectively are land-use regulations being enforced?
- Who are the main stakeholders to involve in the assessment?

7.3.3 Nutrient loads from wastewater, stormwater and commercial wastewater

Wastewater and stormwater inflows chiefly reach waterbodies as point sources and can cause significant nutrient loads. As point sources are more readily identified than diffuse sources a range of approaches is available to control them (see section 7.5.1). A fairly complete inventory of them is therefore an important basis for assessing and managing loads.

7.3.3.1 Sources

In municipal wastewater, human excreta are the dominating source of P. The average person-specific amount of P in excreta depends to some extent on the populations' nutrition but varies only within relative small boundaries of 1.3 – 1.7 g P per person and day (Zessner & Lindtner, 2005) with the lower end of this range reflecting the emissions of populations with a low consumption of meat (Thaler et al., 2015). Where detergents containing P are used, the daily P load discharged to wastewater may vary between 2.0 and 3.0 g per person. Thus, the density of the population living in the catchment of a sewage system determines the P load of municipal wastewater and its potential impact on waterbodies. Other significant point sources may be P from commercial and industrial wastewater, particularly from food processing enterprises or fertiliser industry.

While conventional wastewater treatment with biological organic carbon removes 30–40% of the P load, this is relatively easily improved by simultaneous precipitation techniques and/or biological P removal as "tertiary treatment", which typically achieve 80–90% P removal, leading to effluent concentrations in the range of 500–1000 μg/L. With an additional post-treatment step (e.g., post-precipitation and filtration), effluent P concentrations may even be reduced to < 200 μg/L. Where sewage effluent constitutes a major fraction of river flow, even concentrations in the range of 200 μg/L may cause too high a load of phosphorus to prevent cyanobacterial blooms, and specific filtration steps may be necessary to reduce effluent concentrations yet further. Also, attention to the storage of sewage sludge from the treatment process is important: if it is stored or disposed of inadequately close to the waterbody, run-off or seepage from this may be a further source of nutrient loading.

For assessing nutrient loads from industrial discharges, it is important to check whether the production line involves phosphorus (or nitrogen) compounds which are discharged and if so, whether data on the amounts are available or can be estimated from their content in substances purchased by the company for its production line. Enterprises that do not use phosphorus for their production may be adding it to their wastewater treatment system because the bacteria biodegrading organic substances in wastewater treatment require a minimum amount of P to work effectively. If the industry's wastewater does not contain enough P for an efficient biodegradation of organic substance, it may be dosing this to the biological treatment step. Dosing needs to be precise to avoid excessive P in the effluent, and when identifying P sources, including such enterprises in the assessment may be relevant.

A further nutrient source is rainwater run-off ("stormwater") from impervious areas, that is, roofs, roads, sidewalks and parking lots. It can contain significant nutrient loads particularly after extended periods of "dry deposition" from the air, garbage and excreta (from livestock, pets and where open defecation is practised, also from humans), particularly in the first flush after extended periods of dry weather. Where stormwater is collected by sewers that discharge directly into the waterbody, this will be an intermittent point source in the event of rainfall or snowmelt. While this source is generally less relevant than sewered wastewater, no generic concentration ranges can be given, as amounts depend entirely on local conditions.

7.3.3.2 Pathways

Outfalls of sewers carrying untreated wastewater directly to the waterbody and those of wastewater treatment plants are obvious point discharges in which nutrient concentrations can be directly analysed and/or loads be estimated from the size of the populations served and/or the type of enterprise emitting the wastewater (see section 7.4). Sewer systems carrying both domestic wastewater and stormwater from surfaces, that is, so-called combined sewers systems, can protect waterbodies during precipitation events that do not exceed the sewer capacity: these systems treat stormwater together with the domestic wastewater, and if treatment includes nutrient removal, this will reduce loads from run-off that would otherwise reach the receiving waterbody. However, they can be significant intermittent point discharges during heavy rainfall causing stormwater volumes beyond the capacity of sewerage and/or the sewage treatment system, and then sewage overflows allow this mixture of untreated domestic wastewater and stormwater to flow directly into the waterbodies, bypassing the treatment facility. Even where capacities of stormwater retention basins are large, they can rarely be built large enough to totally avoid such overflow events.

Diffuse pathways originate where wastewater from households and/or commercial activities is not sewered or where many small sewers discharge untreated wastewater directly to the waterbody. While in such situations diffuse loads from agriculture (see below) may be the major nutrient source for surface waterbodies, diffuse wastewater loads can also be significant if, for example,

- A number of dwellings or enterprises located sufficiently close to a waterbody lead wastewater pipes directly into it (possibly undocumented and informal) – a situation commonly causing diffuse loading from dispersed settlements along river courses or lakeshores.
- Open defecation is widely practised close to a waterbody and/or latrines close to the waterbody are poorly managed so that rain can wash excreta directly into a waterbody.
- The underground is very porous and soil filtration is poor so that seepage from latrines and septic system can reach the waterbody.

Otherwise, for phosphorus, even short distances of filtration through soil will achieve quite effective retention. Nitrogen may be less well retained if ammonium or nitrate from unsewered wastewater reaches shallow groundwater that drains into a surface waterbody (for an overview, see MacDonald et al., 2011).

7.3.3.3 *What to look for when compiling an inventory of loads from sewage, stormwater and commercial wastewater sources*

For assessing loads from wastewater and stormwater, Checklist 7.2 suggests a range of questions to address, depending on which appear locally relevant. These questions can support developing a checklist for catchment inspection. The data thus collected can be the basis for calculating not only the current loads from different sources but also the expected impacts of measures to reduce them (see section 7.5). Checklist 6 in "Protecting Surface Water for Health" suggests further questions that may be useful particularly if the purpose of inventory is to address not only nutrient loads, but also health hazards in general, including pathogens (Rickert et al., 2016).

Not all of these questions will be important in all situations, and information for answering all of them may not be available. Nonetheless, it is important to make a beginning with the information available while identifying the gaps and estimating how important it is to fill them in order to plan catchment management measures which are effective for meeting the nutrient load targeted.

Important specific expertise for assessing nutrient loads from sewage and stormwater includes environmental engineering with a focus on wastewater management.

CHECKLIST 7.2: COMPILING AN INVENTORY OF NUTRIENT LOADS FROM SEWAGE, STORMWATER AND COMMERCIAL WASTEWATER

GENERAL:

- Is the catchment primarily urban or rural, or a combination of both?
- Is there a relevant use of detergents containing P in the catchment? If so, could the use of P-free detergents be implemented? Would the P load from wastewater nonetheless remain in a range requiring removal in sewage treatment?
- Are there any enterprises which process food or nutrient-rich materials (fertilisers) in the region? Or any which are adding P to their wastewater treatment system to enhance its performance?
- Are enterprises operating at up-to-date technologies, for example, according to BAT (best available technique) requirements? Are improvements conceivable?

WASTEWATER SEWERAGE AND TREATMENT:

- Is the population density moderate or high and is a high share of people connected to public sewer systems? Is this share known?
- Is sewage treated? If so, with which steps? Are data on nutrient concentrations in treatment plant effluents as well as discharge rates available?
- Are there treatment plants with the removal of organic carbon loads in operation which could be upgraded with simultaneous P precipitation? With the removal of N?
- Are new treatment plants planned? Will they include nutrient removal applying P precipitation and/or biological P removal? If not, are there options to implement such a treatment step?
- Are effluents of treatment plants with P removal nonetheless a significant source of P for the catchment? Can a post-treatment step for additional P removal be implemented?
- Are industrial wastewater discharges significantly contributing to the nutrient load from the catchment? Can their effluent quality be improved by enhanced treatment (or where P-dosage is practised, by better control of the dose)?
- Is there any regulation in place that requires nutrient removal at treatment plants? Is this regulation considering the target concentration in the waterbody necessary to avoid cyanobacteria blooms?

UNSEWERED AREAS:

- How many households are not connected to sewer systems? Which type of disposal do they have? Are there direct discharges into the surface water? Does rainfall rinse the content of poorly managed latrines, open defecation or septic systems directly into surface water?
- If answers to question 12 indicate potential for a significant nutrient load to the waterbody, which options are available to prevent this (e.g., implementing improved on-site sanitation systems, including collecting and transporting the content of septic tanks to wastewater treatment plants or safe use in agriculture)?
- Can safe dry systems for collecting and treating human excreta be promoted as alternative to developing sewerage?
- Is a sewer development planned, and should this approach be further pursued? If so, go back to points 4–11.

SEWER SYSTEMS:

- Are there separate sewer systems in place? Are stormwater sewers draining areas with heavy nutrient pollution (e.g., farmyards, excreta from pets)? If so, could emissions be reduced by installing infiltration ponds?
- Are there connections between stormwater and wastewater sewers, discharging untreated wastewater continuously?
- Are combined sewer systems in place? If so, how frequently and at what type of rain events to the overflow, bypassing treatment?
- Are combined sewer systems equipped with retention tanks or basins? If yes, to which extent? Are regulations in place and if so, how stringently are they implemented?

SEWAGE SLUDGE:

- Is sludge used as fertiliser? (If yes, see Checklist 7.3 for agricultural activities in section 7.3.4.)
- If sludge is disposed, is the site and method adequate to avoid nutrients reaching the waterbody?

For estimating how these nutrient loads relate to loads targeted for the waterbody as discussed in section 7.1, see section 7.4.

7.3.4 Nutrient loads from agriculture and other fertilised areas

While in some regions of the world, agricultural productivity is low due to a lack of fertiliser, in other regions, fertilisation is excessive and the primary cause of diffuse nutrient loads to waterbodies where they cause eutrophication and cyanobacterial blooms. For phosphorus, MacDonald et al. (2011) give an overview of this global imbalance, and Withers et al. (2014) describe agriculture as prominent and persistent cause of diffuse nutrient loads in many parts of the world. However, the latter authors also emphasise the importance of farming and food production, in consequence of which measures potentially imposing restrictions must be reasonable and effective. This requires a sound identification of nutrient loads and an assessment of their relevance for eutrophication of the specific waterbody.

7.3.4.1 Sources

Sources of nutrient loads from agricultural activities are fertilisers and manure or slurry spread on fields as well as excreta from free-range animal herds on pastures. Animal husbandry is typically relevant where feedlots, large stables or manure piles are located close to a waterbody. Nutrient loads from fertiliser and manure/slurry can range from almost negligible to extremely high, depending on how much is applied in excess of that which the crop can take up and convert to biomass. The excessive application of fertilisers and manure in many of the world's more affluent agricultural communities has been based on policies actively encouraging and subsidising intensive fertilisation (Withers et al., 2014) and on the widespread concept of soils serving as storage for P, adsorbing it and releasing it when needed by the crop. Where this has led to amounts applied to soils that exceed their binding capacity, soluble P will leach to the waterbody (Behrendt et al., 2000). Also, as discussed in section 7.3.1, soil particles to which P is adsorbed can release it once erosion carries them to the waterbody (Novotny, 2003). Fox et al. (2016) show that streambank soils can contain from nondetectable to more than 1000 mg P per kg soil. From their evaluation of the modest number of studies available from Europe and North America, these authors conclude that where catchments are impacted by excessive nutrient application, soils are likely to contain more than 250 mg/kg. The fraction of this which becomes available for algae and bacteria when erosion carries such soils into a waterbody strongly depends on the physical and chemical conditions in the waterbody. Where the "legacy phosphorus" from excessive fertilisation in agricultural soils is high and/or the time span for which it is likely to cause loads to a waterbody is difficult to assess, it is particularly important to assess the erosion pathways to the waterbody (Sharpley et al., 2015).

While excessive fertilisation also increases nitrogen (N) loads, these are often due to the large size of intensive animal husbandry operations: where these produce amounts of manure and slurry that cannot be spread on nearby fields and pasture without exceeding the uptake capacity of crops and meadows, this causes loads of both N and P – possibly significant or the predominant source of eutrophication and cyanobacterial blooms (additionally, excessive manure and slurry spread on land can cause elevated nitrate concentrations in groundwater used as source of drinking-water; see Schmoll et al., 2006).

In some situations, substantial fertilisation of other land, such as golf courses or lakeside lawns, may also be a relevant source of loads to a waterbody.

7.3.4.2 Pathways

Where erosion occurs, soil particles will be carried towards the waterbody, thus transporting the P adsorbed to them. There is consensus that streambank erosion is a highly relevant pathway for phosphorus loading: Fox et al. (2016) review case studies of P loads from streambanks and conclude that 7–92% of the total P loads could be accounted for by streambank and gully erosion. Peacher et al. (2018) also review streambank erosion as a major source of nutrient loads transported with sediment and report own results for P loss rates with soil eroded from riverbanks in the range of 38–49 g/m and year for the riverbanks of two streams in Missouri; these loads amounted to 67% of the P transported in these creeks. Although there are examples of situations in which plant root growth contributes to riverbank erosion, in general an intact cover of vegetation ("riparian buffer strip") stabilises the riverbank and can serve to intercept soil in surface run-off (see discussion in Fox et al., 2016).

In tributaries and drainage ditches, P thus transported will interact with the channel bed sediments, leading either to a reduction (through adsorption and sedimentation) or to an increase of P (through resuspension and desorption) transported in the stream – or to periodic alternation of both processes, depending on river flow and stormwater events. Often only a fraction of such a P load will become relevant for eutrophication of the downstream waterbodies, and the size of this fraction depends on a range of chemical and physical variables. Quantifying these variables is still challenging, and Fox et al. (2016) review publications on methods and models for this purpose.

In contrast to pathways for P, excessive nitrogen (N) from fertiliser or animal excreta scarcely binds to soil. Animals release N as urea which rapidly degrades to ammonium, some of which is lost to the atmosphere by volatilisation (where in the form of N_2O, it acts as greenhouse gas, enhancing climate warming) and some of which is oxidised to nitrate by bacteria in the soil (nitrification). Nitrate is also the form in which fertilisers contain N. As nitrate is very well soluble, excessive N readily leaches from soils and reaches waterbodies not only by surface run-off, but also via tile drainage (Novotny, 2003).

Nutrient loads not only depend on the amounts of fertilisers and manure applied, but also depend on timing of the application as well as on conditions determining pathways to the waterbody. These include natural geographical conditions such as the slope of the land as well as agricultural practices: untimely application of manure (e.g., on frozen ground or before strong rainfall) may cause major nutrient loading. This not only pollutes water, but also loses potentially valuable fertiliser from the farmland. Methods of ploughing have a strong impact on the extent of erosion, and so does leaving fields barren, without vegetation cover. Access of cattle and other farm animals to a waterbody or its tributaries can cause loading through a direct input of faecal material when animals wallow in the water or defecate near it. In particular, cattle can cause massive erosion of shorelines saturated with the animals' faeces: the trampling of larger herds can destroy the vegetation cover and also create pathways for erosion farther into the catchment, as reviewed by Wilson and Everard (2018).

Pathways for both nutrients are also created by clear-cutting of forests and woodland by logging on steep slopes or burning of woodland to convert it into farmland. Without vegetation cover or through trampling by herds of livestock, steep slopes become unstable and susceptible to heavy erosion. Particularly in climates with heavy rainfall, such practices may massively promote erosion and thus nutrient loads.

7.3.4.3 What to look for when compiling an inventory of loads from agricultural activities

As pathways for nutrients from land to water depend so strongly on the general geophysical characteristics of the land, for assessing nutrient loads collecting information about these characteristics is as important as developing the inventory of the activities that potentially release nutrients. Checklist 2 in "Protecting Surface Water for Health" (Rickert et al., 2016) supports this with questions on local climatic and hydrological characteristics, tributaries and their discharges, topographical data and soil types, signs of erosion and flooding.

The following checklist 7.3 is intended as point of departure when planning the assessment of nutrient loads from agriculture. As for the checklist above for loads from wastewater and stormwater, aspects of this may feed into developing a checklist for inspecting a specific catchment, and the information thus serves to estimate both current loads and the impact of measures to control the loads. Checklist 4 in Rickert et al. (2016) adds further aspects.

CHECKLIST 7.3: COMPILING AN INVENTORY OF NUTRIENT LOAD FROM AGRICULTURAL ACTIVITIES, GOLF COURSES, LAWNS AND OTHER FERTILISED AREAS

LAND USE AND REGULATIONS:

- What types of land use are being conducted that could cause nutrient emission, for example, arable land, pasture, irrigated or drained agriculture, horticulture, market gardening, golf courses, lawns and parks reaching all the way to the shoreline? Which types are being conducted on land with steep slopes (more than 8% grade)?
- Which regulatory frameworks (specific legislation, regulations, recommendations, voluntary cooperation agreements, codes of good practices, restrictions, bans) exist, particularly for the application of fertiliser and manure? How well are they known to the farmers? Could their implementation being enforced?
- Are drinking-water protection zones established around the reservoir and/or its tributaries? If so, is a map of their delineation available? Which limitations do they involve, and how stringently are these implemented? If not, could they be established?
- Are policy instruments in place such as financial incentives (e.g., subsidies, low-interest loans or compensation for lost income during transition to more environmentally friendly practices) or financial disincentives (e.g., penalties for nutrient loads caused by poor agricultural practice) that can be used to initiate agricultural practices with low nutrient emissions? Are any future incentives reasonable and realistic?

- Are agricultural advisory services in place, and what practices do they recommend to farmers, particularly regarding fertilisation, stock size and practices of animal husbandry? What have they recommended in the past, possibly having led to legacy P in soils?

APPLICATION OF NUTRIENTS:

- Is manure or sewage sludge being applied to fields or lawns? If so, are amounts and dates of application documented? What information is available about the storage conditions and handling practices for manure or sewage sludge? Are application rates on farms mostly based on farm nutrient budgets (see Box 7.3) and crop uptake rates, or are they roughly estimated, or are they based on the need of getting rid of manure or sewage sludge, for example, in areas with high livestock densities, or in proximity to a wastewater treatment facility? Are incentives operating (e.g., expert consultations) to improve practice and achieve a balanced soil nutrient budget?
- Is application timed in relation to hydrological events and seasonal aspects, for example, presence/absence of vegetation cover, frozen ground? How adequate are spreading methods and timing in relation to weather conditions? Are there any incentives to improve current practice?
- If fertilisers are applied, which types and products with which composition (e.g., nitrogen and phosphorus contents) and in which amounts? Is information available on amounts applied? On concentrations in soils? Are application rates based on plant needs and up-to-date information? Are there any guidelines to support the calculation of appropriate fertilisation? If not, can they be provided?
- Are arrangements in place that limit the amounts to be applied? For example, agreements between farmers and drinking-water suppliers or managers of waterbodies used for recreation?

NUTRIENT LOSSES DUE TO AGRICULTURAL PRACTICES:

- What main crops are cultivated currently and during the past seasons? What trends or changes are anticipated? Which of the main crops have a low vegetation cover especially during rainy seasons? Are they cultivated on steep slopes? Can this be avoided?
- What ploughing practices are being applied? To which extent does ploughing promote soil erosion? Are any guidelines on best practice in place? Is any consultancy to farmers in place?

- Are winter cropping, mulch seed or any other practices to avoid soil loss from steep fields in place? Are there financial incentives on regional, national or catchment scale in place to support these practices?
- Is there indication of gullying, soil scouring and land slipping in steep areas in the catchment (including changes over time)? If so, what are possible causes (trampling of herds, ploughing practices, barren fields)? Is there an awareness of possible causes?
- Is the land drained, and do drainage ditches or pipes carry dissolved nutrients to the waterbody?
- Is there any other indication of fertiliser, manure or nutrient-rich soils being lost from land to the waterbody, such as periodic heavy loads of suspended solids in the tributaries?

LIVESTOCK AS NUTRIENT SOURCE AND CAUSE OF PATHWAYS TO THE WATERBODY:

- What are the livestock densities, animal species and amount of manures produced? Are they exceeding the nutrient needs on farm level? Can they be better utilised by better distribution?
- Are stables and/or feedlots close to the waterbody or its tributaries? If so, are there run-off pathways (gullies) to the waterbody? If yes, could manure collection and storage be improved?
- Is there sufficient storage volume for manure and slurry? Is the storage time long enough for seasons where applications are not favourable (e.g., winter)?
- Are pastures fenced, or can livestock access the waterbody or its tributaries? Are fences intact and regularly inspected?
- If there is an indication of direct impact of livestock excreta on the waterbody or its tributaries, how many heads of stock are there in the area? How much nutrient input can their excreta cause at maximum? Is this relevant in respect to P loading to the waterbody?
- Is there an indication of erosion damage from livestock?

INTERCEPTING TRANSPORT OF SOIL NUTRIENTS FROM LAND TO WATER:

- Can specific areas or practices be identified as likely main causes of nutrient loading, particularly of phosphorus? Can areas be identified which could be used as buffers to interrupt the transport of soil particles into surface waters or to allow denitrification to take place before the inflow of drainage to the waterbody?

- Are vegetation-covered buffer strips in place between fields or pastures and the waterbody or its tributaries? If so, are they properly located in respect to erosion transport? How wide are they, and are they intact or are they frequently interrupted? Are they managed and/or well maintained?

As for Checklist 7.2 on nutrient loads from point sources, neither will all of these questions be equally important in all situations, nor is information for answering all of them likely to be available, and identifying the gaps relevant for planning catchment management measures is an important element of an initial assessment of diffuse nutrient loads.

BOX 7.3: AGRICULTURAL NUTRIENT BUDGETS

A nutrient budget estimates the nutrient surplus as the difference between nutrient inputs and nutrient outputs for a certain boundary, for example, the amount of nutrient that enters a farm with fertilisers and feedstuff for animals minus the amount that leaves the farm with the produce. Nutrient budgets for agriculture can be distinguished by the definition of the boundary (farm, soil or land) they refer to.

A soil nutrient budget estimates nutrient surplus from nutrient inputs to the soil (e.g., fertilisers) and nutrient outputs from the soil (e.g., harvest).

Nutrients accumulate in soils as nutrient stock, changes of which are difficult to quantify. Therefore, they are frequently accounted in the surplus.

Nutrient budgets provide a valuable information about the link between agricultural activities and environmental impacts of nutrient use and management in agriculture. Nutrient budgets can be used to determine areas at risk of releasing nutrients to waterbodies (when estimated at low regional levels), to identify driving factors behind nutrient pollution resulting from agriculture and to follow trends over time. For further information, see Eurostat (2013).

Important specific expertise for assessing nutrient loads from agriculture particularly includes agricultural practitioners (preferably from the region and thus familiar with local practices, habits and attitudes), soil scientists, hydrologists and – if modelling loads is intended – also catchment modellers.

For estimating how these nutrient loads relate to loads targeted for the waterbody as discussed in section 7.1, see section 7.4.

7.3.5 Nutrient loads from aquaculture and fisheries

Aquaculture and fishponds in a catchment may be a major point source where their effluent reaches a waterbody. They are not typically the main source of nutrient loading, but in many regions, aquaculture and fish production are increasing. In particular, cage cultures ("net pens") within waterbodies may also introduce substantial nutrient loads directly into waterbodies. So may fisheries involving feeding or even fertilisation of the waterbody to enhance its productivity. Fisheries management within the waterbody can further impact water quality through its internal effects on the food chain and/or through bottom-dwelling fish which resuspend sediment, as discussed in Chapter 8 in the context of waterbody management.

The maximum amount of nutrients introduced can be calculated from the amount in the applied feed minus the amount in the fish biomass harvested from the system. While this approach disregards potential losses through sedimentation occurring in the tributary between the fishpond and the waterbody of concern, it provides a useful worst-case estimate for assessing the relative importance of loads from aquaculture and fisheries. An estimate is also possible from the biomass of fish produced, using factors that describe the amount of feed necessary for this growth and the efficiency of the conversion of fish food into fish biomass.

Nutrient concentrations in a fishpond effluent can vary widely over time, depending on current operations such as the cleaning of tanks, backwashing filters or emptying ponds. Alabaster (1982) showed that a 30-min cleaning operation discharged 75% of the total phosphorus and 10% of the total nitrogen (TN) from a fishpond, highlighting that such events may be important when estimating nutrient loads. Such short-lived nutrient pulses in the receiving waterbody may be rapidly utilised for the growth of cyanobacterial and/or algal biomass, causing sudden increases and triggering blooms.

7.3.5.1 What to look for when including aquaculture and fisheries in the inventory of activities causing nutrient loads

Checklist 7.4 suggests questions to address when assessing the contribution of aquaculture and fisheries to the nutrient load of a waterbody as well as for assessing the expected impacts of measures to reduce these loads. When using this for catchment inspection, adaptation to the questions which appear locally relevant is recommended. Including specific expertise from aquaculture and fisheries is valuable for estimating the nutrient loads (e.g., from feeding rates) as well as for assessing the efficacy of control measures in place or to be implemented. See also Checklist no. 5 in Rickert et al. (2016) for further information, particularly if the assessment is to include the wider context of health hazards from aquaculture and fisheries in water.

CHECKLIST 7.4: IDENTIFYING SOURCES FROM AQUACULTURE AND FISHERIES

- If aquaculture is practised in the catchment or waterbody, where are which operations located, and how much fish do they produce per year or season?
- If cage culture ("net pens") or fisheries are practised within the waterbody, where are they located, and how much fish do they produce per year or season?
- Are data on feeding and the source, amount and type of feed applied available, and on its phosphorus and nitrogen contents? If not, can nutrient loads be estimated from fish production rates and conversion factors?
- Are fertilisers applied? If so, what amounts, types, products and composition of fertilisers are used?
- Are manures applied? If so, what are the source, amount, composition and application patterns for the manure?
- Is wastewater or sewage sludge applied? If so, what information is available 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?)
- Do regulations (specific legislation, recommendations, voluntary cooperation agreements, codes of good practices, restrictions, bans) for these activities exist, and if so, how well are they being enforced?
- Are flow-through or recirculating systems being used?
- Is effluent discharged directly to the waterbody, or is it treated? If it is treated, how? Are data available on nutrient concentrations in the effluent and on the water volume of the effluent?
- Are data on nutrient concentrations in the effluent available from the aquaculture operator? Can nutrient loads from their discharge be estimated, for example, from fish food consumption and the amount of fish produced?

- What time patterns of these operations (e.g., emptying and cleaning of tanks) might be relevant to nutrient loading? Which nutrient sources may be relevant that are not readily detected through inspection of the operations (e.g., in sludge and sediment at the bottom of the tanks)?

For estimating how these nutrient loads relate to loads targeted for the waterbody as discussed in section 7.1, see section 7.4.

7.4 APPROACHES TO QUANTIFYING THE RELEVANCE OF SOURCES AND PATHWAYS

Obviously quantifying the loads introduced to the waterbody from the major sources via major pathways will provide the best basis for identifying the most effective measures to control nutrient loads. However, key parameters necessary for quantitative models are often unknown and not readily measured. Qualitative assessments then are a valuable beginning. Rickert et al. (2016) describe a qualitative approach to assessing loads, roughly categorising their relevance from negligible to extreme and highlighting uncertainties necessitating more in-depth assessment.

In some settings, a qualitative assessment of potential sources of nutrient loading can provide a sufficiently clear basis for planning control measures even without quantifying the relative relevance of different sources and pathways of loads. This is possible if conditions are quite clear. For example, in a densely settled, largely urbanised catchment, much of the nutrient load will originate from sewerage, and focusing on measures that reduce sewage nutrient emission loads will directly impact concentrations in the waterbody. For such a setting, it will be clear that without control of such substantial point sources, further load reduction measures cannot achieve sufficiently low loads to the waterbody to reach target nutrient concentrations. Similarly, for a largely agricultural catchment, identifying the steepest slopes for implementation of the most stringent management of fertilisation and tillage may be a sufficiently effective basis for achieving a substantial load reduction, even if the reduction achieved can hardly be quantitatively predicted and only assessed by subsequent monitoring of the change in concentrations in the waterbody. A merely qualitative approach – based on "getting the job done" for obvious measures – can provide substantial load reductions, particularly in situations in which resources for more elaborate approaches are lacking. Qualitative or semiquantitative approaches may suffice for estimating loads that are either self-evidently major or likely to be low.

Quantification becomes important where the load that a source contributes may be relevant but uncertainties are too significant to make decisions on investments or regulations to reduce it. Approaches to quantification cover a wide range, requiring different levels of information, staff capacity and resources. The European Union summarises some in its Guidance Document No. 28 (EC, 2012) in the context of its Common Implementation Strategy for the EU Water Framework Directive. This document has the advantage not only of being harmonised as outcome of discussions between a number of countries, but also of giving guidance at 4–5 different levels of complexity and data requirements. Thus, the technical guidance on the development of an inventory of emissions, discharges and losses of substances described in this document can be used for a range of situations with different resources. While this document focuses on priority hazardous substances, it outlines general principles which can be applied for nutrients as well. It therefore uses some key considerations from the Guidance Document No. 28 (EC, 2012), giving specific attention to situations where data availability is lower than can be expected in EU countries.

In face of the complexity of systems and the challenges associated with data collection, three broad quantitative approaches in the establishment of inventories can be distinguished, which are shown in Figure 7.2 with their scope indicated by the dashed boxes in diagram and their complexity increasing from right to left:

- the riverine load-oriented approach, which estimates the observed total load that a river carries into a lake or reservoir. This information can be used together with a quantification of point source inputs to calculate an estimate of the diffuse inputs (green dashed line in Figure 7.2);
- the pathway-oriented approach (POA), also called “regionalised pathway analysis” (RPA), which models the different transport phenomena for the final input routes to the river system starting from the “interface media” as soil, groundwater or wastewater treatment plants. This approach calculates regionalised emissions for small catchments (termed “analytical units”), which can be subsequently aggregated to river basins or subunits (yellow dashed line in Figure 7.2);
- the source-oriented approach, which addresses the whole system starting from the principal sources of substance release. Such an approach includes substance flow analysis (SFA; red dashed line in Figure 7.2).

As situations differ strongly in the range of information and data sources available, the following introduces a tiered (or level) approach whereby the complexity increases with each progressive tier, beginning with purely qualitative (tier 0) or semiquantitative (tier 1) assessment. Quantitative tiers (2–4) require further data as well as more in-depth understanding of sources and pathways, resolution and detail. On this basis, they allow a better discrimination of the relevance of sources, for example, the relative contribution of those emitting nutrients to sewers and wastewater treatment plants rather than the (lower tier) lumped treated effluent discharge which does not allow for discrimination of the original source. Thus, the different tiers support a progressively improved understanding of the emission situation and, therefore, the ability to effectively allocate financial resources and evaluate (cost-)effective measures for emission reduction.

The approach to select for a given catchment will depend on its size, the availability of data and resources as well as the relevance of the problem. Five levels or "tiers" (one qualitative, one semiquantitative and the three quantitative approaches outlined in Figure 7.2) of emission estimation methods are summarised in Table 7.1 and explained in the following.

Table 7.1 Five tiers for the elaboration of emission inventories in catchments – overview

Tier	*Required information*	*Expected output*	*Results from the inventory*
0. Qualitative assessment	• Catchment inspection and/or qualitative description of main activities in the catchment	• Overview over catchment characteristics	• Identification of potentially relevant sources and pathways
1. Emission factors (semiquantitative)	• Data on population, land use and wastewater disposal • Population and area-specific emissions	• Availability of data • Assessment of the quality of data • Identification of information gaps	• First rough estimate of point source emissions in relation to diffuse emissions • List of identified data gaps
2. Riverine load approach	In addition to tier 1: • Data on point discharge • River concentration • Data on river discharge • In-stream processes	• Riverine load • Trend information • Proportion of diffuse and point sources • Identification of information gaps	• Rough estimation of total lumped diffuse emissions • Verification data for emission estimates and for results from tier 3 and 4 • Listing of identified data gaps

(*Continued*)

Table 7.1 (*Continued*) Five tiers for the elaboration of emission inventories in catchments – overview

Tier	*Required information*	*Expected output*	*Results from the inventory*
3. Pathway-orientated approach	In addition to tier 2: • Agricultural statistics (fertiliser, crops…) • Soil data • Data on hydrology • Others depending on the applied model	• Quantification and proportion of pathways • Identification of hotspots • Information on adequacy of pathway-oriented protection measures (scenario calculations)	• Pathway-specific emissions • Additional spatial information on emissions
4. Source-orientated approach	In addition to tier 3 • Production and use data (nutrition statistics) • Substance flow analyses • Others depending on the applied model	• Quantification of primary sources • Complete overview about substance cycle • Information on adequacy of source protection measures	• Source-specific emissions • Total emissions to environment and proportion to surface waters

Source: Adapted from European Commission (EC) (2012).

7.4.1 Tier 1: Assessment using emission factors

In more heterogeneous and larger catchments or in situations with enhanced wastewater disposal, the main sources of nutrients in a catchment might not be obvious, nor may be the pathways by which they enter the river system. In such a setting, the tier 1 approach based on emission factors (also called “export coefficient method”) is helpful to obtain a first semiquantitative overview of the contribution of main sources of nutrient emissions to a waterbody – namely, municipalities (including households and industries) and agriculture.

7.4.1.1 Municipalities

As discussed in section 7.3.3, phosphorous is an essential nutrient in human nutrition and human excreta, which therefore are the dominating source of P in municipal wastewater, and other significant sources may be P from detergents or commercial and industrial wastewater, particularly from food processing enterprises or fertiliser industry. An estimation of P emissions from municipalities (which includes wastewater from households, commerce and industries) is possible on the basis of the following information:

- the number of people in the catchment, with 1.3–1.7 g P emitted per person and day (Zessner & Lindtner, 2005);
- whether or not detergents used locally are P free (i.e., which type is typically sold on local markets), with emissions per person amounting to 2–3 g if detergents contain P;
- the share of the population connected to sewer systems;
- the estimated amount of commerce and industry likely to emit P;
- the level of wastewater treatment (no treatment, biological treatment with removal only of organic substance ["C removal"], or treatment with P removal/P precipitation).

In municipalities without any significant commercial and industrial activity, P in wastewater predominantly originates form households. In case of high commercial and industrial activities, experience shows that those activities may increase P loads in wastewater by up to 1.5 g per person and day (Zessner & Lindtner, 2005), and this may serve as first rough estimate. Any large-scale fertiliser or food processing industries are not included in this number and would have to be accounted separately.

The impact of populations not connected to sewer systems on P emissions is highly dependent on their sanitation system. Where this is through subsurface or soil treatment, the impact will usually be small and can be neglected for a first estimate. Where household wastewater is directly discharged into a river or its tributary, the total load from the population would have to be accounted as emission into the surface waters.

Wastewater collected in sewers is usually discharged to surface waters, with P emissions depending on the level of treatment. Emissions are:

- 100% of P in raw wastewater in case of no treatment;
- 60–70% of the P concentration in raw wastewater in case of biological treatment without P removal;
- 10–20% of the P concentration in raw wastewater in case of biological treatment with P precipitation or biological P removal (with further reduction by a factor of up to 10 if a combination of post-precipitation and filtration step is added after conventional treatment) (Heinzmann & Chorus, 1994).

Example: There are four municipalities in a catchment. The first is a town and has 50 000 inhabitants (inh), all connected to the public sewer system, an average amount of commercial and industrial activity and a wastewater treatment plant, including biological C removal without P removal. The markets in town sell P-free detergents for washing laundry and dishes. The other three municipalities are small settlements with all together 1500 inhabitants not connected to sewer systems and buying in the markets of the town.

P emissions from the town to surface waters = (1.5 g P/(inh × d) [from households] + 0.75 g P/(inh × d) [from commercial activity]) × 50 000 inh × 0.65 (P in effluent after treatment) = 73 kg P/d = 2.7 t P/yr.

P in wastewater from settlements = 1.5 g P/(inh × d) × 1500 inh = 2.3 kg P/d = 0.8 t P/yr. The fate of this P load is not known. Catchment inspection would serve to collect evidence whether wastewater disposal from these settlements could directly seep into surface waters of the catchment.

7.4.1.2 Agriculture

The main external pathway by which nutrients reach a farm is the input of external (mineral) fertiliser and the input of feedstuff for livestock. Farm animals process their feed, excreting faeces and urine which is then spread as manure and slurry on fields. Nutrient exports from the farm as loads to a waterbody can ideally be avoided if feed and manure are kept in an internal on-farm cycle, with the phosphorus content of the agricultural products (as output of P from the agricultural production process) approximately balancing the P input through externally imported fertiliser and feedstuff. While this situation appears idealistic, agricultural nutrient budgets (see Box 7.3) have indeed proven to be a highly effective approach to controlling nutrient loads (see section 7.5.2).

Soil is the essential medium in this production process as it provides the nutrients to the plants for their growth. As discussed above, during the production process, nutrients not taken up by the plants may be transported from agricultural areas to the waterbody, and while nitrogen in form of nitrate is very soluble, P is usually adsorbed to a high extent to soil particles, if supplied to soil in higher amount as needed by the plants. This may lead to increased concentrations of P in agricultural soils, and if erosion occurs, this can transport P together with soil particles to surface waters. Depending on soil properties and soil saturation with P, it might also be transported in soluble form and reach surface waters with surface run-off, tile drainages, interflow or groundwater, but in most settings, particulate transport with erosion dominates. Losses of P from agricultural soil are impacted by many factors, and the load emitted into surface waters is determined by the concentrations of P in soils and the amount of soil mobilised from the field that reaches the waterbody. Because of the high numbers of factors that determine this process, even rough estimates of P emissions from agricultural soils to waterbodies are less straightforward than for wastewater from municipalities. Nonetheless, a first rough tier 1 estimate based on emission factors is possible for this source as well. Where more precise quantification is needed, more elaborated quantifications (tier 3) are recommended in cooperation with modelling specialists. For this tier 1 approach, the following information needs to be known:

- arable area in the catchment;
- basic information on slopes of land used for agriculture;
- connectivity of arable land to the waterbody or its tributaries (ranging from "well connected" to "poorly connected", e.g., due to the interception of erosion through natural vegetation or buffer strips);
- plant cover of crops during rainy seasons (missing to high);
- soil properties (clay, silt, loam, sand);
- density of livestock, particularly cattle, and fertilisation level (high to none);
- erosion abatement in place (high to none).

Inputs of P from the catchment to the waterbody range from about 0.1–0.2 kg P/(ha×yr) from areas with dense perennial vegetation cover up to 5.0 kg P/(ha×yr) from arable land (Franke et al., 2013). The highest values can be expected if high P concentrations in soils occur in situations with pronounced soil erosion and the eroded soil is easily transported to the surface waters. High P concentrations can be expected if agricultural management is characterised by high livestock densities and/or fertilisation levels exceeding plant requirements resulting in high P surpluses. P surpluses in soils can be estimated via soil nutrient budgets from the amount of nutrient in fertiliser, manure and slurry spread on the fields and pastures in relation to the amount in the harvests leaving the farm (for further information and data, see EUROSTAT (2019) and FAOSTAT (2019)). With clay/silty soils, the concentrations in eroded soil material may be further enriched as fine particles usually have the highest concentrations and are predominately transported.

Several local factors determine the levels of soil erosion. Firstly, soil erosion is impacted by the energy with which raindrops mobilise soil particles when they reach the surface. This is especially high if the crops grown have a low plant cover during rainy season (which is often the case for, e.g., maize, soya bean) and in regions with high rainfall intensity (volume per area and time). Secondly, the slope of a field and its length determine the transport capacity of water during surface run-off. Therefore, soil erosion increases at fields with steep and long slopes. Clayey/silty soils are especially vulnerable against soil erosion as small particles are more readily mobilised and transported as larger particles from sandy soils. Further, high organic (humus) content of the soil and improved soil structure reduce erodibility. If specific erosion abatement measures are in place, erosion is reduced.

Winter crops and mulch seed, for instance, increase the coverage of soils and thus hinder rain to mobilise and transport soil particles. High transport to surface waters of eroded material can be expected if the fields where erosion takes place are well connected to surface waters (high connectivity): run-off from such fields may directly enter surface water because there are no other types of land uses (e.g., buffer stripes) between them and the river is not able to hinder the transport of soil particles.

Example: A catchment of 50 km^2 has a share of 30% arable land. The amount of fertiliser applied is in a medium range; the region is hilly with a significant share of steep slopes and pronounced connections between arable land and creeks of the catchment. Silty soils prevail; no specific erosion abatement measures are in place. About 35 km^2 in the catchment is covered with natural vegetation or grassland. Input into surface waters can be assumed to be at the low end of the range given above, that is, 0.1–0.2 kg P/(ha×yr) from these areas as soil loss from these areas and P content of soil material are usually low:

- P emissions form naturally covered land and grassland = 0.1–0.2 kg P/(ha×yr)×3500 ha = 0.35–0.70 t P/yr.

About 15 km^2 are covered with arable land. We assume relatively high levels of P emissions due to unfavourable conditions with respect to erosion (high soil loss) but only average fertilisation levels (moderate P concentrations in soils) of 1.5–3.0 kg P/(ha×yr):

- P emissions form arable land = 1.5–3.0 kg P/(ha×yr)×1500 ha = 2.25–4.50 t P/yr.

Franke et al. (2013) present a more elaborate tier 1 approach for nutrient emissions from agricultural fields in the context of grey water footprint calculations. This can be applied if fertilisation levels are known. If requirements for the quantitative assessment of nutrient emissions are higher, the higher-level tiers discussed below should be applied. These tiers require including experts in the field of nutrient monitoring and nutrient emission modelling in the planning team.

7.4.2 Tier 2: Assessment using the Riverine Load Approach

The riverine load approach (RLA) as presented in EC (2012) is based on data measured on site, that is, for the water, the suspended solids, river discharge as well as monitoring data from relevant point sources, and it calculates the basic processes of transport, storage or temporary storage and degradation of substances. The resulting riverine load provides quantitative information about the recent status of loading and, provided long-term information is available, also about trends over time (see Figure 7.3). In particular, it allows the allocation of observed river loads to point and diffuse sources (i.e., a basic source apportionment). If a reservoir or a lake is fed by different rivers, RLA needs to be implemented for each one significantly contributing to the nutrient inputs into the reservoir or lake. High nutrient concentrations, an increasing trend, or a high relevance of diffuse sources indicate a need for a more detailed analysis using the approaches in tiers 3 and 4.

The nutrient load transported by a river is estimated by taking the product of the mean flow-weighted concentration and the total river flow, expressed by the following formula (OSPAR, 2004a):

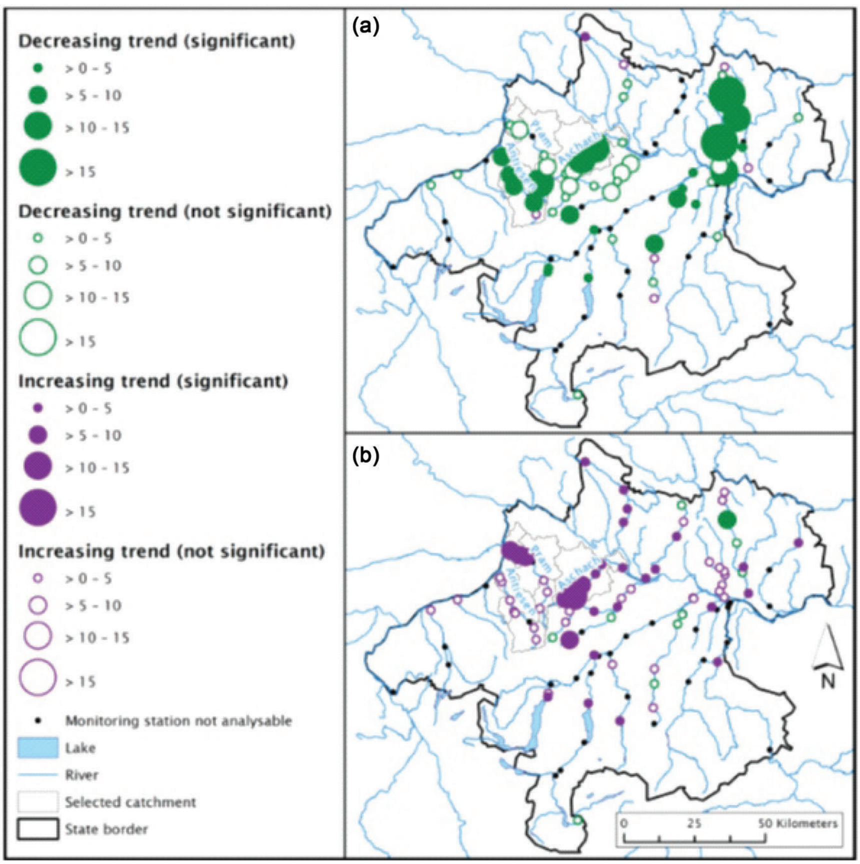


Figure 7.3 Utilisation of riverine data: Trends of total phosphorus concentration (flow adjusted in μg TP/L×year) in surface waters in Upper Austria for the periods: (a) 1990–2000 and (b) 2001–2004. (From Zessner et al., 2016.)

$$L_Y = \frac{Q_d}{Q_{Meas}} \times \left(\frac{1}{n} \sum_{i=1}^{n} C_i \times Q_i \times U_f \right)$$

L_Y = annual load (t/yr)
Q_d = arithmetic mean of daily flow (m^3/s)
Q_{Meas} = arithmetic mean of all daily flow data with concentration measurement (m^3/s)
C_i = concentration (mg/L)
Q_i = measurement of daily flow (m^3/s)
U_f = correction factor for the different locations of flow and water quality monitoring station
n = number of data with measured concentrations within the investigation period.

Periods of high river flow typically carry a disproportionately large amount of the annual load of a contaminant (Zessner et al., 2005). To avoid underestimation of annual loads, it is therefore important that water quality sampling strategies are designed to capture periods of high river flow (Zoboli et al., 2015). Sites selected for sampling should be in a region of unidirectional flow in an area where the water is well mixed and of uniform quality. Both the particulate and soluble load of a contaminant should be quantified.

7.4.2.1 Flow normalisation to avoid misinterpretation of causalities

Riverine nutrient loads and, in particular, certain diffuse source components vary strongly with rainfall and hence river flow; typically, the wetter the year, the higher the load. Without the application of flow normalisation procedures, natural interannual variations in flow can mask or lead to misinterpretation of trends in nutrient loads. Genuine reductions in nutrient inputs attributable to the implementation of measures, for example, can be masked by the occurrence of higher annual river flow during more recent monitoring. Conversely, an apparently declining trend can be incorrectly attributed to the success of measures, but in reality reflects a drier year or years. Flow normalisation addresses this issue and can be undertaken via a variety of methods. Harmonised flow normalisation procedures are given by OSPAR (2004a). An example of a trend analysis of P concentrations in a river under consideration of flow normalisation is given by Zessner et al. (2016).

7.4.2.2 Estimation of diffuse loads

As discussed above, riverine loads can be used to calculate diffuse and unknown inputs of nutrients providing point source information is available. In the most basic approach, the diffuse load can be estimated as the difference between the total load (measured from river discharge multiplied by concentrations; see above) and the load discharged from point sources, as follows:

$$L_{\mathrm{Diff}} = L_{\mathrm{yr}} - D_{\mathrm{P}}$$

where, for a given contaminant, L_{Diff} is the anthropogenic diffuse load, L_{yr} is the total annual riverine load, and D_{P} is the total point source discharge. Such an approach ignores any potential in-river processes such as sedimentation and remobilisation, but provides a useful approximate estimate of the diffuse load of a given substance.

A more detailed formulation will be necessary where processes in the river or stream and natural background loads are thought to be significant. The following formula is based on an approach established by OSPAR (2004b) for the calculation of diffuse nutrient loads; in-river nutrient processing is typically significant:

$$L_{\mathrm{Diff}} = L_{\mathrm{Y}} - D_{\mathrm{P}} - L_{\mathrm{B}} + N_{\mathrm{P}}$$

where, for a given contaminant, L_{B} is the natural background load of the contaminant, and N_{P} is the net outcome of in-river processes upstream of the monitoring point. There are several methods to estimate N_{P} on a catchment scale. For example, Vollenweider and Kerekes (1982) derived a formula which described the relationship between the nutrient concentration at the inflow of a lake or reservoir and the concentration within it based on the water residence time. This formula can be used to calculate the retention of nutrients by in-lake processes (N_{P} for lakes). Behrendt and Opitz (1999) proposed something similar for rivers at a catchment-scale level. They derived a relationship between area-specific run-off (river flow subdivided by the area of the catchment) and nutrient retention induced by processes within the stream or river as well as a relationship between hydraulic load of a river (river flow subdivided by the surface of the waterbodies in the catchment) and retention. If the flow of a river, the nutrient load, the catchment area and/or the surface of waterbodies in the catchment are known, this approach can be used to estimate N_{P} for rivers on a catchment scale (OSPAR, 2004c).

The riverine load approach (RLA) provides a useful means of estimating diffuse inputs and/or validating modelled predictions. However, diffuse inputs from different sources are merged into a single value and are not, for example, distinguished between inputs arising from agriculture and those arising from urban run-off.

7.4.3 Tier 3: Pathway-Oriented Approach

The pathway-oriented approach (POA) (see EC (2012) for more detail) uses more specific information about the land use, hydrology and basic transport processes involved. It adds an estimate of the impact of key processes of transformation, removal and temporary storage taking place between the source of emission and the receiving waterbody to the assessment. Therefore, data requirements are higher than for the lower tiers, but so is the level of information available for the inventory and for deciding on priorities for load control because this approach quantifies specific emissions (e.g., area-specific loads, stormwater run-off loads). It thus allows the identification of the main nutrient pathways and regional emission hotspots as well as providing a holistic overview of the emission status. POAs are well established and applied, for example, in many European River Basin Districts (RBDs) for the quantification of nutrients and heavy metal inputs.

As defined above, inputs can be caused by point and diffuse sources. Accordingly, point source pathways are defined by being discrete, having distinct locations and in many cases a quasi-continuous discharge, for example, the discharge of municipal wastewater treatment plants and industrial plants. Diffuse source inputs use different pathways and are discharged via different run-off components into surface waters, often driven or augmented by extreme events. A differentiation of the run-off components is necessary as substance concentrations as well as the underlying processes may differ significantly for the considered substances and localities. Actually 12 potential pathways for inputs into surface waters are identified for nutrients. This is summarised in the general working scheme (Figure 7.2). The pathways can be classified into three blocks:

1. pathways transporting nutrients from point sources;
2. pathways transporting nutrients from diffuse nonurban sources;
3. pathways transporting nutrients from diffuse urban sources.

The calculation of emissions from point sources can be straightforward if data on effluent concentration and the amount of water are available, or can be derived from statistical data with the required accuracy.

The inputs caused by diffuse sources are the result of more or less complex interactions with different interfaces, including temporary storage, transformation and losses. These processes have to be adequately integrated into the approaches.

As outlined above, pathways from agricultural diffuse sources include erosion, surface run-off, interflow, tile drainage and groundwater as well as direct discharges and wind drifting (e.g., of slurry sprayed on fields). The principles of POAs are best illustrated using the example of erosion, particularly as P can readily attach to soil and eroded sediment (Figure 7.4).

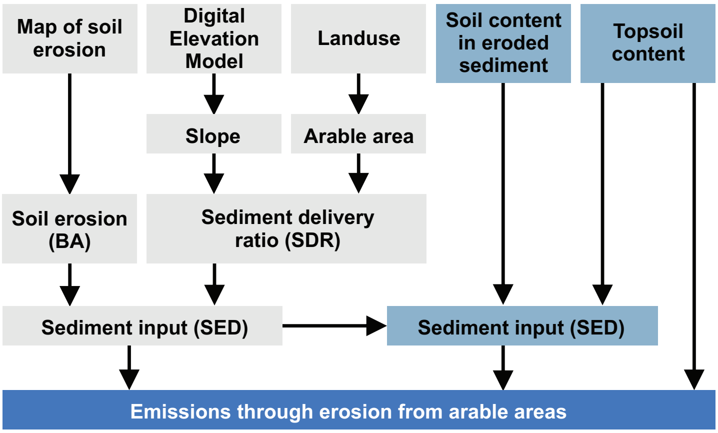


Figure 7.4 Input data to quantify the emissions from erosion. (Adapted from Fuchs et al., 2010.)

As discussed above, erosion begins with the mobilisation of top soil caused by heavy rainfall. At a river basin scale, the soil loss from arable land is commonly calculated using an adapted version of the universal soil loss equation (Wischmeier & Smith, 1960), which considers the slope, rainfall (energy input), soil characteristics, land cover and cultivation as well as erosion protection measures in place. The proportion of eroded soil entering the surface water is called "sediment delivery ratio". Different approaches can be applied for its calculation. As an example, individual areas within a catchment can be identified where eroded soil reaches a waterbody based on a Geographical Information System (GIS)-supported submodel, giving a relationship between sediment delivery and catchment characteristics (Behrendt et al., 2000).

During the erosion process, fine particles accumulate in the transported sediment. Phosphorus is predominantly bound to finer grains which accumulate during the transport process. The enrichment of a substance in the erosion material is described by the enrichment ratio (EnR), which is the ratio between the substance concentration in the topsoil and that in the sediment reaching the waterbody. Beyond the initial substance concentration, the grain size distribution of the topsoil and the intensity of the classification process are the most important factors influencing sediment concentrations.

As discussed above, in urbanised parts of a river basin, the important diffuse pathways for nutrients are overflows from stormwater sewers (i.e., those carrying rainwater run-off from paved or otherwise sealed surfaces) and in particular overflows from sewers carrying both stormwater and raw sewage. Their relevance is highly variable as overflows are caused by heavy precipitation when run-off volumes exceed the storage capacity of the sewer system, depending very much on local conditions. In general, a more complex situation can be assumed in combined sewer systems where a certain portion of stormwater is routed to a central wastewater treatment plant with the advantage of this being treated, but when overflows occur, untreated sewage reaches the waterbody. For combined sewer systems, the overflow rate and the proportion of discharged wastewater that is mixed with the stormwater should be estimated. The overflow rate is strictly dependent on the storage volume in the catchment and the hydraulic capacity of the wastewater treatment plant.

Many models using the pathway oriented approaches (POAs) focusing on diffuse nonurban sources have been developed (Kroes & van Dam, 2003; Groenendijk et al., 2005; Siderius et al., 2008; Gebel et al., 2009; Smit et al., 2009; Lindström et al., 2010; Venohr et al., 2011; see Table 7.2 for a compilation of models). As models are generally developed under specific conditions, they vary in strengths and weaknesses, which limits their applicability, depending on specific regional requirements. Schoumans et al.

Table 7.2 Examples of models for watershed-scale distributed simulation of nutrient transport in river basins (in alphabetical order)

Model	*Temporal scale*	*Description*	*Reference*
AnnAGNPS	Day or less	Annual-scale agricultural nonpoint-source pollution model, annualised version of AGNPS for continuous simulation of hydrology, erosion, transport of nutrients, sediment and pesticides	Young et al. (1995) Bingner & Theurer (2001)
ANSWERS-continuous	Day or less	Areal Nonpoint Source Watershed Environment Response Simulation, expanded with elements from other models (GLEAMS, EPIC) for nutrient transport and inputs	Bouraoui et al. (2002)
Hydrological Simulation program – Fortran	Hour	Continuous watershed simulation of water quantity and quality at any point in a watershed, developed for US Environmental Protection Agency (EPA).	US EPA (2011) Skahill (2004)
IBIS-HYDRA	Variable, 1 day to 1 year	Land surface and terrestrial ecosystem model IBIS with hydrology model HYDRA, used for modelling dissolved inorganic nitrogen fluxes and removal	Donner et al. (2002) Donner et al. (2004)
IMAGE DGNM	Month	Same as above, but with mechanistic instream model for C, Si, N and P, including sediment–water exchange	Vilmin et al. (2018)
IMAGE-GNM	Year	Detailed description of delivery of nutrients, at annual scale globally and by river basin; includes aquifer transport and processing	Liu et al. (2018)

(*Continued*)

Table 7.2 (*Continued*) Examples of models for watershed-scale distributed simulation of nutrient transport in river basins (in alphabetical order)

Model	*Temporal scale*	*Description*	*Reference*
INCA	Day	Integrated flow and nitrogen model for multiple-source assessment in catchments	Wade et al. (2002) Whitehead et al. (1998b) Whitehead et al. (1998a)
MIKE-SHE	Variable, depending on numerical stability	Comprehensive, distributed, physically based model to simulate sediment and water quality parameters in two-dimensional overland grids, one-dimensional channels, and one-dimensional unsaturated and three-dimensional saturated flow layers, with both continuous and single-event simulation capabilities	Refsgaard & Storm (1995)
MONERIS	Month or year	Empirically derived nutrient emission model, considering all relevant input pathways and instream retention processes on subcatchment level with a size of > 100 km^2.	Venohr et al. (2011)
NL_{CAT}		A combination of the models ANIMO/ SWAP/SWQN/SWQL. Based on the representation of system processes, nutrient concentrations can be calculated (inorganic and organic components). Furthermore, water flow and overland particulate and nutrient flow are modelled (run-off, erosion, subsurface run-off/leaching) in order to assess the total nutrient load to surface waters.	Groenendijk et al. (2005) Kroes & van Dam (2003) Smit et al. (2009) Siderius et al. (2008)
Riverstrahler	Reach, decade	Riverstrahler allows for analysing, apart from other disturbances, the impact of changing nutrient load and changing nutrient ratios, and potential saturation of retention processes such as denitrification and P retention by sediment. While in-stream processes are modelled with a mechanistic model, the delivery processes are described with coefficients, lumping soils, aquifers and riparian zones	Garnier et al. (1995) Billen & Garnier (2000)
SWAT	Day	Soil Water Assessment Tool to predict the impact of management on water, sediment and agricultural chemical losses in large ungauged river basins	Arnold & Fohrer (2005)

(2009) give an overview of some of the emission models and their specific applicability, and Moriasi et al. (2007) give guidelines for the estimation of accuracy in catchment models.

Monitoring → Modelling → Management are the key steps in a successful strategy for the development of sound policies for nutrient load control. Well-developed and appropriate emission modelling is central for this target. In addition to being necessary for assessing the relevance of different emission pathways, modelling helps to extrapolate information to locations or situations where monitoring has not been done or is not possible. Therefore, models use process relations or empirically derived relations expressed in quantitative formulas. Technically sound model applications, validated against measurements, implemented in a river basin or a watershed provide many potential applications, beginning with improving system understanding, increasing insights into cause–effect relationships and helping to identify emission hotspots.

For locations in a basin where monitoring is missing, modelling can provide an assessment of the risk to exceed water quality targets, and this can support the development of future monitoring schemes. Models are particularly useful to calculate scenarios in order to estimate the impact of a measure under consideration or – if the model structure allows – other potential future developments such as trends in population, land use or climate (Schönhart et al., 2018). The ability of calculating scenarios depends on the specific model structure and to which extent it depicts the complexity of the system. Whether models are able to assess scenarios quantitatively can be checked by running them with older data to see how well they are able to depict developments of the past.

The information derived from these investigations further provides a basis for cost-effectiveness or cost–benefit analyses. However, even technically sound models, the plausibility of which is validated by data from monitoring, will never provide an exact information. Therefore, uncertainty considerations are an important element of good practice in modelling.

7.4.4 Tier 4: The Source-Oriented Approach

This tier is based on substance-specific information on production, sales and consumption. It provides a comprehensive picture of the life cycle of a substance, for example, a nutrient. The benefit of this approach is that the information gained on the relative contribution of a source to the total nutrient load is far more precise than that gleaned from tiers 0 to 3, and thus, this provides a better basis for prioritising control measures addressing the primary sources of the nutrients. This level of precision may be relevant when advocating for control measures that require substantial investments (e.g., larger storage volume for stormwater to avoid overflow) or substantial changes of practice that may impact on people's livelihoods. (e.g., reducing fertiliser use or stock density) or require more elaborate management practices (e.g., introducing farm nutrient budgets; see Box 7.3).

Substance Flow Analysis (SFA), a source-oriented approach, is a method of analysing the flows of a substance in a well-defined system, including through industries producing and using it, households, wastewater treatment plants and all connected media such as soil, air and water. All the applications and uses of a substance are collated, enabling the development of strategies to reduce the impact of the substance. Such measures can also encompass source controls such as changes in consumption patterns (e.g., nutrition). SFA is applied in connection with the early recognition of potentially harmful or beneficial accumulations and depletions in stocks, as well as the prediction of future environmental loads. SFA methods, as we know them today, were first applied by Wolman (1965) in the wake of introducing metabolism studies for cities. Later, Baccini and Brunner (2012) developed a more specific method for the evaluation of the metabolism of the anthroposphere.

For nutrients, many SFAs have been performed on a supranational, national or district scale. Examples are the P balances of EU countries by Ott and Rechberger (2012) or the N and P balance of Busia District, Uganda, which was performed to identify the potential of improved waste uses for agricultural balances and productivity (Lederer et al., 2015). Zoboli et al. (2016a; 2016b) developed a time series in phosphorus flow analysis for the Austrian P-budget from 1990 to 2011 to assess drivers for changes in the national P metabolism and analysed the potential of different strategies for optimising the national P budget (Figure 7.5). This work goes far beyond just addressing P releases into waterbodies and possibilities for their reduction, but additionally includes measures addressing resource-efficient management strategies such as recycling technologies and changes in nutrition behaviour of people, which in turn affects agricultural practices.

One drawback to SFA is that applicable data tend to be limited to specific spatial or temporary solutions. Data sets are often only available on a country level. If the perspective is limited to a river basin, proxies may have to be used to illustrate the regional situation. And even though national data may be of high quality because they were compiled accurately, downsizing to the regional level can incorporate errors. On the other hand, it is also possible to combine a source-oriented approach of tier 4 with a pathway-oriented tier 3 approach by subdividing a country or region into subcatchments which form the basis for pathway-oriented emission modelling and integrate the aggregated subcatchment results for agricultural nutrient turnover and emissions into river systems into a regional or national SFA. This would consider the overall nutrient turnover, including imports, exports, production and consumption. Thaler et al. (2013; 2015), for instance, implemented such an approach, showing that in Austria P imports and emissions into the environment on country level could be reduced by about 20% if the population would change from its actual (meat-rich) diet to a healthy balanced diet (reduction of meat consumption by 50%) as recommended from nutritional experts. A further example is the reduction of P loads to a country's waterbodies merely by banning P from laundry detergents: this has reduced loads by about 50%, as has been shown for the Upper Danube in Germany and Austria by Zessner (1999).

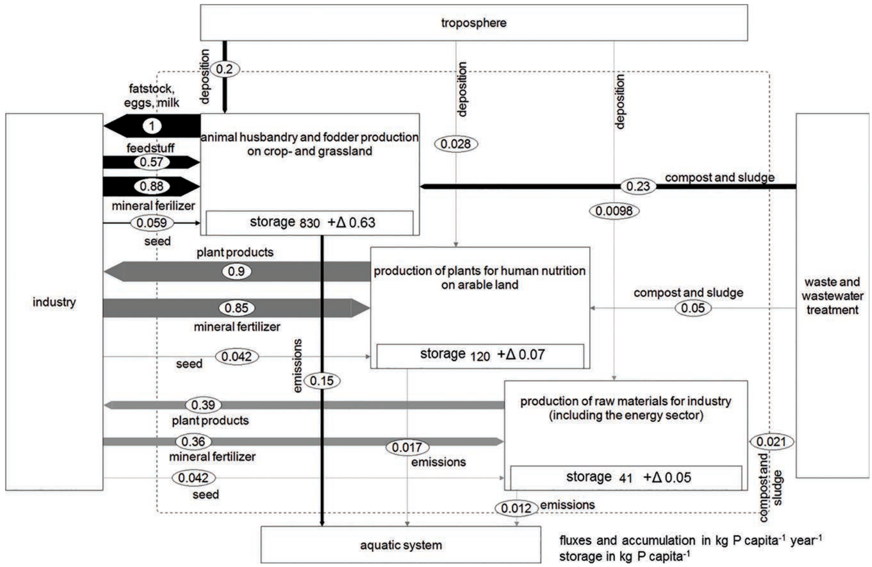


Figure 7.5 Phosphorus fluxes in the agricultural system of Austria differentiated by production for animal products, production for plant products and production for industrial raw materials (Thaler et al., 2013).

7.5 MANAGING NUTRIENT LOADS

The next step after identifying the relevant nutrient sources is to develop a management plan to mitigate them to the level targeted in order to reach the concentration targeted for the waterbody. Even if quantification of loads is only rudimentary or can only be roughly estimated, major source may be evident, and it will be important to get started with the implementation of measures to control them. The case study of the Santa Lucia River Basin (SLRB) in Box 7.4 shows that addressing major sources can lead to a substantial load reduction within a few years.

BOX 7.4: REDUCING EUTROPHICATION OF THE SANTA LUCIA RIVER BASIN IN URUGUAY

Juan Pablo Peregalli, Carolina Michelena and Giannina Pinotti

The Santa Lucia River Basin (SLRB) is the drinking-water source for 60% of Uruguay's population. Although it is not the biggest catchment in the country, it concentrates a major portion of Uruguay's industrial and agricultural activities. From 2004 to 2011, studies for assessing the water quality in the basin were conducted by the municipalities. The national authority responsible for the environment, in cooperation with external support, is implementing a water quality monitoring plan that includes 25 monitoring stations in different waterbodies of the basin. Most of the results show eutrophic to hyper-eutrophic conditions, and during March 2013, taste and odour events in supplied drinking-water were related to cyanobacterial blooms in the Santa Lucia River.

The initial assessment of the catchment showed that an average of 80% of the organic matter and nutrient load (N and P) received by the waterbodies originated from diffuse sources, including soil erosion and agricultural activities such as forage areas, fruit and vegetable plantations, dairy farms and feedlots. Point source contamination accounts for 20% of the total load and is mainly from nonsewered or insufficiently sewered settlements and from industrial facilities, mainly slaughterhouses, dairy, tannery and solid waste processing plants.

NUTRIENT LOADS MANAGEMENT STRATEGY

Based on these monitoring results, in 2013, the National Authority of Environment launched the "Action Plan for the protection of environmental quality and drinking - water sources in the SLRB". This plan included a series of measures to "control, stop and reverse the deterioration of the water quality and ensure the quantity and quality of water resources for a sustainable use of water in the river basin" (Table 1).

Table 1 Control measures in the Action Plan for the protection of the SLRB

MEASURE 1	• Reduce the impact of effluents dicharge from industrial activities
MEASURE 2	• Reduce the impact of municipal wastewater discharge
MEASURE 3	• Control the excessive use of fertilizers
MEASURE 4	• Control the load discharge from feedlots
MEASURE 5	• Control the load discharge from dairy farms
MEASURE 6	• Management of sludge from the drinking-water treatment plant.
MEASURE 7	• Limit the access of animals to water in the waterbodies of the catchment.
MEASURE 8	• Establishments of riparian buffer zones
MEASURE 9	• Require licences for surface water and groundwater extraction.
MEASURE 10	• Declare the catchment of Casupá stream as drinking-water reservoir.
MEASURE 11	• Involve the different actors in the management of the basin.

PRELIMINARY RESULTS AFTER 6 YEARS OF WORK IN PROGRESS

Industries were already under governmental surveillance, and the quality of the wastewater discharge was regulated by the Decree 253 from 1979, which includes targets for total phosphorus (TP) and ammonium. However, most of the wastewater treatment plants focus on organic matter removal, mainly stabilisation ponds, and did not achieve the levels targeted for nutrient emissions (5 mg/L for total phosphorous and ammonium). Measure 1 therefore focused on 24 industries that were responsible for 90% of the organic matter and 95% of nutrients discharged to the river basin from the industrial sector. For the emissions of those industries, additional standards were set and they were urged to build wastewater treatment systems with nutrient removal processes. As a result, discharge loads were reduced by 18% for biological oxygen demand (BOD5), by 52% for TN and 30% for TP, from 2014 to 2018 (Figure 1a).

Regarding municipal wastewater, measure 2 focused mainly on settlements of more than 2000 inhabitants. The existing wastewater treatment plants were urged to include nutrient removal, two new plants were built, the wastewater of two major settlements was transferred to the Rio de la Plata Basin (a much larger and less vulnerable catchment), and two plants were relocated from flooding areas. Because of the construction works that these measures require, most of these changes are still in progress; however, some results are already visible in the discharge data (Figure 1b).

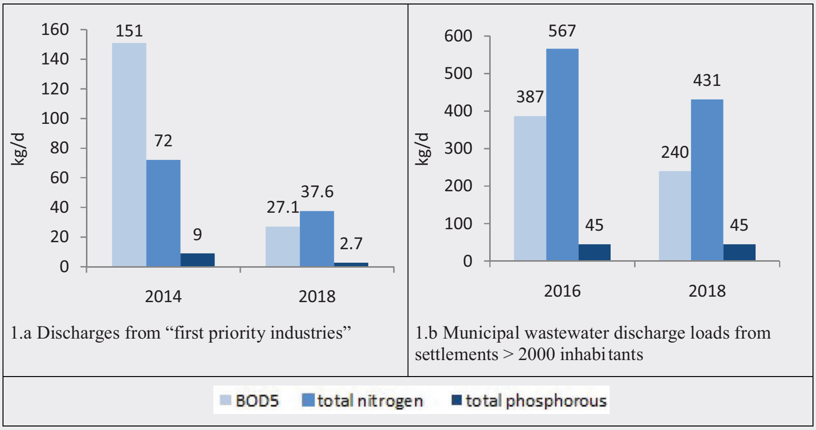
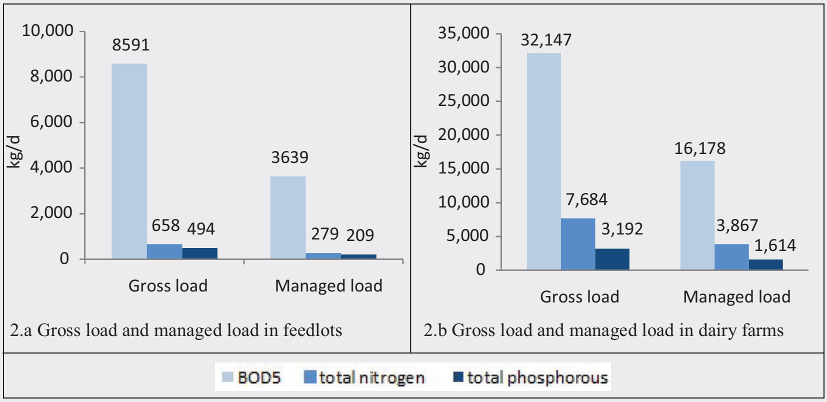


Figure 1 Results of measures 1 and 2 to control point source loads. (a) Discharges from "first-priority industries". (b) Municipal wastewater discharge loads from settlements > 2000 inhabitants.

Measure 4 banned the installation of new feedlots on most of the catchment and also the extension of existing ones. Also, in 2014, Decree 162/014 regulated environmental aspects of feedlots. Since then, national authorities regulating environment and livestock production and the association of feedlot owners are collaborating to establish the application of good environmental practices. In particular, this includes recommending the use of wastewater from feedlots and farms for irrigation instead of discharging it directly to waterbodies. For nine of the 20 feedlots in the catchment, that is, those with more than 500 animals, wastewater management systems were implemented. This has considerably reduced the loads of organic matter, N and P that otherwise would potentially be discharged to the basin (Figure 1a).

SLRB concentrates a major portion of the dairy farms in the country with a total of 1200 establishments, 92% of which are small (<300 animals), 5% are medium (300–500 animals) and 3% are big farms with more than 500 animals. Control measures first focused on the large farms, with a similar approach to the one used for feedlots. An interagency activity was launched to train farmers about sustainable wastewater management and to encourage its use for controlled irrigation. Additionally, a project was launched to provide economical support to more than 50% of the small farms to build wastewater management systems (drainage, accumulation ponds and irrigation systems). The rest of the small farms and medium-sized establishments still needs to be addressed but so far, about 50% of the organic matter and nutrients load discharged from dairy farms is being managed by the aforementioned initiatives (Figure 2).



2.a Gross load and managed load in feedlots

2.b Gross load and managed load in dairy farms

Figure 2 Results of measures 4 and 5 to control feedlots and dairy farms. (a) Gross load and managed load in feedlots. (b) Gross load and managed load in dairy farms.

In order to mitigate nutrient loads from soil erosion and run-off that reach the waterbodies of the catchment, measure 8 defined buffer strips on which agriculture and agrochemicals are banned to preserve and restore the riparian vegetation. Their width was set as 100 m for water reservoirs, 40 m for main rivers and 20 m for main tributaries. Analyses of satellite images show that most of the areas were already in compliance with the restriction (>98%), without considering urban areas that cover 14% of the buffer zones. Additionally, work with the local community to re-grow native riparian vegetation around the Paso Severino Reservoir is ongoing.

FUTURE STEPS

The action plan is still in progress, and it will take time to see the effects of the control measures on the water quality of the catchment. In December 2018, an update of the plan, based on the experience gained until then, implemented the so-called second-generation measures which are structured in four strategic lines: to ensure water quality, to reduce discharge loads, to protect and restore the ecosystems and to improve the understanding of the river system's dynamics.

7.5.1 Measures to control nutrient loads from sewage, stormwater and commercial wastewater

Wastewater is a key point source of nutrient emission, and it is usually easier to control and monitor than diffuse sources because loads are more readily measured. Effective treatment technology is available to remove nutrients from effluents, and success can be readily demonstrated by comparing upstream and downstream nutrient concentrations in the receiving waterbody. In consequence, as highlighted by a country example in Figure 7.6, the reduction of phosphorus loads from sewage has been far more successful than their load reduction from most other sources. For controlling nutrient loads from wastewater and stormwater, Table 7.3 gives examples of measures in the areas of planning, design and construction as well as operation and maintenance.

The necessary degree of nutrient removal in wastewater treatment depends on its contribution to the total nutrient load, and the assessment discussed above will show whether simultaneous precipitation or biological elimination removes P sufficiently in a given situation, or whether more advanced treatment (e.g., filtration) is necessary. This may be the case where treated sewage contributes a large fraction of a river's discharge, as is the case for, for example, River Spree in Berlin with 20–50% of the discharge being treated sewage (Fritz et al., 2004) but also for numerous other densely populated lowland river basins.

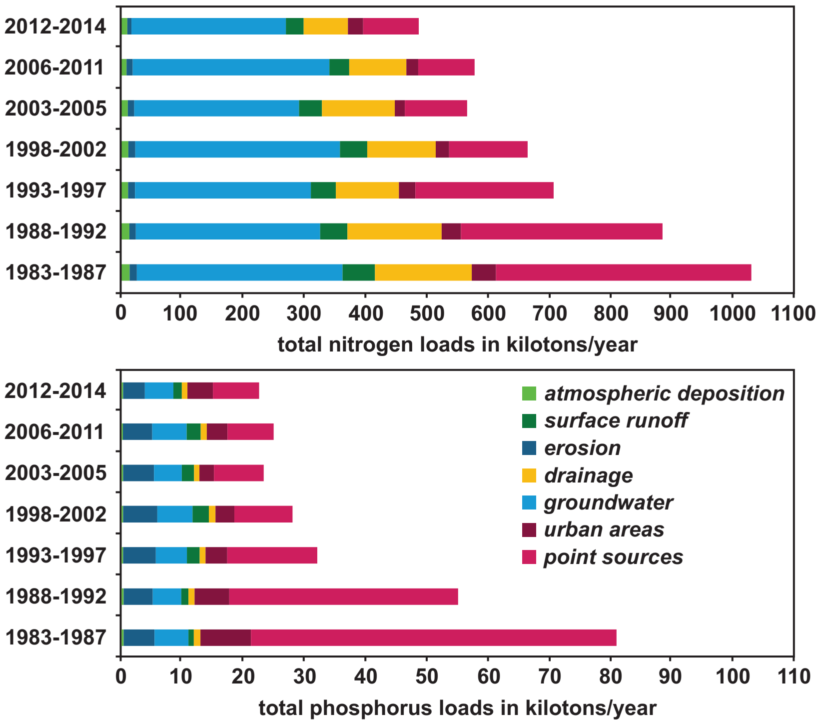


Figure 7.6 Loads of nitrogen and phosphorus from variable sources to surface waterbodies in Germany in kilotons per year (kt/yr). (Modified from UBA, 2017.)

A pronounced contribution to source abatement of P from municipal sewage, which affects all related emission pathways, is using P-free detergents. P loads and concentrations have been substantially and immediately reduced in countries introducing them. However, where wastewater causes substantial P loads, this may not suffice to achieve the target concentration for P in the waterbody, and the remaining P load from excreta nonetheless renders measures to reduce the P load from wastewater necessary.

Where loads from sewer systems carrying stormwater need to be reduced, an effective measure can be to intercept this on its pathway to the waterbody by constructing sufficiently large storages for flushes of rainwater: in such retention basins, a fraction of the suspended solids will settle to the sediment (which, however, needs to be removed periodically). From these storages, stormwater can also be gradually fed to a wastewater treatment, as capacity allows. A further option to retain stormwater is to create wetlands or to construct depressions for on-the-spot infiltration into the underground during storm events (e.g., areas in parks, covered

Table 7.3 Examples for control measures in the management of sewage, stormwater and commercial wastewater with options for monitoring their functioning

Process Step	*Example of control measures in catchment management*	*Options for monitoring their functioning*
Planning	Plan sufficient collection and treatment capacity to avoid overflow of untreated sewage Plan sufficient capacity for stormwater retention	Review the existing systems and/or plans and permit applications for new ones in relation to demand, including peak loads (e.g., at tourist season or during rainy seasons)
	Plan the target for nutrient concentrations in effluents in relation to the critical nutrient load determined for the waterbody, taking other loads into account	Review the existing systems and/or plans and permit applications for new ones in relation to the critical load (do they reduce the load sufficiently?) and with respect to their validity (can technologies proposed reach the effluent concentration targeted?)
Design, construction	Design and construct sewer and stormwater systems to avoid clogging and overflow, that is, with the necessary integrity and durability	Inspect during construction; monitor selected parameters (indicator organisms and/or substances typically occurring in the sewage), which would indicate leakage
	Design and construct treatment plants to ensure that they can achieve the effluent quality targets defined in their planning	Inspect plants during construction and operation
	Design and construct stormwater retention and infiltration systems to meet integrity and durability criteria	Inspect during construction and integrity during operation and when emptied for maintenance
Operation and maintenance	Clean sewers and drains at intervals necessary to avoid clogging	Inspect conditions; review records of cleaning and maintenance
	Keep wastewater treatment plants operating effectively	Monitor process parameters (see above) indicating process functioning; monitor nutrient concentrations in the discharge; monitor nutrient concentrations in effluent at regular intervals and during events (e.g., drought, heavy rainfall)
	Remove sludge from stormwater retention basins at appropriate intervals	Inspect condition of retention basins; monitor basin effluent suspended solids levels; monitor sludge levels in basin periodically; review records of sludge removal and maintenance
	Minimise nutrient accumulation on surfaces flushed by stormwater	Inspect street-sweeping and garbage-collection operations and records

with scenic vegetation). Figure 7.6 shows an example on the nation-wide level demonstrating the potential efficacy of the reduction of loads from combined sewer overflows and separate sewer systems (= urban systems in the figure).

For controlling diffuse nutrient loads from wastewater emitted by dispersed settlements along a river course or lakeshore, there are several options. One is the introduction of sewerage. Communities often construct sewers for the undisputable benefits of reducing infections spread through inappropriate disposal of excreta, and if this is not accompanied by sufficient treatment, it may dramatically increase phosphorus loads as compared to – for example – latrines from which a lesser fraction of these loads will reach surface waters. To prevent cyanobacterial blooms, it is therefore essential to introduce sewerage together with introducing appropriate wastewater treatment, including sufficient nutrient removal, to avoid exceeding critical loads to the receiving waterbody. An effective measure to ensure that no insufficiently treated sewage reaches the waterbody is to intercept its pathway by sewage diversion, for example, through installing a sewage channel between the settlements and the shore, that is, a channel or pipe which collects all of the wastewater and carries it to a treatment plant.

An alternative to sewerage is to implement sufficiently effective on-site treatment. A further option in dispersed settlements is to avoid sewerage and rather install dry sanitation systems, which, however, need to be safely designed and managed in order to avoid the contamination of groundwater or surface water (particularly with pathogens) and to achieve acceptance by users. In rural areas, when safely operated, such systems can have the benefit of providing fertiliser to use in agriculture (for safe use of wastewater, excreta and greywater, see WHO (2006); specifically for groundwater, see Howard et al. (2006); and for surface water, see Rickert et al. (2016)).

7.5.1.1 Operational monitoring for control measures in wastewater management

As discussed in Chapter 6, complementary to water quality monitoring, the purpose of operational monitoring is to continuously check whether or not a control measure is working as it should. For technical controls in wastewater treatment, effective parameters indicating treatment performance include, for example, flow rates and detention times in the treatment plant, suspended solids, dissolved oxygen, pH and chemical oxygen demand. These parameters can be measured with continuous, online recording by operators of the wastewater facilities. However, as Table 7.4 shows, many control measures which are important to ensure that nutrients from these point sources do not reach the waterbody are best monitored by inspection and reviewing of records. Time patterns for such operational monitoring can be at larger, irregular intervals, and it may be important to monitor when events occur that affect the process, or when operations change.

7.5.1.2 Validation of control measures in sewage and stormwater management

Where advanced wastewater treatment technology is implemented, the validation of whether or not these measures are actually achieving the targeted effluent nutrient concentration is quite straightforward: it requires a regular monitoring of effluent discharge and nutrient concentrations in it, that is, of the nutrient load leaving the plant. This applies equally to most alternative treatment technologies such as artificial wetlands: it is often feasible to run a focused programme to validate whether the loads discharged are within the targeted limits. Even where such monitoring programmes appear expensive, their costs need to be viewed in relation to the investment and operation costs, and such considerations typically show that it is worthwhile to validate whether or not a measure is sufficiently effective before taking decisions, for example, on continuing its operation or even upgrading it.

In contrast, it is challenging to validate whether the load management from overflows of mixed sewage systems and from stormwater in separate systems meets its targets: estimating nutrient loads during stormwater run-off requires sampling effluents and measuring their flows under conditions of heavy precipitation, and these samples are needed with a tight resolution over time (both water volumes and nutrient concentrations may change within minutes, and possibly also in space if numerous (usually dry) overflows come into operation more or less simultaneously). This can be achieved with automated sampling and/or a sufficiently large team of highly motivated staff.

Waterbody data on nutrient concentrations may support validation if they have a high resolution in time and space so that sudden concentration peaks can reflect loading patterns.

7.5.2 Measures to control nutrient loads from agriculture and other fertilised areas

Agriculture is a key diffuse source of nutrients, and in many cases, reducing the loads it causes has been less successful than reducing the point sources from wastewater discussed above. Improving practices of fertilisation to optimise the balance between crop yield and nutrient load control requires not only engagement of farmers and managers for the target of protecting the water source, but also expertise and training. Furthermore, the overall socioeconomic context strongly influences the locally realistic options for agricultural practice. Agriculture needs to remain productive

Table 7.4 Examples for control measures in agriculture and fertilised land use with options for monitoring their functioning

Process Step	*Example of control measures in catchment management*	*Options for monitoring their functioning*
Planning	Define criteria for exclusion or restriction of activities (e.g., stock density, type of crop) in vulnerable catchments (e.g., implement protection zones or riparian buffer strips)	Monitor land use in 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 the nutrient load expected from the area
	Set financial incentives (subsidies, credit, low-interest loans to fund changes, compensation for lost income during transition periods to new practices) and/or disincentives such as penalties for nutrient loading caused by poor management practice	Check compliance with practices negotiated before granting financial incentives or applying penalties; check compliance to restrictions set in regulations
	Regulate operations (e.g., types of crop; stock density on fields and in stables; use of fertiliser and/or manure) in vulnerable catchments	Review considerations as to whether they can achieve the target load estimated to be tolerable for the waterbody
Design and construction	Apply best management practices for treating wastewater from feeding operations	Check compliance of treatment structures with best management practices
	Construct fencing to protect waterbodies from livestock	Inspect integrity regularly
Operation and maintenance	Implement regulations for operations (e.g., types of crop; stock density on fields and in stables; use of fertiliser and/or manure) in vulnerable catchments	Inspect records of crops grown, fertiliser and manure application; count heads of stock
	Require soil tillage methods that minimise erosion	Visual site inspection
	Grow winter crop cover to reduce erosion	Visual site inspection
	Match irrigation and fertilisation (mineral fertiliser and/or manure) to the needs of crops or lawns; implement farm nutrient management plans budgeting fertiliser purchased against nutrient content of crop leaving the farm	Inspect drainage and monitor its nutrient concentrations; inspect farm records for nutrient budgets, amounts and timing of fertiliser/manure application

Source: Adapted from Rickert et al. (2016).

and economically viable, and measures to control eutrophication need to be sustainable also in this respect. Thus, aspects to consider when planning measures may therefore include a wide range, for example, prices achievable for produce, habits and demands of consumers, education status of farmers, messages conveyed by agricultural advisory services, access to sites for watering animals and costs of fertiliser or material for fences to keep stock away from water courses.

A range of measures to control nutrient emissions from fertilised land to surface waters is available. They can be summarised in three groups: (i) to avoid to high nutrient surpluses and enrichment in soils by crop choices and fertilisation limited to actual plant needs and uptake; (ii) to avoid nutrient (soil) loss from land by, for example, maintaining a vegetation cover on fields or other erosion abatement measures; and (iii) to intercept the transport of nutrients (soil) from agricultural land into surface water (e.g., with densely vegetated riparian buffer strips). They cover the areas of planning, design and construction as well as operation and maintenance (Table 7.4).

Good agricultural practice as implemented in some larger enterprises with accordingly trained staff involves balancing a farm's nutrient budget to where the farm does not import more N and P than the amount that leaves the farm with the produce (see Box 7.3). Regulations may require a farm operator to keep records of the amounts of fertiliser purchased and spread on the fields, or financial support from the water supplier or a government authority can be made dependent on demonstrating that the farm maintains this balance. Where large-scale intensive animal husbandry can lead to an imbalance between farm fertiliser needs and manure production, measures to avoid excessive spreading of manure on land are important.

Implementing farm advisory systems (or strengthening the existing ones) and providing information on appropriate or innovative approaches are important to optimise practices. Information campaigns can communicate best management practices such as fertilisation on demand. Such campaigns are most effective if combined with the analysis of soil nutrient content at the end of the growing season as a sound basis for assessing the seasonal fertiliser application needs for next year's crop. Successful multiple-stakeholder approaches have shown that funding soil analyses and information campaigns, for example, by state authorities or even the water supplier are cost-effective: the money invested for better raw water quality saves investment in treatment technology and is a more sustainable approach. Stock density and fertiliser application rates may also be limited by law, for example, by banning manure application during specific seasons with heavy rainfalls or snow and ice-cover or limiting stock density. Where large-scale animal husbandry operations cause amounts of manure and slurry significantly exceeding the nutrient demand of fields and pastures, loads may be controlled by organising manure export to other farms and regions with a need for nutrients (MacDonald et al., 2011). Further control measures may include requiring sufficiently large storage volumes for manure and slurry and banning manure application during specific seasons with heavy rainfalls or snow and ice-cover. Nutrient loads from agricultural activities, golf courses, lawns or other land uses involving fertilisation can be avoided if these loads are sited sufficiently far from the waterbody in order to avoid a direct input of fertiliser or manure during application or from grazing animals.

For mitigating phosphorus loads transported via erosion, it is generally important to establish and manage water retention measures that minimise the concentrated run-off. Such measures include avoiding devegetated land where slopes will allow erosion by heavy rainfall. On sloping land, it is particularly important to control run-off (e.g., by water retention measures such as retention ponds, vegetated buffer strips) and to avoid practices that enhance erosion, that is, planting of specific crops with low vegetation cover (e.g., maize), deep ploughing, ploughing groves perpendicular to the slope, intensive grazing or slash-and-burn agriculture. Winter cropping and mulch seed increase vegetation cover of arable land and therefore may significantly reduce erosion if professionally implemented. Maintaining the soil organic content and soil structure reduces soil erodability. Other measures for erosion abatement are contour ploughing, conservational tillage (see examples and discussion in Tiessen et al. (2010)), avoiding tillage altogether or creating terraces (Novotny, 2003). Intensive grazing and animal access to watering points near rivers can cause severe erosion of riverbanks, and such destruction of riparian vegetation as well as faecal loads should be avoided. Peacher et al. (2018) give an overview of publications discussing the benefits of fencing to exclude cattle from streams, thus preventing riverbank erosion; they also review publications on the relevance of vegetation cover directly on the areas on top of riverbanks to prevent erosion.

Riparian buffer strips covered with dense vegetation can effectively intercept surface run-off carrying phosphorus-rich soil eroded from arable land and pastures. If they are applied at sufficient width (i.e., up to 30 m) and at the right locations (where they effectively interfere to relevant P transport – this can be along the riverbank but also somewhere else in the catchment), they may effectively reduce particle-bound P transported by soil erosion. Nevertheless, in contrast to erosion abatement measures mentioned above, buffer strips may retain soil particles by being a sink and avoid their input into surface waters but they do not avoid soil and nutrient losses from productive agricultural areas. Furthermore, to maintain their longer-term efficiency, proper management of buffer strips is important. Other potential nutrient transport control measures include grassed waterways, grass filters, constructed ponds, reservoirs and wetlands as well as connected or reconnected floodplains.

7.5.2.1 Operational monitoring of control measures in agriculture and land use involving fertilisation

In contrast to monitoring effects on water quality, monitoring whether or not a measure is operating as intended can be simple and be performed by those managing the agricultural activities. Operational monitoring should provide a timely signal if the specified control measure is not operating within the acceptable limits, so that operators can take corrective action before nutrients are washed from the land to the waterbody. Monitoring the operation of many measures that can control nutrient losses from agricultural land or from fertilised lawns to water needs to be done by farmers or gardeners themselves, and motivation for such measures can effectively be developed by involving these stakeholders in planning the protection of the waterbody, as highlighted in Table 7.4. Time intervals for the monitoring of control measures in agriculture can often be much larger than for operational monitoring of technical control measures (such as wastewater treatment, which may even involve continuous reading and recording of parameters). For many measures, operational monitoring can simply be visual, that is, through inspection, for example, of the integrity of erosion control structures, fences or riparian buffer strips. It may also include desk work to assess whether reports required by regulations (e.g., on stock density or farm nutrient budgets) have been submitted and the information reported complies with the requirements. This is most effective if sporadically checked personally on site, for example, in the context of catchment inspection. Satellite data can support visual inspection. Some continuous, online recording is feasible for some agricultural control measures as well, for example, using the interruption of an electrical current as a monitoring parameter for the integrity of an electrical fence.

While enforcing compliance particularly in agriculture and of home owners has been experienced as notoriously difficult in many countries, experience is also that it tends to improve as the education level of farmers (and home or golf course owners) increases. It is also likely to improve where these stakeholders are successfully involved in the planning process or obtain support in implementing measures, for example, in the context of co-operation agreements with water suppliers.

7.5.2.2 Validation of control measures in agriculture and for land use involving fertilisation

In contrast to the rather straightforward options for validating the efficacy of measures to control nutrient loads from effluents discussed in section 7.5.2, validating whether or not the measures taken actually achieve the target of retaining nutrients on the land rather than losing them to the waterbody is more challenging: it requires quantitative approaches to estimating diffuse loads as discussed in section 7.4. Validation of measures controlling diffuse loads is typically a discontinuous activity to be repeated at intervals, particularly after changes in the system, with time scales for changes in nutrient losses from land to water usually being in the range of seasons or years.

Where improvement is substantial and visibly evident – for example, the reduction of soil erosion – validation may be possible by inspection. Another approach to validation is trend analysis of the development of agricultural practices which impact the nutrient emissions to surface waters, that is, of livestock densities, fertiliser applications, farm nutrient balances, cultivated crops and tillage practices.

7.5.3 Measures to control nutrient loads from aquaculture and fisheries

Where cage cultures and fisheries within a waterbody cause nutrient loads in excess of the load which is acceptable in order to meet the phosphorus concentration target for the waterbody, the only option available to control nutrient loads from feeding is to restrict or totally ban these activities from the waterbody. In practice, clear water with no or only low cyanobacterial biomass and productive fisheries are conflicting, scarcely compatible targets that require a decision on priorities.

In contrast, for aquaculture operations in the catchment, effluent treatment can be an option to reduce nutrient loads. Treatment can include technical methods as well as treatment through a wetland or even – provided concentrations of other contaminants such as medication are not too high – application of effluent on farmland, combining irrigation with fertilisation. However, the latter requires a tight control in order to avoid application in excess of demand, as it may risk "getting rid of the waste" driving the effluent amounts applied, which can in turn cause run-off to the waterbody. It further requires assessing whether such effluent causes inacceptable loads with treatment chemicals and pharmaceuticals (Table 7.5).

7.5.3.1 Operational monitoring of control measures in aquaculture and fisheries

Operational monitoring of control measures in aquaculture and fisheries may be difficult to implement particularly in small-scale operations that typically have poor recording and documentation. Specific motivation and training of operators can be important, and this may be facilitated by involving them or their representatives in planning (e.g., in the team for developing a Water Safety Plan). Where the target of clear water without cyanobacterial blooms is in conflict with fisheries and cage cultures as the basis for people's livelihoods, resolving this may require substantial discussion, potentially resulting either in an alternative drinking-water source or in alternative sources of income and potentially also of the local population's protein.

Table 7.5 Examples for control measures in the management of aquaculture and fisheries with options for monitoring their functioning

Process Step	*Example of control measures in catchment management*	*Options for monitoring their functioning*
Planning	Plan operations *within a waterbody* (such as cage cultures or feeding of fish) in relation to targets for the maximum acceptable nutrient load (see section 7.2)	Review the existing systems and/or plans and permits for the nutrient load; the operations are likely to introduce in relation to the nutrient load acceptable for the waterbody
	Where targets are in conflict, that is, between a TP concentration in the waterbody and aquaculture or fisheries, decide on the water-use priority	If the decision is against aquaculture or fish stocking, inspect the waterbody or catchment to check for compliance
	Plan aquaculture operations *in the catchment* with respect to the nutrient load acceptable for the waterbody, potentially introducing effluent treatment (settling ponds, wetlands)	Review the removal efficiency treatment that can potentially achieve the resulting load in relation to the nutrient load acceptable for the waterbody
Design, construction	Line or reline fishponds from which water may seep to a waterbody with impervious material; protect from storm and flood damage, for example, through stormwater bypasses	Inspect structures as to suitability of design for the purpose and their integrity. Monitor water balance in ponds to determine if seepage is occurring
	Use closed re-circulation system with treatment, aeration, sustainable stocking rates and controlled feeding rates	Inspect design and construction; review the management plan for stocking and feeding rates
	Avoid discharge of untreated effluent – treat it or use it as liquid fertiliser on land areas that are not susceptible to run-off and leaching	Review information about its designation
	Construct and maintain particle traps in tanks (with separate sludge outlet)	Inspect structures
	Use removed sludge as fertiliser on land areas that are not susceptible to run-off and leaching	Inspect storage and application sites; review records of sludge application

(*Continued*)

Table 7.5 (*Continued*) Examples for control measures in the management of aquaculture and fisheries with options for monitoring their functioning

Process Step	*Example of control measures in catchment management*	*Options for monitoring their functioning*
Operation and maintenance	Match amount of feed to intake by the fish, 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 Estimate fish stock density; discuss practices and use of specific diets with operators and feed supplier
	Use low-polluting feed, high levels of lipid, lowered protein content, typically with high digestibility value, low in phosphorus	…
	Collect waste from tanks and cages	Inspect records of waste collection and cleaning activities, with waste volume estimated and disposal practice (sites) noted
	When emptying and cleaning basins, ponds and tanks, avoid discharge of untreated water	Discuss attention to this point with operators
	Keep fish stock density below a threshold defined as acceptable in relation to the nutrient loading target for the waterbody	Inspect records of fish stock density

7.6 INCLUDING CLIMATE CHANGE SCENARIOS WHEN PLANNING MEASURES

Climate change is expected to increase the frequency of extreme events such as rainfall patterns, floods or drought, and such events will impact on nutrient loads to rivers, lakes and reservoirs (WHO, 2017a). The extent to which such events are likely to change nutrient loads to a given waterbody, however, strongly depends on local conditions. For example, a heavy rainfall event may enhance erosion and thus increase the phosphorus load. In contrast, depending on the soils eroded, this may be accompanied by increased loads of silt that binds phosphorus with which it settles to the sediment. Also, if previous drought has rendered the soil surface hard and almost impermeable, such an event may dilute the concentration in the waterbody rather than increasing it. For example, Schindler (2006) found that for lakes in the Canadian Experimental Lakes Area, dry periods with less inflow actually reduced the phosphorus load, and this effect more than compensated that of a reduced flushing rate, actually reducing P concentrations in the lakes.

Generalised predictions of the impact of climate change on nutrient loading on a specific waterbody are therefore not possible; rather, site-specific scenario considerations are a prerequisite for including potential climate change impacts when planning measures to control nutrient loads. Past observations during extreme events are useful for such considerations. Where models can be constructed to depict nutrient loads relative to weather events, these are a highly useful tool to test climate change scenarios. Schönhart et al. (2018), for instance, include climate scenarios to assess climate-driven impacts on land use and nutrient emission in an integrated impact modelling framework (IIMF) for the whole Austrian territory. To address the uncertainty of predictions for precipitation, these authors tested two scenarios, one with increasing precipitation in future and another with decreasing precipitation. Results show that drier conditions could increase the pressure on freely flowing river stretches because reduced dilution of permanent emissions would cause higher concentrations, while increasing precipitation would, in contrast, increase the pressure on stagnant waterbodies because of increasing transport of loads from diffuse sources.

As discussed in the World Health Organization's guide on "managing health risks associated with climate variability and change" (WHO, 2017a), developing a Water Safety Plan provides a good platform to include the experts and specialists "*to understand potential climate change impacts in the context of their water supply*" and thus integrate aspects of climate resilience into planning improved management of a catchment.

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