EUROHARP 9-2004

Nutrient Retention Handbook

Software Manual for EUROHARP-NUTRET
&
Scientific Review on Nutrient Retention

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Executive Summary

The first primary objective of the EUROHARP project is to provide end-users (national and international European policy-makers) with a throrough scientific evaluation of nine contemporary quantification tools and their ability to estimate diffuse nutrient (N,P) losses to surface water systems and coastal waters, and thereby facilitate the implementation of the relevant policy instruments (eg. EC Water Framework Directive; EC Nitrates Directive). EUROHARP will contribute substantially to improve the comparability, transparency and reliability of the quantification of nutrient losses from diffuse sources, and thereby to improved efficiency of abatement strategies related to the implementation of e.g. the Nitrates Directive and the Water Framework Directive.

The retention of nutrients in different water body types as streams, rivers, lakes, reservoirs and riparian wetlands is important as physical, chemical and biological processes either permanently remove nitrate through denitrification or store organic N and phosphorus for shorter or longer time periods thus delaying the transport in the River Basins. When analysing nutrient pressures against observed nutrient exports from River Basins a knowledge on the current importance of nutrient retention is demanded. Moreover, nutrient retention processes can be altered by human interventions through eg. reclamation of former lake and wetland areas for other land use as agricultural production, recreation of wetlands and lakes, restoration of river channels, building of reservoirs, etc. National and regional mitigation strategies for combating nutient polllution often includes measures that reinstates the natural nutrient retention potential in River Basins.

The EUROHARP Retention Handbook was developed as a main deliverable under the EUROHARP project (www.EUROHARP.org). The Handbook consists of two parts: i) a software manual for the EUROHARP-NUTRET retention calculation tool; ii) a scientific review of nutrient retention in streams, rivers, lakes, reservoirs and riparian wetlands. The scientific review part of the report is a result of a thorough inspection of the internal literature on nutrient retention in streams, rivers, lakes, reservoirs a nd riparian wetlands. Existing mass-balance data on nutrient retention in lakes and reservoirs were also collected as part of the review. Results from the review and from analysing the data collected were used to develop the EUROHARP-NUTRET software. EUROHARP-NUTRET is developed as a tool intended to assist River Basin Managers to calculate nutrient retention in catchments or in single water body types. EUROHARP-NUTRET offers the possibility for users to perform nitrogen and phosphorus retention calculations utilising more or less simple methods giving in the software as different Tier's (Tier 1-5). A Tier 1 calculation is the most simple calculation method and also the least input demanding. The EUROHARP-NUTRET software is free for downloading at the EUROHARP homepage together with the Nutrient Retention Handbook.

1.   Introduction

This Nutrient Retention Handbook and EUROHARP-NUTRET software manual was developed as part of the EC-funded EUROHARP project encompassing 22 research institutes from 17 European countries (2002-2005). The overall objective of the EUROHARP work is to guide end-users to a choice of appropriate quantification tools in order to meet existing European requirements on harmonisation and transparency for quantifying diffuse nutrient losses, e.g. the implementation of the Water Framework Directive and the Nitrates Directive. The project encompasses both performance assessment of the individual models and the applicability of the same models in European catchments with different data availability and environmental conditions. A minor part of the EUROHARP project is devoted to information on nutrient retention in surface waters in the European river basins.

Identification of pressures and assessment of impacts in river Basins are the first tasks in the implementation of the EU Water Framework Directive (WFD) to be completed by 22 December 2004. WFD requires subsequently that River Basin Management Plans are prepared and adopted before the end of 2009 in order to achieve a good ecological status in all natural water bodies. The Member States must therefore collect and maintain information on the type and magnitude of significant anthropogenic pressures on water bodies leading to ecological impacts. Among these pressures are the diffuse losses of nutrients. Excess nutrient loadings into rivers, lakes, reservoirs and estuaries lead to eutrophication that can severely impact freshwater and coastal and open marine ecosystems by means of algal growth.

The River Basin District Authorities have to conduct an analysis for each catchment based on existing data on catchment characteristics such as land use, pollution sources and monitoring data. In the case of nitrogen and phosphorus, the catchment manager will have to analyse existing monitoring data in water bodies for main nutrient pressures by conducting a source inventory to quantify the importance of the main nutrient sources, viz.:

- Point sources, such as waste water discharges from wastewater treatment plants, industrial plants, scattered dwellings not connected to sewage, and fish farms.

- Diffuse sources, such as background nutrient losses, nutrient losses from agricultural activities, atmospheric deposition of nutrients and nutrient losses from forestry.

Nutrient sources can be assessed by conducting a riverine load apportionment into different nutrient sources ('source apportionment') (OSPAR 00/9/2, 2004). The method is based on the assumption that the total nitrogen and phosphorus loads at the selected river measurement site (L_{river}) represent the sum of the various components of the nitrogen and phosphorus discharges from point sources (D_P) entering inland surface waters, the nitrogen and phosphorus losses from anthropogenic diffuse sources entering inland surface waters (LO_D), and the natural background losses of nitrogen and phosphorus entering inland surface waters (LO_B). Furthermore, it is necessary to take into account the retention of nitrogen and phosphorus within inland surface waters in the catchment (R).

This may be expressed as follows:

$$L_{river} = D_P + LO_D + LO_B - R \quad (1)$$

The aim of the source apportionment is to estimate anthropogenic diffuse losses of nutrients and to evaluate the contributions of point and diffuse sources of nitrogen and phosphorus to the total riverine nitrogen and phosphorus load, i.e. to quantify the nitrogen and phosphorus losses from diffuse sources (LO_D) as follows:

$$LO_D = L_{river} - D_P - LO_B + R \quad (2)$$

In the anthropogenic diffuse losses in equation (2) are included discharge/losses from scattered dwellings.

Nitrogen and phosphorus discharges/losses from anthropogenic and natural sources are affected by temporary and more permanent sinks, as well as by cyclical and removal processes (e.g. denitrification and sedimentation in streams, lakes, reservoirs and on flooded riparian areas). These river system internal retention processes should be taken into account in order to assess the relative importance of the discharges/losses of nitrogen and phosphorus from different sources,. If the retention is not considered in the riverine load apportionment quantification, the initial nitrogen and phosphorus loss from diffuse sources will be underestimated.

The information gathered on pressures and their impacts should be taken into account when setting environmental objectives for the water bodies and the development of river basin management plans. The quantitative aspect is important, especially with regard to evaluating the precise pollution control needs for making each waterbody meet its environmental objectives. Most of the required WFD activities mentioned above depend on detailed knowledge of the anthropogenic pressures and their impacts on the aquatic ecosystems. This knowledge is acquired mainly through the existing monitoring programmes implemented for the aquatic ecosystems and for the significant pressures.

One important topic to include when dealing with source inventory of nutrients in river systems is the impact of nutrient retention. Nutrient retention takes place in different parts of the hydrological cycle:

Terrestrially

- Nutrient sinks in buffer zones along downslope arable fields experiencing soil erosion.

- Nutrient removal and storage on inundated riparian wetlands and floodplains.

Sub-surface

- Nitrogen removal in groundwater

- Phosphorus sorption in upper soils.

Surface waters

- Nitrogen removal in streams, rivers, lakes and reservoirs.

- Phosphorus storage in streams, rivers, lakes and reservoirs.

Thus, it is very important to be able to quantify nutrient retention at catchment level in order to establish a reliable nutrient budget and depict the important nutrient sources. The most accurate quantification of nutrient retention at catchment level is achieved if it is based on measured data (e.g. mass-balances) from the area. However, such measurements are very costly and time-consuming and nutrient retention is therefore often quantified by applying a certain nutrient model or tool. It is important that such nutrient retention models or tools results are transparent and based on standardised methods.

The EUROHARP project involves studies on nutrient retention in surface waters. A EUROHARP Expert Retention Group was therefore established in order to identify different nutrient retention tools and possibly develop a Decision/Support tool to be used by end-users to quantify nutrient retention in surface waters at the catchment level.

The EUROHARP-NUTRET tool for calculating nitrogen and phosphorus retention is able to produce preliminary rough average annual estimates for entire river basins using the Tier 1 tools having access

to only limited information from the river basin on lakes, reservoirs, rivers and wetlands. More precise estimates for nitrogen and phosphorus retention can also be calculated for individual lakes and reservoirs, but it requires specific information for each water body. Preferably, the calculations performed with the EUROHARP-NUTRET tool should always be validated against mass-balance estimates in the catchment for individual lakes and reservoirs. This is especially important when end-users conduct the simple Tier 1 approach built into the EUROHARP-NUTRET tool. However, also use of higher Tiers in the EUROHARP-NUTRET tool can give wrong estimates of nitrogen and phosphorus retention as processes such as phosphorus release from lake sediments are not included, and the information behind the different Tiers in EUROHARP-NUTRET mostly come from the temperate region.

Part 1

Software Manual

for

EUROHARP-NUTRET

2. EUROHARP-NUTRET software developed for calculation of nutrient retention

2.1 Introduction to the tool

The EUROHARP-NUTRET software is programmed in DELFI. The software enables end-users to calculate nutrient retention in lakes, reservoirs, streams, rivers and riparian wetlands with more or less sophisticated tools presented as different Tiers (Figure 2.1). The higher the Tier, the more advanced and input-data demanding the nutrient retention calculation method is. However, all the methods included in the EUROHARP-NUTRET are empirically derived and therefore relatively simple with a low input-data demand.
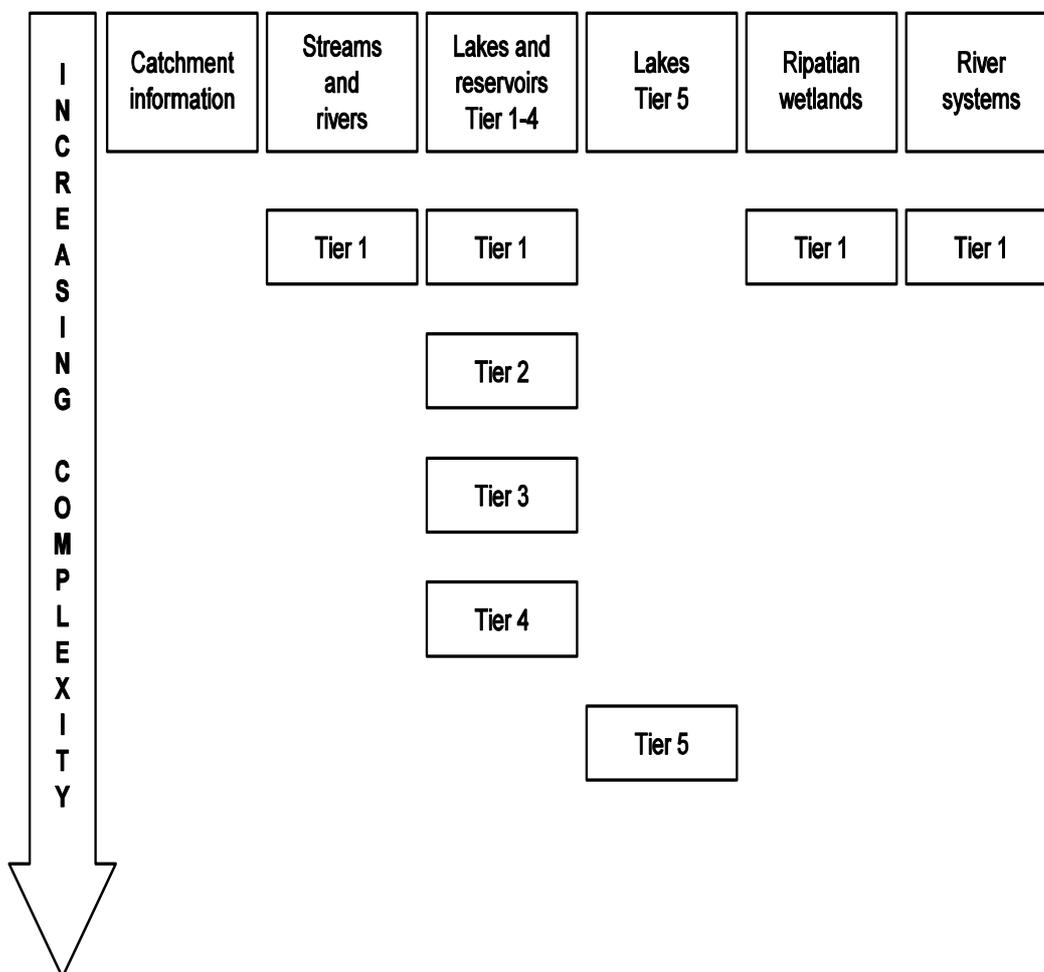
Figure 2.1 Conceptual diagram of the contents of EUROHARP-NUTRET Software for assistance with nutrient retention calculations in River Basins.

Figure 2.2 shows the start-up menu of EUROHARP-NUTRET.

Figure 2.2 The start-up menu in EUROHARP-NUTRET

Activation of the CLOSE button on the start menu at the right hand lower corner will simply close the programme.

Activation of the ABOUT button on the start menu will display background information of the EUROHARP project and the people involved in the development of the software.

Before being able to perform any calculations of nutrient retention in the different water bodies (before the buttons become activated) you must either load an old file by clicking on the LOAD button or you must save your information by clicking on the SAVE button. Your information can be saved in a text file at a destination chosen by you. After saving or loading a file the SAVE RESULTS and CATCHMENT INFO buttons on the left side of the start menu become activated (Fig. 2.2).

If you want to save the results of your calculations you must click on the SAVE RESULTS button at the left side lower corner of the start menu. You must specify a file-name of the document (text-file) that stores your calculation results and the file will be saved at the destination chosen by you.

The next step is to activate the CATCHMENT INFORMATION button. Always enter catchment information before using the software for nutrient retention estimation. You only need to identify the catchment by its name and state the total area of the catchment and the area of agricultural land. After entering the requested information, the OK button becomes activated and you must click on it to confirm. The information is needed in later calculations and is kept in the output file from the programme where you results are stored.

When you have filled in the catchment information the buttons for different water bodies become activated. Each of these can assist you in calculating nutrient retention in different Tiers (see detailed description of the content in chapters 4-8).

Activation of the STREAMS AND RIVERS button offers the possibility of conducting only a Tier 1 calculation of average annual of both nitrogen and phosphorus retention. For detailed descriptions of the methods, see chapter 5. The software is, however, prepared for inclusion of more advanced methods at a later stage.

Activation of the LAKES AND RESERVOIRS - Tier 1-4 button offers the possibility to choose among up to four different Tiers for calculation of annual nitrogen and phosphorus retention in lakes and reservoirs. For detailed descriptions of the method, see chapters 3 and 4. A total of 3 Tiers for nitrogen and 4 Tiers for phosphorus are available.

Activation of the LAKES AND RESERVOIRS - TIER 5 button offers the possibility of calculating monthly nitrogen and phosphorus retention in a specific lake or reservoir.

Activation of the RIPARIAN WETLANDS button offers the possibility of choosing only the simple Tier for calculation of nitrogen and phosphorus retention (Tier 1). For detailed descriptions of the method, see chapter 6. The software is, however, prepared for including more advanced methods at a later stage.

Activation of the RIVER SYSTEMS button offers the possibility of calculating annual nitrogen and phosphorus retention in surface waters (lakes, reservoirs and rivers) by applying a simple empirical model. For detailed descriptions of the method, see chapter 7.

All the results of your calculations performed by using the STREAMS AND RIVERS, LAKES AND RESERVOIRS - Tier 1-4 and RIPARIAN WETLANDS buttons are automatically transferred to the result file you have named under the SAVE RESULTS button, together with the information you have provided under the CATCHMENT INFO button (See example of output file in Figure 2.3). The result file can be loaded into a spreadsheet for calculating the total nutrient retention in the catchment by summing the calculated figures for nitrogen and phosphorus for each type of water body.
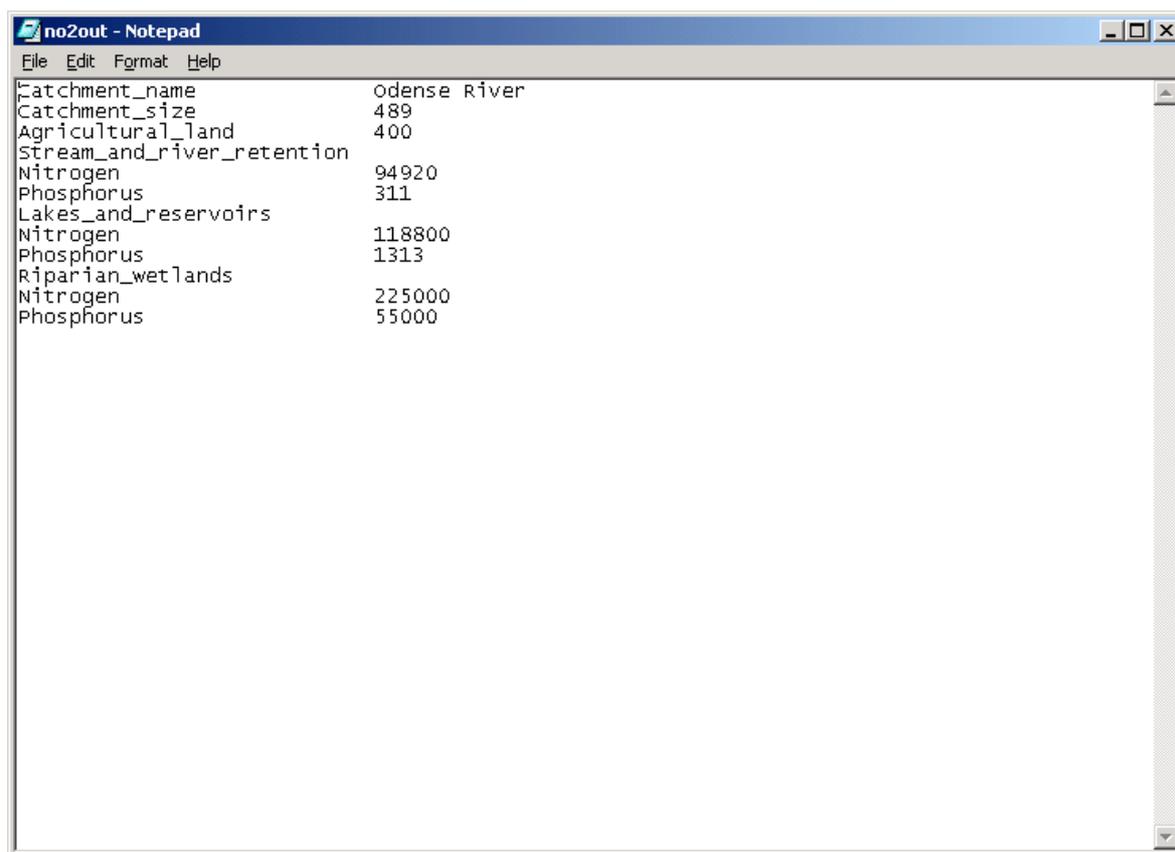
Figure 2.3 Example of the result file stored after performing calculations for STREAMS and RIVERS, LAKES AND RESERVOIRS –TIER 1-4 and RIPARIAN WETLANDS.

Activation of the CLOSE button will close the software when you have finished your calculations. The information you have entered will be saved in the file specified by you when pressing the SAVE button or the file you have re-opened using the OPEN button.

2.2 How to use the tool for calculation of nutrient retention in a river basin

The tool can be used for calculating nitrogen and phosphorus retention for single water bodies (a lake, reservoir or riparian wetland) by activating the specific button and entering the input data for the chosen water body or wetland. However, the NUTRET tool can also assist in performing a total nutrient retention calculation for a River Basin. In that case, follow the procedure described below.

1. Open NUTRET tool.

2. Press SAVE to save your calculation in a text-file.

3. Activate the Catchment Info button and enter the required information.

4. Activate the Streams and River button and enter the required information of stream length and stream areas in your river basin. If you do not have data on stream and river areas, the tool can assist you in estimating the area based on catchment area. Press the CALCULATE button and the tool will return the calculated nitrogen and phosphorus retention in the stream and river network in your river basin. The result is automatically transferred to an output file.

5. Activate the Lake and Reservoir Tier 1-4 button and enter the required information on all lakes and reservoir sin your river basin. The tool will return a Tier 1 estimate of nitrogen and phosphorus retention in all lakes and reservoirs in your river basin. If you have more specific information from one or several lakes and reservoirs, you should choose to calculate retention using a higher Tier. After entering the input data required for the lakes and reservoirs in the different Tiers, the tool will return an estimate of nitrogen and phosphorus retention for water bodies in each Tier. Finally, the tool calculates nitrogen and phosphorus retention in all lakes and reservoirs in the entire river basin summing up for calculations conducted in each of the Tiers you have chosen. The final result is transferred to the output file.

6. If you have riparian wetlands in your river basin, the programme can assist you in making an estimate of nitrogen and phosphorus retention based on some required input data. The result is transferred to the output file.

7. The total nutrient retention in the river basin can now be calculated from the information in the output file. You will need to export the output file to a spreadsheet and in this conduct the simple summing the three outputs from the NUTRET tool: retention in streams and rivers, retention in lakes and reservoirs, and retention in riparian wetlands.

8. Another way of achieving an estimate of nutrient retention in the river basin is to activate the RIVER SYSTEM button. Based on some required input data the tool estimate nitrogen and phosphorus rentention in surface water in the river basin. The result is transferred to the output file. Total nutrient retention in the river basin can then be calculated from the output file by summing the retention in the river system calculated with the retention in riparian wetlands.

The two separate ways of obtaining and estimating river basin retention assist you by providing a range of nutrient retention in your river basin within which the 'true' nutrient retention possibly lies.

3. Nitrogen retention calculation for lakes and reservoirs

3.1 Introduction

The concentration of nitrogen in lakes and reservoirs results from a dynamic equlibrium between inputs, outputs and different retention processes that remove nitrogen from the water or store it. In the case of nitrogen, retention processes are volatilisation of nitrogen through denitrification of nitrate to N_2 or N_2O and sedimentation of particulate nitrogen from the water phase to the lake or reservoir sediment.

Nitrogen retention in lakes and reservoirs can be calculated in many different ways depending on the available information from the catchment. The EUROHARP Retention Tool - EUROHARP-NUTRET, offers 4 different Tiers for end-user calculation of nitrogen retention in lakes and reservoirs. An increasing amount of input data information on individual lakes and reservoirs from a catchment is needed between Tier 1 and Tier 5. The Tier 1 calculation requires only basic information about the lakes and reservoirs in a catchment and returns a longer-term average annual figure describing nitrogen retention. In contrast, the Tier 4 calculation requires more specific input data on a monthly basis from a specific lake or reservoir and return monthly nitrogen retention.

3.2 Data sets collected on nitrogen mass-balances

The content of the EUROHARP-NUTRET for nitrogen retention calculation in lakes and reservoirs was developed based on measured data of nitrogen inputs and nitrogen outputs collected from 65 lakes and 113 reservoirs in different parts of the world (Table 3.1). The database for nitrogen included a total of 118 records for calculation of nitrogen mass-balances for the different water bodies. The predominant part of the data originated from Central, West and Northern Europe and North America.

Table 3.1 The number of lakes and reservoirs in the database with nitrogen mass-balances.

Country	Number of water bodies
Lakes, Norway	13
Lakes, Denmark	23
Lakes, The Netherlands	6
Reservoirs, Europe	20
Reservoirs, USA	58

3.3 Description of the water bodies covered in the database

The database for nitrogen retention includes research and monitoring data on monomictic and dimictic water bodies located in the temperate zone. Wide ranges of water body depths, water body areas, hydraulic residence time and input nitrogen concentrations were covered (Fig. 3.1 and 3.2).
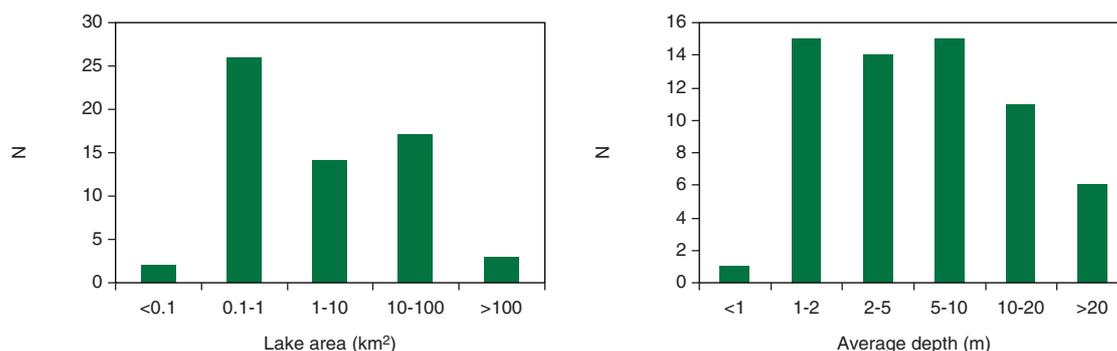
Figure 3.1 Lake area and average depth of the lakes and reservoirs in the database.
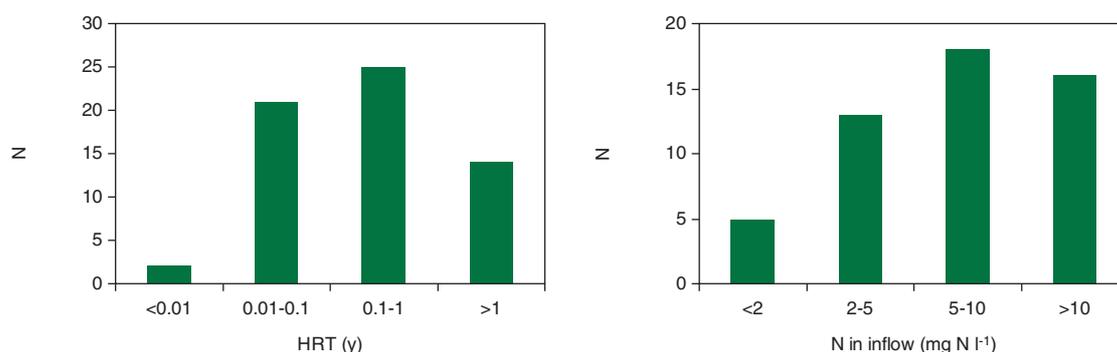
Figure 3.2 Residence time and total nitrogen concentration in in-flowing water for the lakes and reservoirs in the database.

3.4 General statistics on nitrogen retention in lakes and reservoirs

Table 3.2 shows the results of the general statistics of nitrogen retention on the different datasets held in the database. The average and median nitrogen retention rates in Table 3.2 are in good accordance with the maximum nitrogen retention water in temperate freshwater lakes (about 35 g N m^{-2} yr^{-1}) measured as denitrification measurements (Van Luijn, 1997; Seitzinger *et al.*, 1998). However, sedimentation of particulate nitrogen will also be of importance in water bodies.

Table 3.2 Nitrogen retention rates for the lakes and reservoirs in the database calculated for the entire dataset and for different combinations of countries/regions.

	Average (g N m^{-2} y^{-1})	Standard Deviation (g N m^{-2} y^{-1})	Median (g N m^{-2} y^{-1})
All data (n=117)	47	191	20
Reservoirs Walker (n=58)	20.4	61	15
Lakes Denmark & Netherlands (n=28)	40.5	24.5	40
Reservoirs Europe (n=19)	26.4	23	17
Lakes Norway (n =12)[*]	60.6	555	105

[1]: Some lakes with very short residence time (<5d) in this group.

3.5   Tier 1 nitrogen retention calculation

Description of method

The Tier 1 nitrogen retention calculation is developed on the basis of an overall statistic of nitrogen retention in lakes and reservoirs from the database.

Table 3.2 shows the summary statistics on nitrogen retention for the lakes in the database. Average annual nitrogen retention is 40 g N m^{-2} or 400 kg N ha^{-1} water body area. Nitrogen retention in lakes and reservoirs is calculated by applying an average annual retention rate for the total area of water bodies in the river basin or for the the water bodies where no higher Tier calculation is performed.

Menus in EUROHARP-NUTRET

Figure 3.3 and Figure 3.4 show the Tier 1 input data menu and result menu.

Figure 3.3 Example of the start input menu under LAKES and RESERVOIRS – Tier 1-4.
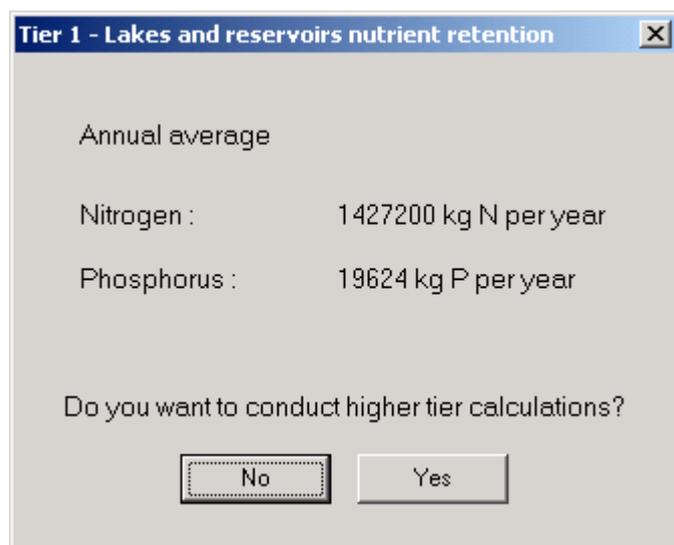
Figure 3.4 Example of the results of your Tier 1 calculation under LAKES and RESERVOIRS – Tier 1-4.

The input menu can be filled in with the number of lakes smaller or larger than 5 hectares in area in your catchment. The result menu displays the Tier 1 calculation of nitrogen and phosphorus retention in lakes and reservoirs in your catchment. At the bottom of the Tier 1 result menu you will be asked if you want to perform a higher Tier calculation for some of the lakes and reservoirs.

Input data requirement for Tier 1

Use of the Tier 1 calculation level requires only very basic information on lakes and reservoirs in the catchment about the total surface area of the water bodies for which nitrogen retention calculation should be performed. Such information can be easily obtained from land cover maps held in Geographical Information Systems (GIS). In many catchments the volume of information on single lakes and reservoirs is restricted and in these cases a first rough estimate of nitrogen retention can be calculated by applying Tier 1.

Restrictions when applying Tier 1

Large downstream lakes and reservoirs in the catchment may not receive enough nitrogen in the in-flowing water to support the retention rate by using Tier 1. In these cases a higher tier calculation should be performed for the individual water body depending on information on nitrogen loading (Tier 3). In catchments with a low percentage of agricultural land (< 15%) or sub-catchments to lakes and reservoirs with such low proportion of agricultural land, the use of Tier 1-calculated estimates could give erroneous results due to low nitrogen loading to the water bodies. Nitrogen retention in lakes situated in Southern Europe was not included in the database. The use of Tier 1 calculations for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for lakes in the region.

3.6   Tier 2 nitrogen retention calculation

Description of method

The Tier 2 nitrogen retention calculation was developed on the basis of an overall statistic of nitrogen retention in lakes and reservoirs from the database, taking into consideration the hydraulic residence time for each water body or group of water bodies (Table 3.3). The retention calculation is performed either by applying standard retention rates to the surface area of lakes and reservoirs in the catchment

grouped into different hydraulic residence time categories, or by applying the percentage retention to be multiplied to the nitrogen loading to specific or groups of lakes with different hydraulic residence times.

The calculation of nitrogen retention can be performed by applying the standard retention rates in Table 3.3 for the total area of the different categories of water bodies. Another and more precise approach is to apply the percentage retention in Table 3.3 to the estimated total nitrogen inflow to the different categories of water bodies. The latter approach will take into account if not enough nitrogen is transported to sustain the standard retention rates in the water bodies due to small catchment area to water body area ratio, or a generally low proportion of agricultural land in the catchments.

Table 3.3 Nitrogen retention in lakes with different hydraulic residence times (τ_w).

	Nitrogen retention	
HRT (years)	(g N m^{-2} yr^{-1})	(% of load)
0.001-0.01	36.5	-
0.01-0.1	36.5 (11-73)	16
0.1-1	58.4 (18.3-110)	50
1-10	21.9 (3.7-43.8)	60
> 10	18.3	-

Menu in EUROHARP-NUTRET

If you choose to perform a higher Tier nutrient retention calculation from the Tier 1 result menu, the menu in Figure 3.5 appears. You can specify the number of lakes and reservoirs exceeding 5 hectares for which you wish to perform a Tier 2, Tier 3 or Tier 4 calculation of nutrient retention. Figure 3.6 shows the input menu for Tier 2.
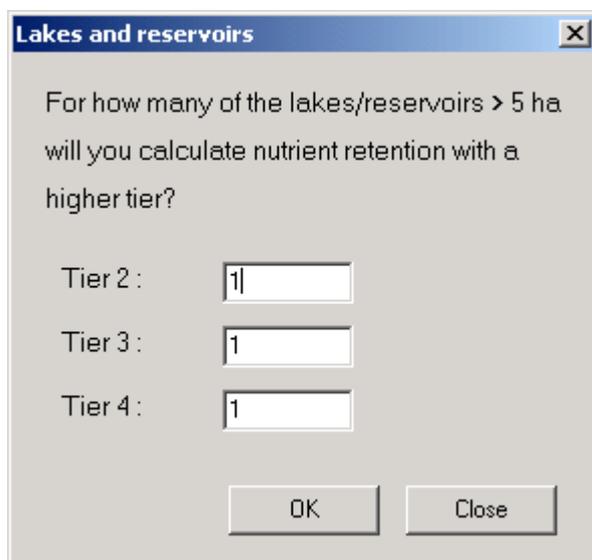
Figure 3.5 Menu providing the opportunity of entering the number of lakes for which you to perform higher Tier nutrient retention calculations.

Figure 3.6 Input menu to the Tier 2 nutrient calculation.

Input data demand for Tier 2

Application of the Tier 2-calculation level requires that lakes and reservoirs in the catchment can be subdivided into categories of water bodies with different hydraulic residence times. The hydraulic residence time *(HRT* in years) can be calculated on the basis of knowledge of the annual inflow of water (Q) to a water body and the volume (V) of the water body (V/Q). The minimum required information is a general knowledge on mean annual runoff in the catchment and the ability to subdivide lakes and reservoirs into different categories depending on water body volumes. The latter is in many cases possible for larger lakes, whereas smaller lakes may be categorised based on knowledge from a small sub-sample of water bodies in the catchment.

Restrictions when applying Tier 2

Even though Tier 2 sub-divides lakes and reservoirs into water bodies with different categories of hydraulic residence time, the water bodies may not receive enough nitrogen in in-flowing water to support the retention rates used in Tier 2. Thus, for catchments with a low percentage of agricultural land (< 30%) or sub-catchments to lakes and reservoirs with such low proportions of agricultural land, the use of Tier 1 retention rates could give erroneous results due to low nitrogen loading to the water bodies. In these cases a higher tier calculation should be performed for the individual water body depending on information on nitrogen loading (Tier 3). Another approach is to apply the percentage retention in Tier 2 to an estimated nitrogen loading to the different categories of water bodies. One option is to subdivide water bodies in a catchment into two main classes of nitrogen loadings depending on the percentage of agricultural land, and then group these main classes into categories of different hydraulic residence times. Lakes and reservoirs situated in Southern Europe were not included in the database. The use of Tier 2 calculations for water bodies in Southern European

catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for the region.

3.7   Tier 3 nitrogen retention calculation

Description of method

The Tier 3 nitrogen retention calculation was developed on the basis of an initial assessment of different existing nitrogen retention models from the literature.

Nutrient retention data were evaluated by applying a steady-state, mass balance model (Chapra, 1975, Reckhow and Chapra, 1983, Kelly *et al.*, 1987) that relates mean long-term substance concentration in water bodies to substance inputs, flushing rate, and total loss rate to the atmosphere and sediments. The model is single-compartment and assumes that the water body is well mixed and material influx and efflux are constant over time. A mass balance equation relating inputs and outputs for a substance, *X*, is given by

$$L_i = L_o + L_{ret} \tag{1}$$

where L_i is the sum of all external inputs, from e.g. precipitation, groundwater, and streams, L_o is the water body output via discharge, and L_{ret} is the sum of losses of substance *X* to the atmosphere and sediments expressed in mass m^{-2} yr^{-1}. Assuming that the discharge and loss rates can be described by first-order kinetics, i.e. they are proportional to the concentration of substance *X*, the equation above becomes

$$L_i = q_w[X] + v_x[X] \quad \text{or} \quad [X] = L_i/(q_w + v_x) \tag{2a) or (2b}$$

where $[X]$ is the mean annual whole-water body concentration of substance *X*, q_w is the mean annual water load (runoff volume/lake area), and v_x is the mean annual mass transfer (loss) coefficient of substance *X* to lake sediments and the atmosphere (units – m yr^{-1}). The fraction of substance *X* retained or lost in a water body (i.e., retention), R_x, is defined as $(L_i - L_o)/L_i$ and at steady state is given by

$$R_x = v_x/(q_w + v_x) \quad \text{or} \quad R_x = \left(1 - \frac{1}{1 + \frac{v_x}{z} HRT} \right) \tag{3}$$

The mass transfer coefficient is calculated from the measured data as $v_x = z \times (X_i - [X])/(HRT \times [X])$, where $[X_i]$ is the volume-weighted mean concentration of substance *X* in input, *z* is mean depth, and *HRT* is hydraulic residence time.

We calibrated the model on the data collected from different reservoirs and lakes and found that the mass transfer coefficient was only slightly different between the different water bodies (Table 3.4).

Table 3.4 Mean transfer coefficient in lakes and reservoirs in different regions and for the entire dataset except reservoirs in USA.

Water Bodies	Mass transfer coefficient (v_x) (m yr^{-1})
Czech reservoirs	5.01
Lakes – Denmark and The Netherlands	7.26
Lakes – Norway	7.59
Reservoirs – USA	8.23
All cases, except reservoirs USA	7.30

Figure 3.7 shows the comparison of estimated and measured nitrogen retention for the different lakes and reservoirs in the database.
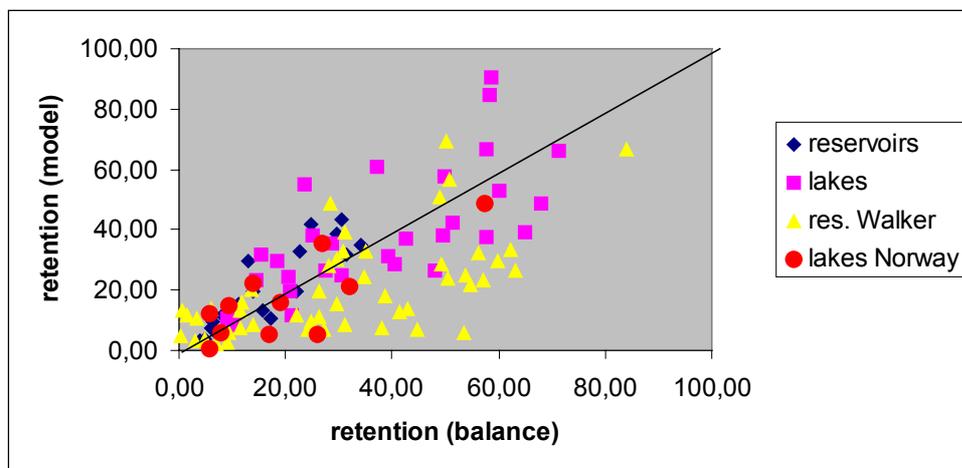
Figure 3.7 Comparison between model calculated annual nitrogen retention and the measured nitrogen retention from mass-balances.

The final model included in Tier 3 for estimation of annual nitrogen retention as percentage of incoming load can be calculated from the model:

$$R_N = \left(1 - \frac{1}{1 + \dfrac{7.3}{z} \cdot HRT} \right) \qquad (4)$$

where R_N is the fraction of the incoming nitrogen load retained in the water body, z=average water depth (m) and HRT = hydraulic residence time in years. The retention of nitrogen can thus be calculated from:

$$L_{ret} \text{ (kg)} = R_N * \text{N-load} \qquad (5)$$

where L_{ret} (kg) is the amount of nitrogen retained in the water body, Rret R_n?? is estimated every year from equation 4, and N-load is the annual nitrogen load to the water body.

Menus in EUROHARP-NUTRET

Figure 3.8 shows the Tier 3 input data menu. Choosing the reservoir option will only affect the phosphorus retention calculation (see chapter 4.7).

Figure 3.8 Input data menu for the Tier 3 nutrient retention calculation.

Input data requirement for Tier 3

Use of the Tier 3 calculation requires specific information on single lakes or reservoirs about hydraulic residence time, water depth and external nitrogen loading. This information requires either access to measured data on nitrogen loadings to the water body or modelled nitrogen loadings using a catchment N-model.

Restrictions for applying Tier 3

Nitrogen retention in lakes situated in Southern Europe was not included in the database. The use of a Tier 3 calculation for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for the region.

3.8   Tier 4 nitrogen retention calculation

Description of method

EUROHARP-NUTRET does not include a Tier 4 nitrogen calculation tool.

3.9   Output from the Tier 1-4 nitrogen retention calculation

Figure 3.9-3.11 show the output of the Tier 1-4 nitrogen retention calculations.. Figure 3.9 shows the input data that you have entered for the water bodies in the different Tiers. . The calculated retention as a percentage of incoming load and in kg if input on nitrogen load was entered, is shown for Tier 2-4 in Figure 3.10. Figure 3.11 shows the total nitrogen retention in lakes and reservoirs calculated for Tier 1-4.

Lakes and reservoirs

Tier 2 data :

Lake name	Lake suface area	Lake mean depth	Annual N-loading	Annual P-loading	Residence ti	Anual runof
lake xxx	15	1	15000	400	0,5	1

Tier 3 data :

Lake name	Lake suface area	Lake mean depth	Annual N-loading	Annual P-loading	Residence ti	Anual runof
lake yyyy	3568	7,4	167420	11480	0,88	7

Tier 4 data :

Lake name	Area	Average water depth	P-concentration in inflow	Annual P-load	Mean annua	Eutrophica
lake zzzz	45	2	25	500	5000000	Oligotrophi

Calculate   Close

Figure 3.9 Table showing the information provided on the specific lakes and reservoirs in Tier 2 and 3 for nitrogen.
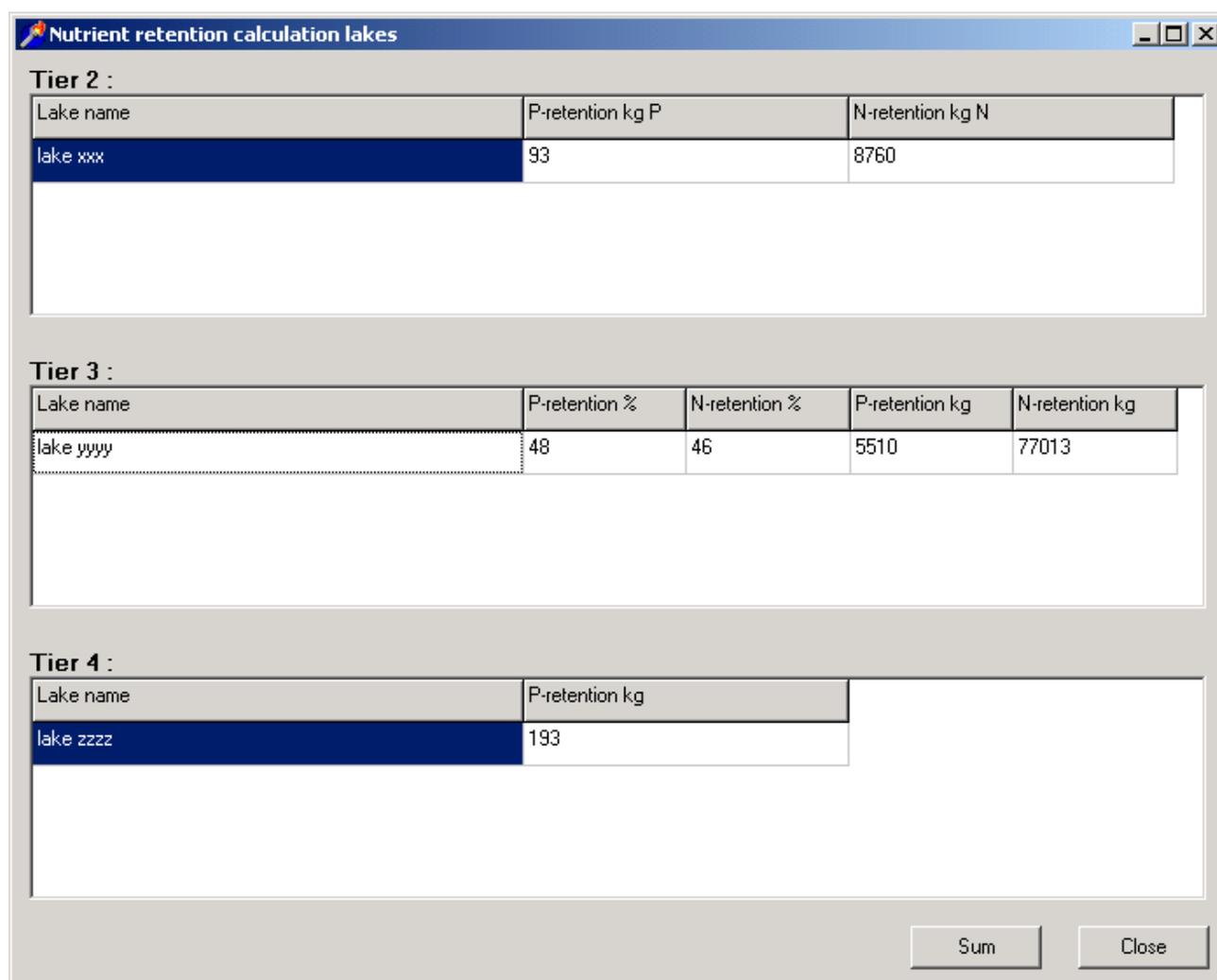
Figure 3.10 Calculated nitrogen retention in the different lakes and reservoirs in Tier 2 and 3 both as percentage of incoming load and in kg N, if input data on nitrogen load was provided.

Figure 3.11 Final result of the Tier 1-4 nitrogen retention calculation showing the lake and reservoir areas in each Tier, the nitrogen retention calculated under each Tier, and the total retention.

3.10 Tier 5 nitrogen retention calculation

Description of method

The Tier 5 nitrogen retention calculation was developed on the basis of an assessment of data from 16 mainly shallow Danish lakes (Table 3.5). The model is therefore only directly applicable for similar lakes, but the model could be calibrated to serve local conditions.

The seasonal dynamics of nitrogen retention in lakes differing in hydraulic and N-loading can be estimated by applying Tier 5.

The model of lake retention of total nitrogen on a monthly basis is given by:

$$R_N(\text{mg N m}^{-2}\text{ d}^{-1}) = a \bullet \theta^{(T-20)} \bullet N_{retmax} \tag{6}$$

Where T is water temperature (ºC); and N_{retmax} is the average daily pool of nitrogen (mg N m^{-2} d^{-1}) available for retention in the lake as given by the sum of the inflow of total nitrogen from month i to i+1 and the pool of total nitrogen in the lake water in month i divided by the number of days in the month (month i to month i+1).

The constants in the model have been calibrated on the basis of data from 16 shallow Danish lakes (Windolf *et al.,* 1996).

a = 0.455 and θ =1.087

The calibration of the constants was performed on 3-4-year series of monthly data on water balance and nitrogen mass balances from 16 Danish lakes. Some of these lakes were permanently stratified during summer and they were all quite shallow (mean depth below 6 m), c.f. Table 3.5.

Table 3.5. Characteristics of the 16 lakes.

Lake	z	TP	Chla	Secchi depth	TN	N02 + N03	n
	(m)	(µg P/ 1)	(µg /1)	(m)	(mg N /1)	(mg N /1)	
Vesterborg sø	1.4	241 (27)	105	0..70 (0..04)	5..21 (0,45)	3.70 (0.55)	4
Søgård sø	1.6	272 (34)	153	0.58 (0.05)	6.69 (0.61)	4.67 (0.79)	4
Lemvig sø	2.0	239 (11)	45 (4)	0.74 (0.05)	4.30 (0.48)	3.10 (0.36)	4
Hejrede sø	0.9	123 (6)	75 (10)	0.65 (0.05)	4.34 (0.29)	2.18 (0.36)	4
Fuglesø	2.0	256 (22)	75 (4)	1.12 (0.03)	4.18 (0.37)	2.39 (0.41)	3
Fårup sø	5.6	92 (5)	37 (4)	1.77 (0.08)	1.51 (0.05)	0.79 (0.02)	4
Langesø	3.1	279 (30)	62 (8)	1.24 (0.04)	3.80 (0.15)	2.39 (0.13)	4
Kilen	2.9	187 (17)	103 (22)	0.68 (0.09)	2.17 (0.07)	0.76 (0.06)	4
Jels Oversø	1.2	273 (26)	100 (12)	0.85 (0.05)	6.90 (0.18)	5.34 (0.26)	3
Ørn Sø	4.0	108 (2)	36 (2)	1.57 (0.05)	1.43 (0.04)	0.55 (0.02)	4
Hinge Sø	1.2	122 (3)	90 (9)	0.68 (0.03)	4.44 (0.20)	2.95 (0.17)	4
Dons Nørresø	1.0	216 (29)	251	0.56 (0.04)	5.05 (0.08)	3.05 (0.11)	4
Borup Sø	0.9	150 (10)	78 (9)	0.92 (0.04)	4.93 (0.46)	2.97 (0.36)	4
Gundsømagle	1.2	1127	276	0.55 (0.02)	5.92 (0.42)	2.85 (0.44)	4
Store Søgård	2.7	465 (53)	41 (1)	0.79 (0.05)	6.27 (0.32)	3.33 (1.65)	3
Bryrup	4.6	107 (7)	33 (4)	2.10 (0.10)	4.15 (0.11)	3.10 (0.11)	4

Menus in EUROHARP-NUTRET

Figure 3.12 and 3.13 show the Tier 5 input data menu and result menu. You must specify the period for which you will perform the nitrogen retention calculation (Fig. 3.12). You can enter information for a maximum period of 5-year. In the second menu you will have to enter the starting pool of nitrogen in the lake water and monthly input data on water temperature and nitrogen input to the lake or reservoir (Fig. 3.13). Figure 3.14 shows the output menu from the Tier 5 nitrogen calculation. The output provides the new monthly nitrogen pool in the water body and the calculated monthly nitrogen retention.

Figure 3.12 Start menu in the LAKES AND RESERVOIRS - Tier 5 nitrogen retention calculation.

Lake and reservoir nitrogen retention - Tier 5

Input data

Lake water N concentration 5 mg N/l   Lake depth   1   m

Lake area   10   ha

| | | | °C | kg N | m³/day |
Year	Month	Mean monthly lake temperature	Total nitrogen inflow to lake	Mean daily water inflow
1990	1	5	2000	4000
1990	2	6	400	1000
1990	3	8	300	500
1990	4	9	300	500
1990	5	12	200	500
1990	6	14	100	500
1990	7	16	100	500
1990	8	20	100	500
1990	9	19	300	500
1990	10	14	600	500
1990	11	10	800	500
1990	12	6	3000	4000

Needed   Needed   Needed

Cancel   Calculate

Figure 3.13 Menu with demand for input data for the Tier 5 nitrogen calculation.

Figure 3.14 Output menu from the Tier 5 nitrogen retention calculation.

Input data demand for Tier 5

Use of Tier 5 requires information on a monthly basis of water and nitrogen loading to the lake as well as more basic information on lake morphology.

Restrictions when applying Tier 4

Since the model is calibrated on shallow Danish lakes, you should be careful when using the model under other circumstances, especially if the lake characteristics differ (eg. Table 3.5). The most critical factor is stratification, since the model will not perform very well for permanently stratified lakes.

4.   Phosphorus retention calculation for lakes and reservoirs

4.1   Introduction

The concentration of phosphorus in lakes and reservoirs results from a dynamic equilibrium between inputs, outputs and different retention processes that store phosphorus from the water in lake sediments. Thus, phosphorus retention in lakes is sedimentation of externally delivered particulate phosphorus or dissolved phosphorus incorporated into phytoplankton biomass and deposited into bottom sediments. Part of the deposited phosphorus will return from the sediment pool to the water pool due to processes related to diffusion between sediment and overlying water, resuspension of bottom sediments, release of iron-bound phosphorus under anaerobic conditions, bioturbation, biological uptake in macrophytes and release during periods with high pH.

Phosphorus retention in lakes and reservoirs can be calculated in many different ways depending on the available information from the catchment. The EUROHARP Retention Tool - EUROHARP-NUTRET, offers 5 different Tiers for end-user calculation of phosphorus retention in lakes and reservoirs. The input data information needed on individual lakes and reservoirs from a catchment increases from Tier 1 to Tier 5. The Tier 1 calculation requires very basic information about the lakes and reservoirs in a catchment and returns a longer-term average annual figure for phosphorus retention. In contrast, the Tier 5 calculation requires more specific annual input data from a specific lake or reservoir and returns annual phosphorus retention figures, including the impact of sediment-P.

4.2   Data sets collected on phosphorus mass-balances

The EUROHARP-NUTRET for phosphorus retention calculation in lakes and reservoirs was developed on the basis of measured data of phosphorus inputs and phosphorus outputs collected from 29 lakes and 113 reservoirs in different parts of the world (Table 4.1). The database for phosphorus included a total of 149 records for calculation of phosphorus mass-balances for the different water bodies. The predominant part of the data originated from Central, West and Northern Europe and North America.

Table 4.1 Geographical position of lakes and reservoirs included in the evaluation of phosphorus retention.

Country	Latitude, deg.	No. of water bodies	
		Reservoirs	Lakes
Brazil	22	1	0
Canada	45	0	7
Czech Republic	49	9	3
France	49	3	0
Luxemburg	50	2	0
Morocco	35	2	0
The Netherlands	52	3	0
Norway	59-61	0	19
Poland	52	1	0
Spain	40-43	12	0

4.3 Description of the water bodies covered in the database

The database for phosphorus retention includes research and monitoring data on monomictic and dimictic water bodies mostly located in the temperate zone. A wide range of water body depths, water body areas, hydraulic residence times and input phosphorus concentrations were covered (Fig. 4.1).
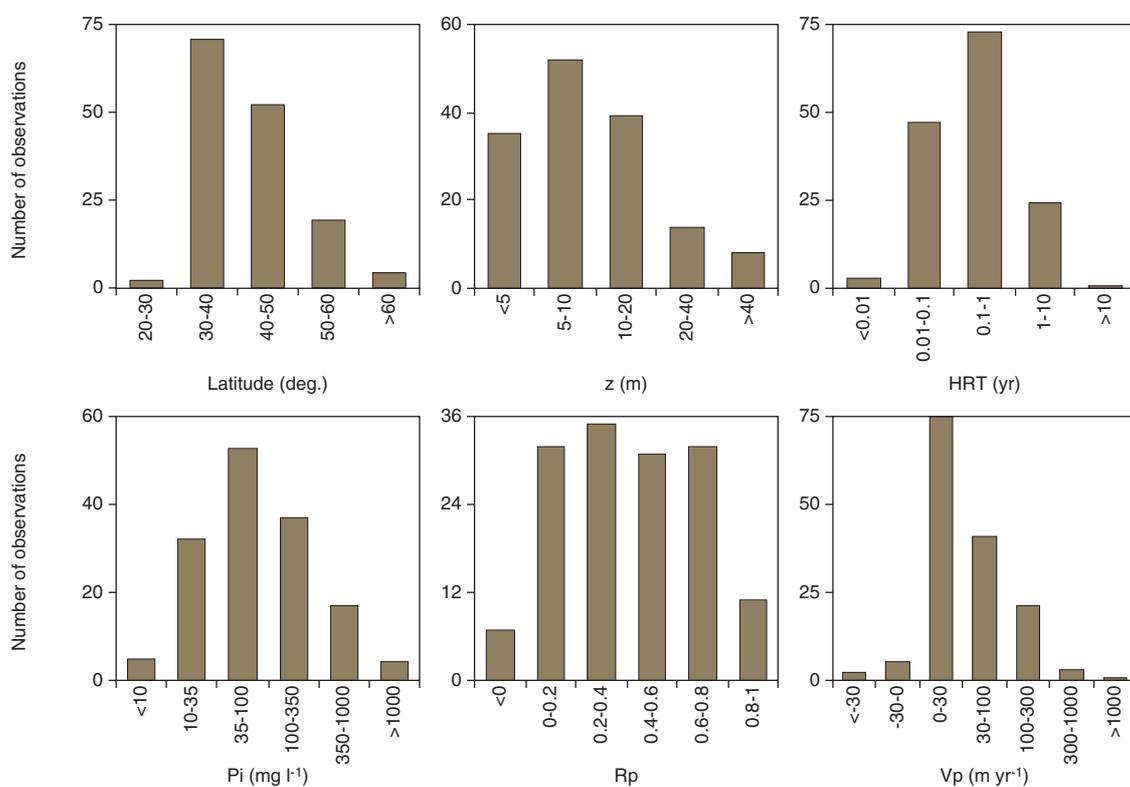
Figure 4.1 Frequency distribution of selected characteristics of water bodies used in the evaluation of phosphorus retention. Symbols: z, mean depth; HRT, mean hydraulic residence time; P_i, inflow total-P concentration; R_P, relative P-retention; v_P, mass transfer coefficient of P loss.

4.4 General statistics on phosphorus retention in lakes and reservoirs

Table 4.2 shows the results of the general statistics of phosphorus retention of the different datasets held in the database.

Table 4.2 Statistics for phosphorus retention in lakes and reservoirs.

Data subset	Average (g P m^{-2} y^{-1})	Standard Deviation (g P m^{-2} y^{-1})	Median (g P m^{-2} y^{-1})
All data (n=149)	5.0	15.0	0.98
Reservoirs (n=120)	6.1	16.5	1.3
Lakes (n=29)	0.36	0.45	0.17
Lakes and reservoirs in Europe (n=60)	7.9	22.2	0.55
Lakes and reservoirs in rest of the world (n=93)	3.0	6.2	1.21

4.5   Tier 1 phosphorus retention calculation

Description of method

The Tier 1 phosphorus retention calculation is developed on the basis of an overall statistic of phosphorus retention in lakes and reservoirs from the database.

Table 4.2 shows the summary statistics on phosphorus retention for the lakes and reservoirs in the database. A median value for annual phosphorus retention in European lakes and reservoirs of 0.55 g P m^{-2} or 5.5 kg P ha^{-1} water body area is used in the Tier 1. The range of the 95% confidence level of this median estimate was from 0.15 to 6.9 g P m^{-2} or from 1.5 to 69 kg P ha^{-1}.

Phosphorus retention in lakes and reservoirs is calculated by applying an average annual retention rate for the total area of water bodies in the river basin or the water bodies where no higher Tier calculation is performed.

Menus in EUROHARP-NUTRET

The Tier 1 input data menu and result menus are shown in chapter 3.

Input data demand for Tier 1

Use of the Tier 1 calculation level requires only very basic information on lakes and reservoirs in the catchment being the total surface area of the water bodies for which phosphorus retention calculation should be conducted. Such information can easily be obtained from land cover maps held in Geographical Information Systems (GIS). In many catchments the amount of information on single lakes and reservoirs is restricted and in these cases a first rough estimate of phosphorus retention can be conducted by applying Tier 1.

Restrictions when applying Tier 1

Phosphorus release from lake sediment can be a major phosphorus source for shorter or longer periods following a decline in external phosphorus loading to lakes and reservoirs. Tier 1 phosphorus calculations should therefore be restricted to only lakes in a steady state or near-steady state situation. Phosphorus retention in lakes situated in Southern Europe was not included in the database. The use of Tier 1 calculations for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for lakes in the region.

4.6   Tier 2 phosphorus retention calculation

Description of method

The Tier 2 phosphorus retention calculation was developed on the basis of an overall statistic of phosphorus retention in lakes and reservoirs from the database taking into consideration the hydraulic residence time for each water body or group of water bodies (Table 4.3). Retention calculations are performed either by applying standard retention rates to the surface area of lakes and reservoirs in the catchment grouped into different hydraulic residence time categories, or by appplying the percentage retention to be multiplied to the phosphorus loading to specific lakes or groups of lakes with different hydraulic residence times.

The calculation of phosphorus retention can be performed by applying the standard retention rates in Table 4.3 for the total area of the different categories of water bodies. Another and more precise approach is to apply the percentage retention shown in Table 4.3 to the estimated total phosphorus inflow to the different categories of water bodies. The latter approach will take into account if not

enough phosphorus is transported to sustain the standard retention rates in the water bodies because of a small catchment area to water body area ratio or a generally small proportion of agricultural land in the catchments.

Table 4.3 Phosphorus retention in lakes and reservoir having different hydraulic residence time (HRT). Median values from the database have been used.

HRT (years)	Phosphorus retention	
	$(g\ P\ m^{-2}\ yr^{-1})$	(% of load)
< 0.1	2.7	17
0.1-1	1.0	45
1-10	0.37	59
> 10	0.12	70

Menus in EUROHARP-NUTRET

The Tier 2 input data menu and result menu are shown in chapter 3.?.

Input data demand for Tier 2

Application of the Tier 2-calculation level requires that lakes and reservoirs in the catchment can be subdivided into categories of water bodies with different hydraulic residence times. The hydraulic residence time *(HRT* in years) can be calculated from knowledge of the annual inflow of water (Q) to a water body and the volume (V) of the water body (V/Q). The minimum required information is a general knowledge on mean annual runoff in the catchment and the ability to subdivide lakes and reservoirs into different categories depending on water body volumes. The latter is in many cases possible for larger lakes, whereas smaller lakes may be categorised based on knowledge from a small sub-sample of water bodies in the catchment.

Restrictions when applying Tier 2

Even though Tier 2 sub-divides lakes and reservoirs into water bodies with different categories of hydraulic residence time the water bodies may not receive enough phosphorus in in-flowing water to support the retention rates used in Tier 2. Thus, for catchments with a low percentage of agricultural land (< 30%) and sparse point sources or sub-catchments to lakes and reservoirs of such character the use of Tier 1-retention rates could give erroneous results due to low phosphorus loading to the water bodies. In these cases a higher tier calculation should be performed for the individual water body depending on information on phosphorus loading (Tier 3). Another approach is to apply the percentage retention in Tier 2 to an estimated phosphorus loading to the different categories of water bodies. One possibility is to subdivide water bodies in a catchment into two main classes of phosphorus loadings depending on the percentage of agricultural land and density of population and then group these main classes into categories of different hydraulic residence time. Lakes and reservoirs situated in Southern Europe were not included in the database. The use of Tier 2 calculations for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for the region.

4.7   Tier 3 phosphorus retention calculation

Description of method

The Tier 3 phosphorus retention calculation was developed on the basis of an initial assessment of different existing phosphorus retention models from the literature (see chapter 8). We tested several of

the existing models on our datasets and found that the Vollenweider model had the best for lakes but some deviations occurred with reservoirs.

Lakes

The final model included in Tier 3 for estimation of annual phosphorus retention in lakes as percentage of incoming load can be calculated from the model:

$$R_P = \left(1 - \frac{1}{1 + \sqrt{HRT}} \right) \qquad (7)$$

Where R_P is the fraction of the incoming phosphorus load retained in the water body and HRT is hydraulic residence time in years.

Reservoirs

It proved necessary to include another version of the Vollenweider model for reservoirs as phosphorus retention was consistently higher in reservoirs than in lakes. Differences between reservoirs and lakes in the proportions of particulate and dissolved P forms in the nutrient inputs, morphology of water bodies, trophic status, dissolved oxygen concentrations in the hypolimnion, depth of outflow, chemistry of water, P binding capacity of bottom sediments, and structure of aquatic ecosystems being dominated either by phytoplankton or macrophytes can be responsible for the observed differences in P-retetention between lakes and reservoirs (Heizlar, pers. comm.).

$$R_P = \left(1 - \frac{1}{1 + 1.86\sqrt{HRT}} \right) \qquad (8)$$

Where R_P is the fraction of the incoming phosphorus load retained in the water body and HRT is hydraulic residence time in years.

The retention of phosphorus in lakes or reservoirs can be calculated from:

$$L_{RET} \text{ (kg)} = R_P \bullet \text{P-load (kg)} \qquad (9)$$

where L_{RET} (kg) is the amount of phosphorus retained in the water body, R_P is estimated every year from equation 8 and P-load (kg) is the annual phosphorus load to the water body.

Menus in EUROHARP-NUTRET

The Tier 3 input data menu is shown in chapter 3. Choose of the reservoir will only affect the phosphorus retention calculation.

Input data requirement for Tier 3

Use of the Tier 3 calculation requires specific information on single lakes or reservoirs regarding hydraulic residence time, water depth and external phosphorus loading. This information requires either access to measured data on phosphorus loadings to the water body or modelled phosphorus loadings from application of a catchment N-model.

Restrictions for applying Tier 3

The Tier 3 calculation should be restricted to lakes and reservoirs in a steady or near-steady state situation as it does not include internal phosphorus release from lake sediments. Phosphorus retention in lakes situated in Southern Europe was not included in the database. The use of a Tier 3 calculation for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for the region.

4.8   Tier 4 phosphorus retention calculation

Description of method

Phosphorus retention data were evaluated as shown for Tier 3 nitrogen in chapter 3.7.

$$R_P = \left(1 - \frac{1}{1 + \dfrac{v_P}{z} \cdot HRT} \right) \qquad (10)$$

The relationship between the mass transfer coefficient (v_P) and water load, q_w, showed large deviations (Fig. 4.2). On the other hand, deviations in the v_P values and increased markedly with increasing P_i concentrations (Fig. 4.3). The data sets were operationally divided? into four categories of potentially oligotrophic, mesotrophic, eutrophic, and hyper-eutrophic water bodies according to their P_i concentrations within the ranges <10, 10–35, 35–100, and >100 µg l^{-1}, respectively (OECD 1982). The P_i concentrations were employed intentionally as opposed to the commonly used in-water body concentrations with respect to their use in the model for prediction purposes (however, it is clear that, for example, deep lakes with long HRT (>1 year) can have P_i concentrations that correspond to the eutrophic status (35–100 µg l^{-1}) here, but their naturally high P-retention capacity may shift them into mesotrophic or even oligotrophic conditions.) This categorisation improved the prediction capacity/predictability of Eq. (3), especially for lower P_i ranges (Table 4.4). The absolute mean error of R_P prediction by Eq. (3) fell to 0.16–0.19 and 0.09 in eutrophic/hyper-eutrophic and oligotrophic input conditions, respectively. The categories 35–100 and >100 µg l^{-1} can be combined with the mean v_P value of 40 m yr^{-1}.
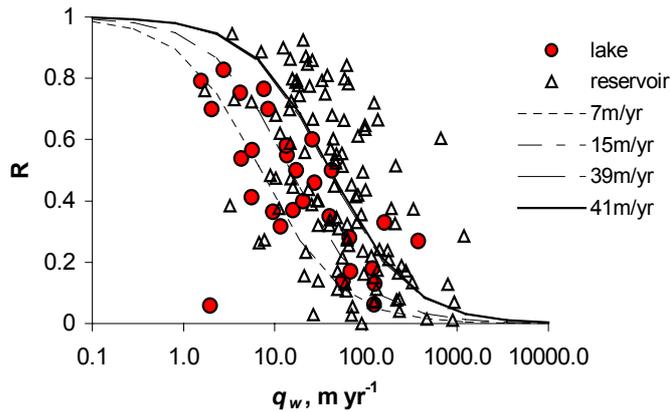
Figure 4.2 Relationship between phosphorus retention data and water load with curves that represent the P-retention model (from Hejzlar et al., 2003).

(b)
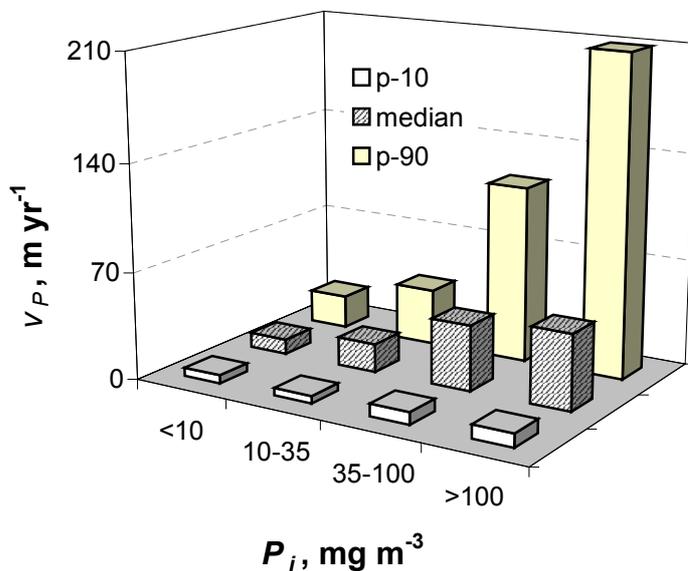
Figure 4.3 Average phosphorus mass transfer coefficients for different categories of inlet P concentrations (from Hejzlar et al., 2003).

Table 4.4 The mass transfer coefficient in different P_i-categories (i) calculated from the real data (v_p) and (ii) obtained by the least-square minimisation procedure during fitting the real data by the model to calculate R_p (v_p'), together with absolute mean error (AME) and error ranges of R_p calculations by the model using the v_p' values. n – number of data (from Hejzlar et al., 2003).

Parameter		Pi, µg l⁻¹				
		<10	10–35	35–100	>100	all
v_P	median	10	19	43	49	26
	(range)	(5–25)	(2–199)	(2–1008)	(2–1008)	(2–1008)
v_P'		7	15	39	41	30
R_P-error	AME	0.09	0.13	0.16	0.19	0.19
	(range)	(0.05–0.19)	(0.01–0.42)	(0.00-0.54)	(0.00-0.59)	(0.00-0.56)
n		4	33	47	54	138

Menus in EUROHARP-NUTRET

Figure 4.4 shows the Tier 4 input data menu and result menu.. You may choose to enter both the P-concentration in inflow water to the lake and the eutrophic status of the lake as input to the Tier 4 calculation. However, if both details are entered, only the latter will be used in the model calculation.

Figure 4.4 Input data menu for the Tier 4 phosphorus retention calculation.

Input data requirement for Tier 4

Use of the Tier 4 calculation requires specific information on single lakes or reservoirs regarding hydraulic residence time, water depth and external phosphorus loading in order to calculate inlet phosphorus concentration for choosing the mass transfer coefficient (v_P). This information requires either access to measured data on phosphorus loadings to the water body or modelled phosphorus loadings using a catchment P-model. However, knowledge of whether the reservoir or lake is ologotrophic, mesotrophic, eutrophic or hypereutrophic from lake monitoring can also be used as input information for selecting the correct mass transfer coefficient (v_P) to be used? in the model.

Restrictions for applying Tier 4

Phosphorus retention in lakes situated in Southern Europe was not included in the database. The use of a Tier 4 calculation for water bodies in Southern European catchments should therefore be treated with due caution and should, if possible, be checked against actual mass-balance data for the region.

Moreover, the Tier 4-calculation tool can only be applied to lakes and reservoirs in a steady-state condition. The model will not apply to lakes and reservoirs that have recently experienced a marked reduction in P-loading after many years with high loading, as these will suffer from internal P-loading due to P-releases from bottom sediment.

4.9   Tier 5 phosphorus retention calculation

Description of method

The model has only two state variables: total phosphorus in lake water (P_l) and exchangeable total phosphorus in sediment (P_s). The driving variables in the model are the monthly inlet concentration of total phosphorus (P_i), the corresponding monthly water discharge (Q_i) and the lake water temperature (T).

The dynamics of lake water and total phosphorus is given by the difference between input and output. The sedimentation of total phosphorus is deducted (S), and the release of total phosphorus from the sediment is added (F) together with a term giving the part of P being immobilised in the sediment (I) , c.f. below

$$\frac{dX_i}{dt} = Q_i P_i - Q_o P_l - S + F$$

$$\frac{dX_s}{dt} = S - F - I$$

Sedimentation (g/d)   : $S = \beta_S X_l$

Release (g/d)   : $F = \beta_F \theta_F^{T-20} X_S$

Immobilisation in sediment (g/d)   : $I = \beta_I X_S$

Inlet and and outlet discharge is equal: $Q_i = Q_o = Q$.

Sediment active in releasing P is the upper 20 cm in the lake Zs = 0.2 m.

Lake average depth = Z_l.

Where

X_l :   Amount of total P in the lake [g]
V_l :   lake volume [m3]
P_l := X_l/V_l : lake concentration of total phosphorus [gP/m3]
P_i :   Concentration of total phosphoprus in inlet [g P/m3]
Q_i :   Discharge in inlet [m3/d]
Q_o :   Discharge in outlet [m3/d]
X_s :   Amoun of total phosphorus in upper 20 cm of lake sediment [g]
V_s :   Sediment volume [m3]
P_s = Xs/Vs : Concentraitn of total phosphorus in lake sediment [g/m3]
T :   Lake water temperature [˚C]

In the case of concentrations (mg/l/d) the model is:

$$\frac{dP_l}{dt} = \frac{Q}{V_l} \cdot (P_i - P_l) - \beta_S P_l + \beta_F \theta_F^{T-20} \frac{0.2}{Z_l} P_s$$

$$\frac{dPs}{dt} = \beta_S \frac{Z_l}{0.2} P_l - \left[\beta_I + \beta_F \theta_F^{T-20} \right] P_s$$

In the case of loadings (g/m2/d) the model is:

$$\frac{d\widetilde{P}_l}{dt} = \frac{Q}{V_l} \cdot (\widetilde{P}_i - \widetilde{P}_l) - \beta_S \widetilde{P}_l + \beta_F \theta_F^{T-20} \widetilde{P}_s$$

$$\frac{d\widetilde{P}s}{dt} = \beta_S \widetilde{P}_l - \left[\beta_I + \beta_F \theta_F^{T-20} \right] \widetilde{P}_s$$

Where loadings (g/m2) is: $\widetilde{P}_l = P_l Z_l$; $\widetilde{P}_i = P_i Z_l$; $\widetilde{P}_S = P_S Z_S = P_S \cdot 0.2$.

The model parameters $\beta_S, \beta_F \, and \, \beta_I$ is given in 1/d while θ_F is dimensionless.

The initial values of P_s (t=0) is given as input data as is the inital value of P_i.

Menus in EUROHARP-NUTRET

Figures 4.5-4-7 show the Tier 5 input data menu and result menu.

Figure 4.5 Start-up menu for the Tier 5 phosphorus retention calculation tool.

Figure 4.6 Input data menu for the Tier 5 phosphorus retention calculation.

Figure 4.7 Results menu for the Tier 5 phosphorus retention calculation.

Input data requirement for Tier 5

The Tier 5 tool has only two state variables: total phosphorus in lake water (P_l) and exchangeable total phosphorus in lake sediment (P_s). The driving variables in the model are the monthly inlet concentration of total phosphorus (P_i), the corresponding monthly water discharge (Q) and the lake water temperature (T). Moreover, data on lake morphology are required.

Restrictions for applying Tier 5

Since the model is calibrated by using shallow Danish lakes, the model should be used cautiously under other circumstances, especially if the lake characteristics differ (c.f. Table 4.3). The most critical factor is stratification, as the model will not perform very well for permanently stratified lakes. Moreover, the model should only be used for turbid lakes that have not shifted to a clear-water state.

5.   Nutrient retention calculation for streams and rivers

5.1   Introduction

The concentration of nitrogen and phosphorus in streams and rivers results from a dynamic equilibrium between inputs, outputs and different retention processes that remove nitrogen or store organic nitrogen and phosphorus into river biota or sediments (Fig. 5.1) (for more information, see also chapter 9). The biological uptake of nitrogen (ammonium and nitrate) and phosphorus (soluble reactive phosphorus) into benthic organisms and macrophytes is normally not considered on an annual basis as nitrogen and phosphorus are either released to river water through the decay of plant tissue during winter, or transported further downstream as organic matter.

Removal of nitrogen takes place through denitrification of nitrate and is emitted to the atmosphere as gaseous nitrogen (N_2 or N_2O). Phosphorus retention in rivers takes place as sedimentation of alloctonuous or allochtonuous particulate phosphorus or as dissolved phosphorus incorporated into biological material which is deposited on river sediments (Svendsen *et al.*, 1995). Part of the deposited phosphorus will return from the sediment pool to the water pool due to processes related to resuspension of river sediments during periods of high flow (spates) where organic and inorganic bound phosphorus will be exported further downstream in the river systems.

The calculation of nitrogen and phosphorus retention in streams and rivers can be conducted in many different ways depending on the available catchment information. The EUROHARP Retention Tool, EUROHARP-NUTRET, offers only one Tier for end-user calculation of nitrogen and phosphorus retention in streams and rivers. The Tier 1 calculation requires only very basic information about the area of streams and rivers in a catchment and returns a longer-term average annual figure for nitrogen and phosphorus retention.

5.2   Data sets collected on nitrogen retention

EUROHARP-NUTRET for nitrogen retention calculation in streams and rivers was developed on the basis of a survey of the existing international literature (see also chapter 9). We found 41 referenced studies of nitrogen retention in streams and rivers in different parts of the world (Table 5.1). The data originated predominantly from Northern Europe and North America. No relationship was established between stream width and denitrification rates based on the information collected in the literature (Fig. 5.2). Another very important factor influencing dentrification is water temperature. However, insufficient data was collected from the international literature for an analysis of the influence of temperature. Nitrate concentrations in stream water will also at some point be a factor limiting denitrification. It was not possible to make an analysis of this with the available data. However, at nitrate-N concentrations lower than 1 mg N/l in the stream water, the denitrification rates can be reduced as compared to the denitrification rates under the present conditions.

Table 5.1 Denitrification rates in streams obtained from the literature with descriptions of location and stream size.

River	Country	Width (m)	Depth (m)	Substrate	Denitrification rate (mg m^2 d)	Reference
Rabis bæk	Denmark	2	0.5	sand	27.4	Christensen and Sørensen 1988
Rabis bæk	Denmark	2	0.5	sand	68.5	Christensen and Sørensen 1988
Rabis bæk	Denmark	2	0.5	stone	1.37	Christensen and Sørensen 1988
Gelbæk	Denmark	2	0.3	stone	5.5	Sørensen *et al.*, 1988
Gelbæk	Denmark	2	0.3	Mud	68.5	Christensen and Sørensen 1988
Gelbæk	Denmark	2	0.3	Mud	191.8	Christensen et al 1990
Dalby bæk	Denmark	2.5	0.4	Sand	13.7	Nielsen and Christensen, unpubl
Gryde Å	Denmark	4	0.5	sand	360	Jeppesen *et al.*, 1987
Suså	Denmark	8	0.3	Mud	973	Jeppesen *et al.*, 1987
Hug white Creeek	USA					Munn and Meyer 1990
Big Hurricane	USA					Webster et al 1991
La Solana	Spain	2.9	0.1	Sand/ cobble		Martin and Sabater 1996
Riera Major	Spain	3.7	0.14	Sand/ cobble		Martin and Sabater 1996
Q. Bisley (QBPR)	PR, USA	4.7	0.13		69.12	Peterson *et al.* 2001
Upper Ball (BCNC)	NC, USA	2.7	0.18		8.6	Peterson *et al.* 2001
Walker Br. (WBTN)	TN, USA	3.1	0.046		64.8	Peterson *et al.* 2001
Bear Br. (BBNH97)	NH, USA	2.1	0.035		0	Peterson *et al.* 2001
Bear Br. (BBNH98)	NH, USA	2.7			0	Peterson *et al.* 2001
E. Fork (MROH)	OH, USA	14.6	0.232		7776	Peterson *et al.* 2001
Eagle Cr. (ECMI)	MI, USA	5	0.192		0	Peterson *et al.* 2001
Amity Cr. (ACMN)	MN, USA	3.5			69	Peterson *et al.* 2001
South Kings Cr. (KCKS)	KS, USA	2.4	0.154		43	Peterson *et al.* 2001
Gallina Cr. (GCNM)	NM, USA	1.3	0.039		52	Peterson *et al.* 2001
Sycamore Cr. (SCAZ)	AZ, USA	5.8	0.042		346	Peterson *et al.* 2001
Mack Cr. (MCOR)	OR, USA	5.1	0.159		61	Peterson *et al.* 2001
E1 Outlet (E1AK)	AK, USA	2.4	0.064		259	Peterson *et al.* 2001
trevor Cr. (TCAK)	AK, USA	2.8	0.11		778	Peterson *et al.* 2001
Gates Cr. (GCAK)	AK, USA	10.4	0.19		864	Peterson *et al.* 2001
Neversink river	USA	1.65	0.2	sand/ gravel	362	Burns 1998
Neversink river	USA	15.6	0.5	sand/ gravel	640	Burns 1998
Pioner Creek	USA	1.9	0.16	gravel	367	Davis and Minshall 1999
Constructed wetland 1-2 order stream	Norway	8	0.5	sand/mud	160	Braskerud 2002
Cliff Creek	USA	2	0.18	Boulder/ gravel	648	Davis and Minshall 1999
Pawinaw Creek	USA	15				Haggard *et al.* 2001
River Råån	Sweden	3		sand	312	Jansson *et al.* 1994
River Råån	Sweden	3		sand	31.2	Jansson *et al.* 1994
River Råån	Sweden	3		mud	381	Jansson *et al.* 1994
River Råån	Sweden	3		mud	98.4	Jansson *et al.* 1994
Vastaadbekken	Norway	0.3	high TOC	sand	360	Faafeng and Roseth 1993
Suibekken	Norway	0.3	low TOC	sand	155	Faafeng and Roseth 1993
Gelbæk	Denmark	2		sand/mud	53	Pind *et al.* 1997

5.3   Data sets collected on phosphorus retention

We found several references to studies on phosphorus retention in the international literature (see chapter 9). However, many of the references in the international literature only studied phosphorus retention in streams and rivers during short periods of the year. Phosphorus retention through processes of sedimentation, sorption and biological uptake takes place during low-flow periods while resuspension of particulate organic and inorganic bound phosphorus mainly takes place during in high-flow periods (see chapter 9 for more information). Therefore, we had very limited data for developing a method to calculate phosphorus retention in streams and rivers. Documentation in several studies showed that phosphorus retention over longer periods in streams and rivers takes place only in the marginal and permanently vegetated zone (emergent vegetation) of larger streams. However, end-users should be aware that phosphorus retention could take place for several years in smaller ditches and streams from where it may later be excavated (see chapter 9).

5.4   Tier 1 nitrogen and phosphorus retention calculation

Description of methods

Nitrogen

An average annual nitrogen retention rate was calculated from the entire dataset collected with the omission of one extremely high denitrification rate. Table 5.2 shows the calculated statistics of the data from the international literature. In Tier 1 we have applied the mean annual nitrogen retention rate of 840 kg N ha^{-1} surface area.

Table 5.2 Denitrification rates in streams and rivers.

	Mean	95% confidence level	Median	Minimum	Maximum
Denitrification rate (kg N ha-1 surface area	840	360	250	0	3550

Phosphorus

Permanent phosphorus retention for a period of several years is in Tier 1 constrained to streams and rivers larger than 6 m in width. We have included an average annual retention rate for total phosphorus retention in the permanently vegetated marginal zone of rivers, which amounts to 55 kg P ha^{-1} surface area of marginal zone in the channel. The extent of the permanently vegetated marginal zone varies from river to river, but data from a large Danish river (River Skjern: approx. 40 m wide) showed an average content of the marginal zone of 5% of the total river width. This figure was included in the Tier 1 calculation of longer-term phosphorus retention in streams and rivers.

Menus in EUROHARP-NUTRET

Figure 5.2 shows the Tier 1 input data menu and result menu for the nitrogen and phosphorus retention calculation. Basic information is catchment size and total length of river network in the catchment. The programme supports calculations of surface water area both for the entire network and for the network of rivers wider than 6 metres. However, information on the surface area of your specific catchment should be used, if available. The surface area of rivers is calculated very simply in the programme by using experience from two catchments in the EUROHARP project. The standard calculation of surface area is therefore considered better suited for small catchments (< 10,000 km^2)

and for catchments in the Northern and Central parts of Europe. Figure 5.3 shows the output menu with the calculated results.

6 m wide

Figure 5.2 Input menu for the streams and river retention calculation.

Figure 5.3 Output menu with the calculated nutrient retention in streams and rivers.

Input data requirement for Tier 1

The Tier 1 calculation of nitrogen and phosphorus retention requires only very basic information about total surface area of streams and rivers in a catchment. If this information is not available, the software can make a calculation of the total surface area based on an input of the total length of stream and river channels from GIS-layers or maps. The Tier 1 calculation returns a longer-term average annual figure for nitrogen and phosphorus retention in streams and rivers.

Restrictions for applying Tier 1

The Tier 1 calculation is very rough, especially when dealing with the estimate of phosphorus retention. The nitrogen retention calculation should only be used if the annual mean concentration of nitrate-N in stream water exceeds 1 mg N/l. Phosphorus retention is only calculated for larger streams and rivers in Tier 1. Therefore, we believe that longer-term permanent phosphorus retention is underestimated in the entire river system, as Tier 1 does not include permanent retention in slow-flowing ditches and streams. Finally, the Tier 1 calculation does not comprise retention of nitrogen and phosphorus taking place in the exchange of water and substances between the surface water and sub-surface water through the hyporheic zone. Several studies have shown the importance of retention processes for both nitrogen and phosphorus in the hyporheic zone (e.g. Valett *et al.*, 1996).

6.   Nutrient retention calculation for riparian wetlands

6.1   Introduction

Nitrogen and phosphorus retention processes take place in riparian wetlands and on floodplains when they are inundated with nutrient-enriched river water during floods (see more about this issue in chapter 10). Biological and chemical denitrification of nitrate, nutrient uptake and deposition of particulate bound nitrogen and phosphorus is the major mechanisms removing or storing nutrients.

6.2   Data sets collected on nitrogen retention

The literature survey for nitrogen retention in inundated riparian wetlands and on floodplains is found in chapter 10. Most studies show that removal of nitrogen takes place in both natural and artificial riparian wetlands and on inundated floodplains.

6.3   Data sets collected on phosphorus retention

The literature survey for phosphorus retention in inundated riparian wetlands and on floodplains is found in chapter 10. Most studies show that deposition of phosphorus takes place in both natural and artificial riparian wetlands and on inundated floodplains.

6.4   Tier 1 nitrogen and phosphorus retention calculation

Description of method

Nitrogen

The Tier 1 nitrogen retention calculation for riparian wetlands and floodplains is based on documented removal rates for Danish river systems. We have applied the removal rates in Table 6.1 for the area of riparian wetlands and floodplains in a river basin.

Table 6.1 Nitrogen retention rates applied for different riparian wetlands.

	Proportion of agricultural area in the catchment > 80%	Proportion of agricultural area in the catchment 30-80%	Proportion of agricultural area in the catchment < 30%	Proportion of agricultural area in the catchment < 10%
Nitrogen removal rate (kg N ha-1 yr-1)	150	100	50	25

Phosphorus

The Tier 1 phosphorus retention calculation for inundated riparian wetlands and floodplains is based on documented deposition rates for Danish river systems. We have applied an annual deposition rate of 55 kg P ha^{-1} inundated riparian areas.

Menus in EUROHARP-NUTRET

Figure 6.1 shows the Tier 1 input data menu and result menu for the nitrogen and phosphorus retention calculation. It is important to provide information of the total wetland area as well as the size of the riparian wetland area and surface water wetland area as nitrogen retention is only calculated for the riparian wetland area and phosphorus retention only for the surface water wetlands. Figure 6.1 shows the results of the calculations.

Figure 6.1 Input data menu for the nutrient retention calculation in riparian wetlands.
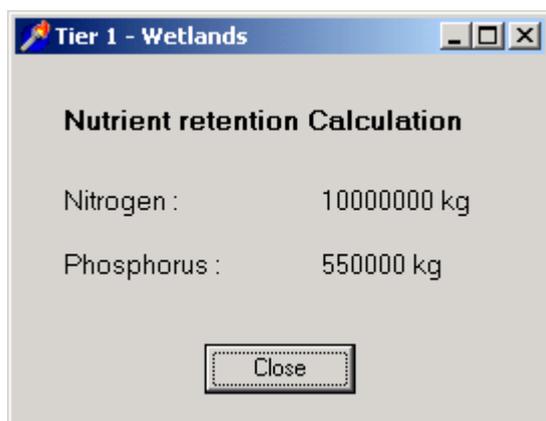
Figure 6.2 Output menu for the results of the nutrient retention calculation in riparian wetlands.

Input data requirement for Tier 1

The calculation of nutrient retention in riparian wetlands requires access by end-users to information on the total area of wetlands in the catchment and the proportion of the wetlands being inundated riparian wetlands. Moreover, information on the proportion of agricultural land in the catchment is required and it is adopted from the information provided under catchment Info.

Restrictions for applying Tier 1

The calculation of nutrient retention is an estimate of longer-term nutrient retention. It can only be estimated and used for specific years if the end-user specifies the area of inundated riparian wetlands for each year in question. Factors such as temperature, existence of easily decomposable organic matter, etc. is not taken into consideration in this very rough estimate of nutrient retention.

7.   Modelling of nutrient retention in river systems

7.1   Introduction to a nitrogen and phosphorus mass balance model for river systems: a German approach

Knowledge about the pathways of nitrogen and phosphorus discharges/losses from point and diffuse sources enables the quantification of the total discharges/losses of nitrogen and phosphorus into a river system. If the nitrogen and phosphorus discharges/losses are known, the retention can be quantified approximately as the difference between the discharges/losses and the monitored load at the river mouth. This approach entails errors due to 'upscaling' and insufficient knowledge about the hydrological processes in the catchment. In the following it is assumed that retention processes are the main reasons for the difference between the observed load (L) and total discharges/losses (D).

In Germany, an analysis has been carried out with data on the discharges/losses and riverine loads of nitrogen and phosphorus in 100 different rivers located in different parts of Europe. The geographical region covered by these rivers ranges between la Loire in France (west), the Drau in Austria (south) and Vataanjoki in Finland (north and east) (c.f. Behrendt & Opitz, 1999). River catchments smaller than 100 km² have not been considered.

The models require the following parameters for the quantification of the retention:

a.   The catchment area (A in km²);

b.   The water-flow (Q in m³/s); and

c.   The area of surface waters within the river catchment (A_s in km²).

The area of the surface waters within the catchment (A_S) can be calculated from detailed statistics on land use or by using the surface area of the lakes and reservoirs (A_{Lake}) on the basis of land use maps (e.g. CORINE Land-cover) and the river surface according to the following equation:

$$A_S = A_{LAKE} + 0{,}001 \cdot A^{1.185} \quad [\text{km}^2] \tag{1}$$

Where;

As   = area of surface waters;

A_{LAKE} = area of lakes in the catchment; and

A   = catchment area.

The second part of the sum is derived from the analysis of different river systems according to stream order (Billen et. al., 1992; Billen *et al.*, 1995) and measurements in rivers of different size (c.f. also Behrendt & Opitz , 1999). The parameters in this equation should be developed specifically for the region/catchment under consideration.

As shown by Vollenweider & Kereekes (1982), the relationship between the discharges/losses of nitrogen and phosphorus into the lake and the state of the lake may be described by the following equation:

$$\frac{C_{N,P}}{C_{INPUT_{N,P}}} = \frac{1}{1 + R_{SN,SP}} \qquad (2)$$

Where:

$C_{N,P}$ = the nitrogen and phosphorus concentration observed in the lake;

$C_{INPUT\ N,P}$= the nitrogen and phosphorus concentration in the inflow; and

$R_{SN,SP}$ = the specific retention of nitrogen and phosphorus.

The specific retention ($R_{SN,SP}$) is estimated by the statistical analysis of lakes in different regions of the world, and appears to be dependent on the residence time of the lakes. Equation (2) may be generalised for a river system with or without lakes by the following equation:

$$\frac{L_{N,P}}{D_{N,P}} = \frac{1}{1 + R_{SN,SP}} \qquad (3)$$

Where:

$L_{N,P}$ the nitrogen and phosphorus load at a specific monitoring station;

$D_{N,P}$ the sum of all nitrogen and phosphorus discharges/losses within the catchment area upstream of the monitoring station; and

$R_{SN,SP}$ the specific retention of nitrogen and phosphorus.

The specific retention is a quantity without dimensions. To date, there appears to be no estimations of the residence time of the water in a whole river system. The quantification of nitrogen and phosphorus retention in the freshwater system (both lakes and rivers) is therefore derived from other relevant parameters. Kelly *et al.* (1987) and Howarth *et al.*(1996) have shown that the nitrogen retention of lakes and rivers is dependent on the hydraulic load (HL: defined as the annual runoff divided by the water surface of the river basin). In the form of equation.3, this model can be characterised by the following equation:

$$\frac{L_N}{D_N} = \frac{1}{1 + \dfrac{S_N}{HL}} \qquad (4)$$

Where:

S_N the average mass transfer coefficient given in m/a.

Behrendt & Opitz (1999) found that the specific nitrogen and phosphorus retention of river systems depends on the hydraulic load and/or specific runoff (q: defined as the runoff divided by the area of the river basins). The following relation between the specific retention of the hydraulic load and specific retention was proposed:

$$\frac{L_{N,P}}{D_{N,P}} = \frac{1}{1 + a \cdot HL^b} \quad \text{or} \quad \frac{L_{N,P}}{D_{N,P}} = \frac{1}{1 + a \cdot q^b} \tag{5}$$

The coefficient of the model of Eq.(5) is the same as S_N for nitrogen, if the coefficient b is –1.

The coefficients of both models were estimated on the base of 100 different river basins in Europe. The results are given in Table 7.1, according to Behrendt & Opitz (1999).

Table 7.1: Results of regressions between the nitrogen and phosphorus retention per load (RL) of river systems and the specific runoff (q) and the hydraulic load for the studied river systems.

	q	HL[1]	HL[2]
Phosphorus:			
R[2]	0,8090	0,6148	0,6130
N	89	89	89
A	26,6	13,3	16,6
B	-1,71	-0,93	-1
Nitrogen:			
r[2]	0,5096	0,6535	0,6173
N	100	100	100
A	6,9	5,9	11,9
B	-1,10	-0,75	-1

[1] Results of a model according to Eq. (5).

[2] Results with a constant mass transfer coefficient - a, according to the model approach of Kelly *et al.* (1987).

The models explain more than 60% of the total variance of the L/D ratio (load/discharge) for both phosphorus and nitrogen. According to equations (4) and (5), the models can be applied to river systems and lakes, if the surface waters area (A_s) and the water flow (Q) are known. Further values of the coefficients for river basins grouped by the basins' size are given in Behrendt & Opitz (1999).

By the comparison of different methods for the quantification of phosphorus discharges, the coefficient A seems to be lower by a factor of 0.49 than the value given in Table 1 (Behrendt, 1999). This is because there are indications that the P-load is to a certain level underestimated by "normal" monitoring, and the discharges/losses of phosphorus seem to be partly overestimated.

The procedures described above concern river catchments larger than 100 km². The data set used for the development of the model represents the situation of different river catchments over a longer time period. Therefore, the models cannot be used for the description of inter-annual fluctuations in one river system.

The application of the retention models is only given for freshwater systems with a hydraulic load and a specific runoff higher than 1 m/year and 3 l/km²/s, respectively.

Because the availability of data for total nitrogen load has been limited, the coefficients of the models given in Table 1 are based on the load of dissolved inorganic nitrogen ($NO_3 + NH_4 + NO_2$), and the data for the discharges inputs have been based on total nitrogen.

Equations (4) and (5) enable the estimation of the nitrogen and phosphorus load in cases where the area is unmonitored and the discharges/losses are calculated at source, according to the relevant HARP Guidelines. The total nitrogen and phosphorus retention in a freshwater system ($R_{N,P}$) can be estimated by multiplication of the observed or calculated nitrogen and phosphorus loads with the specific retention of nitrogen and phosphorus; according to equations (3) and (4) and/or (5).

$$R_{N,P} = R_{SN,SP} \cdot L_{N,P} \tag{6}$$

Where;

$R_{N,P}$ = total nitrogen and phosphorus retention in freshwater system;

$R_{SN,SP}$ = the specific retention of nitrogen and phosphorus; and

$L_{N,P}$ = the nitrogen and phosphorus load at a certain monitoring station.

Description of method

The method included in EUROHARP-NUTRET for nitrogen and phosphorus retention in surface water in river basins is the model developed by Behrendt and Opus (1999).

$$\frac{L_{N,P}}{D_{N,P}} = \frac{1}{1 + a \cdot HL^b}$$

In the case of total nitrogen the constants a and b are calibrated to:

$a_N = 1.9$

$b_N = -0.49$.

In the case of total phosphorus the constants a and b are calibrated to:

$a_P = 13.3$

$b_P = -0.93$.

The nutrient retention is then calculated according to:

$$R_{N,P} = R_{SN,SP} \cdot L_{N,P}$$

Where;

$R_{N,P}$ = total nitrogen and phosphorus retention in freshwater system;

$R_{SN,SP}$ = the specific retention of nitrogen and phosphorus; and

$L_{N,P}$ = the nitrogen and phosphorus load at a certain monitoring station.

Menus in EUROHARP-NUTRET

Figure 7.1 shows the menu included in EUROHARP-NUTRET catchment retention calculation.

Figure 7.1 Input data menu for the calculation of nutrient retention in surface water in river systems.
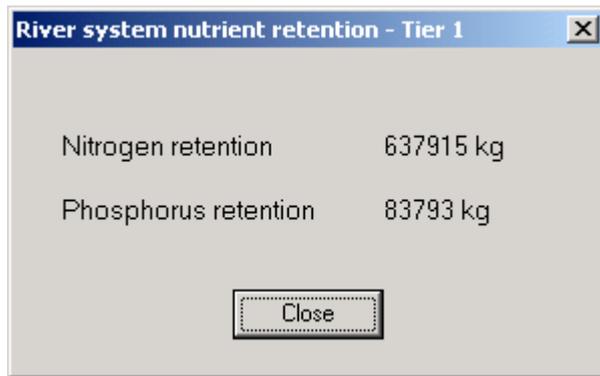
Figure 7.2 Output menu with the results of the calculation of nutrient retention in surface water in entire river systems.

Input data requirement for Tier 1

The Tier 1 calculation of nutrient retention in surface water requires only knowledge of very basic catchment information. This includes the area of the catchment, the total area of lakes and reservoirs in the catchment, the total area of streams and rivers and the runoff from the catchment.

Restrictions for applying Tier 1

The procedures described above concern river catchments larger than 100 km². The data set used for the development of the model represents the situation of different river catchments over a longer time period. Therefore, the models cannot be used for the description of inter-annual fluctuations in one river system. The application of the retention models is only given for freshwater systems with a hydraulic load and a specific runoff higher than 1 m/year and 3 l/km²/s, respectively. Because the availability of data for total nitrogen load has been limited, the coefficients of the models given in Table 7.1 are based on the load of dissolved inorganic nitrogen ($NO_3 + NH_4 + NO_2$), and the data for the discharges inputs have been based on total nitrogen.

Part 2

Scientific review of nutrient retention in streams, rivers, lakes, reservoirs and riparian wetlands

8.   Nutrient retention modelling in lakes – a review

8.1   Introduction

Limnologists usually follow Dillon and Rigler (1974), defining the *nutrient retention coefficient* as the fraction of the nutrient loading that is retained within the lake, i.e. that is not exported via the outflow. Other branches of aquatic sciences use the same term, but often with quite contrasting definitions. For river basin modeling, it is often found more convenient to relate retention to what comes out of the watershed than to what goes in to it (e.g., Behrendt and Opitz 1999). On the other hand, marine plankton ecologists use the term for what is retained in the water column, reserving the term export production for retention in the limnological sense (e.g., Wassmann 1998).

The limnological definition implies that for any lake in equilibrium with its external inputs, the retention will be a dimensionless parameter bounded between 0 and 1. The retention can become negative in transient situations, such as when the external loading has been reduced while internal loading from nutrients previously buried in the lake sediments still prevails. The retention can never be larger than 1, since that would imply the physical impossibility of a negative nutrient concentration.

It is important to notice that the goal of much of the early literature was not to predict retention *per se*, but rather to predict transparency or chlorophyll concentration, or to determine critical nutrient loading limits. Some might say that the retention coefficient was just more or less a convenient intermediate in these calculations. More recently, this procedure has been challenged by e.g. Meeuwig and Peters (1996), who argue that chlorophyll concentrations may actually be better predicted directly from watershed land-use statistics, then from classical phosphorus loading models. On the other hand, the awareness of lakes as important nutrient sinks has also generated renewed interest for in-lake retention models in the context of quantifying nutrient emissions on a watershed scale.

8.2   The foundations: Vollenweider (1969)

The retention concept has become a key element in standard nutrient loading models of the Vollenweider type. Even if not explicitly mentioned in the original Vollenweider (1969) paper that the basic model serves well as starting point for various derivations based on the retention concept. As pointed out by Dillon (1974), this paper was an extract of several models presented by e.g. Biffi (1963), Piontelli and Tonolli (1964), and Vollenweider (1964). The main difference was perhaps that by 1969, Vollenweider had simplified assumptions to a level where the model could actually be put into practical use. Vollenweider (1969) assumed that a lake could be considered a well-mixed, single compartment, input-output system with total nutrient as the single state variable. In a phosphorus-centric notation we can write the mass balance equation of total phosphorus (P – mg m^{-3}) as

$$\frac{dP}{dt} = \frac{A}{V}L_P - \frac{Q}{V}P - S_P \qquad\qquad 1$$

where A, V, and Q are lake surface area (m^2), volume (m^3), and water flow (m^3 y^{-1}). This formulation implicitly assumes that the lake maintains a constant volume (inflow equals outflow). L_P and S_P are areal phosphorus loading rate (mg m^{-2} y^{-1}) and volumetric net phosphorus loss rate (mg m^{-3} y^{-1}), respectively. Areal P-load can also be expressed in terms of an input concentration (P_L – mg m^{-3}) defined such that $AL_P = QP_L$. Furthermore, if we introduce the standard definitions of mean depth

($\bar{z} = V/A$, m) and water renewal rate ($\rho = Q/V$, y^{-1}), we can express the equilibrium solution ($dP/dt = 0$) of the total P mass balance as

$$P = \left(1 - \frac{S_P}{L_P/\bar{z}}\right)P_L = (1 - R_P)P_L \qquad\qquad 2$$

The last identity introduces the dimensionless phosphorus retention (R_P) as the ratio between volumetric net P loss rate (S_P) and *volumetric* P loading rate ($L_P/\bar{z}$). It also shows the close to trivial – but nevertheless practically important – result that the outflow concentration (*P*) resulting from a given inflow concentration (P_L) can be predicted when the retention is known. In fact, the majority of the classical phosphorus loading models are mainly concerned with deriving relationships between phosphorus retention and easily measurable, morphometrical and hydrological lake characteristics.

In the most classical example, Vollenweider (1969) assumed that the net P loss term (S_P) was directly proportional to lake concentration (= outflow concentration: *P*). Under this assumption, the mass balance equation can be rewritten as

$$\frac{dP}{dt} = \rho(P_L - P) - \sigma_P P \qquad\qquad 3$$

where c_P is a net P loss rate coefficient with the same dimensions as the water renewal rate ρ (y^{-1}) – i.e., fraction of lake P content lost per unit time. Solving again for the equilibrium situation and apply the definition $P/P_L = 1 - R_P$ we get the hyperbolic relationship

$$R_P = 1 - \frac{P}{P_L} = \frac{\sigma_P}{\sigma_P + \rho}. \qquad\qquad 4$$

For lakes with very long residence times, where $\rho \ll c_P$, we must have $R_P \approx 1$ – i.e., that practically all input is retained within the lake. On the other hand, when residence time becomes very short ($\rho \gg c_P$), the retention approaches zero – i.e., concentrations are practically unchanged by passage through the lake. Both these properties will usually be considered physically intuitive.

8.3   The golden era: 1975-1982

The various refinements since Vollenweider's seminal 1969 paper can be grouped according to which part of (4) they modify, and the assumptions they may introduce. Vollenweider (1975) as well as Chapra and Tarapchak (1976) assumed that if sinking is the major cause of net P loss, and if particles have more or less the same sinking velocity, then c_P would be expected to be inversely proportional to the mean depth of the lake. That is, $\sigma_P = v_P \bar{z}^{-1}$, where v_P (m y^{-1}) is the apparent net sinking velocity of total phosphorus. It should be noticed that typical fitted values for v_P are within the range 10-20 m y^{-1}, which is around 2 orders of magnitude less than typical sinking velocities of e.g. plankton algae. If we define the areal water load as $q = \bar{z} \rho$ (4) can also be rewritten as:

$$R_P = \frac{\sigma_P}{\sigma_P + \rho} = \frac{v_P \bar{z}^{-1}}{v_P \bar{z}^{-1} + \rho} = \frac{v_P}{v_P + q}, \qquad\qquad 5$$

the latter of which is identical to the functional form proposed by Ostrofsky (1978).

Figure 8.1 compares 5 of the early retention models, all with the functional form (4) or (5). All curves are strikingly similar, with Vollenweider (1969) predicting the lowest and Kirchner & Dillon (1975) the highest retention at any given water renewal rate. Kirchner & Dillon (1975) originally fitted a more

complicated sum of exponentials model to their data, but Chapra (1975) showed that their 4-parameter model did not give any better fit that the 1-parameter model (5). The maximum difference between the different models in figure 1 occurs for lakes with residence times around 1 year (R_P = 0.33-0.62).
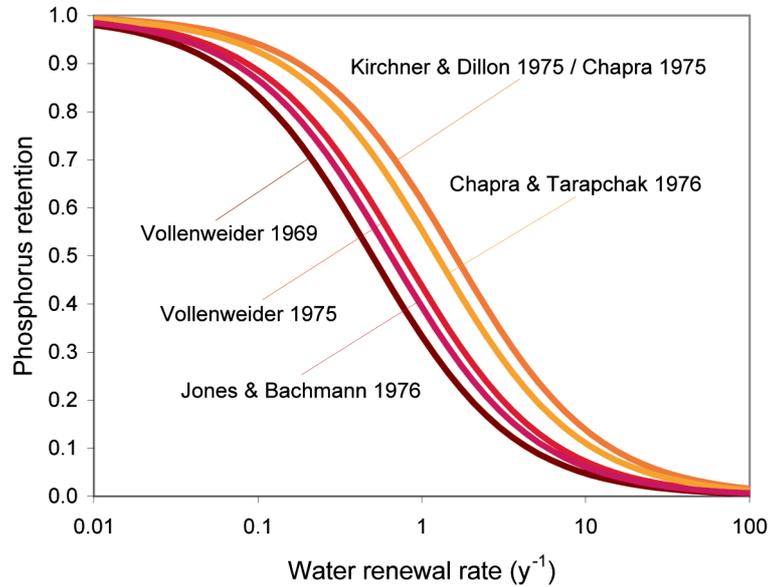
Figure 8.1. Comparison of 5 early models for phosphorus retention as function of water renewal rate (equations 4 or 5). For models of type (5), a mean depth $\overline{z}$ = 10 m is assumed. Parameter values can be found in Table 1.

Larsen and Mercier (1976) retained Vollenweider's original idea of a constant net P loss rate, but noticed that retention seemed to decrease less steeply with increasing ρ, than implied by the rational function (4). Thus they proposed (4) to be modified by an additional shape parameter n:

$$R_P = \frac{\sigma_P}{\sigma_P + \rho^n} \, , \qquad\qquad\qquad 6$$

and fitted values close to n = 0.49-0.51 for different subsets of their data. It should be noticed that compared to (4) and (5), there is *no* mechanistic theory behind(6). In fact, unless n = 1, the denominator in (6) is not even expressed in physically compatible units (y^{-1} vs. y^{-n}). Since Larsen and Mercier (1976) also found fitted values close to $\sigma_P = 1$, they suggested one could actually simplify their model to:

$$R_P = \frac{1}{1 + \sqrt{\rho}} \, . \qquad\qquad\qquad 7$$

The same idea must have struck Vollenweider himself about the same time: in his 1976 paper he presents the equivalent of (7), without any derivation. Apparently, he had some troubles with the lack of dimensional consistency in (7) - the 1's should be in units of $y^{-0.5}$ to make the retention coefficient dimensionless - stating that "we are forced into adopting certain more or less defendable shortcuts."

Table 8.1 Functional comparison of retention models illustrated in figures 1-4: All models conform to the functional relationship

$$R_P(\rho) = \frac{\sigma + R_\infty \rho^n}{\sigma + \rho^n}$$

where ρ is water renewal rate (y^{-1}) , σ is the specific, net sedimentation loss rate (y^{-1}), R_∞ is the load decay coefficient (dimensionless) and *n* is a dimensionless exponent. Whenever nothing else is stated, we assume a lake with mean depth $\overline{z}$ = 10 m, and inflow total P concentration P_L = 50 µg L^{-1}

Source	c	R_∞	n
Vollenweider 1969	0.5	0	1
Vollenweider 1975	$\dfrac{5.5}{\overline{z}^{0.85}} \approx \dfrac{10}{\overline{z}}$ (?)	0	1
Kirchner & Dillon 1975 Chapra 1975	$\dfrac{16}{\overline{z}}$	0	1
Chapra & Tarapchak 1976	$\dfrac{12.4}{\overline{z}}$	0	1
Larsen & Mercier 1976	1.63	0	0.49
Larsen & Mercier 1976 Vollenweider 1976	1	0	0.5
Jones & Bachmann 1976	0.65	0	1
Reckhow 1979	$\dfrac{9.7}{\overline{z}}$	0.17	1
Frisk et al 1980	$0.034\,P_L$	0	1
Canfield & Bachmann 1981	$0.094\left(P_L\right)^{0.42}$	0.2	0.58
Prairie 1988/89	0.18	0.25	1

Although (7) certainly is a simple and esthetically pleasing formula, it is nevertheless just a curve fitting exercise with *no* physical or mechanistic justification. Despite this fact, $\sqrt{\rho}$ or $1 + \sqrt{\rho}$ have been used repeatedly as regressors in empirical retention models ever since. The most famous example being the OECD report on eutrophication monitoring, assessment, and control (OECD 1982), while Uchmanski and Szegligiewicz (1988) and Foy (1992) are more recent ones.
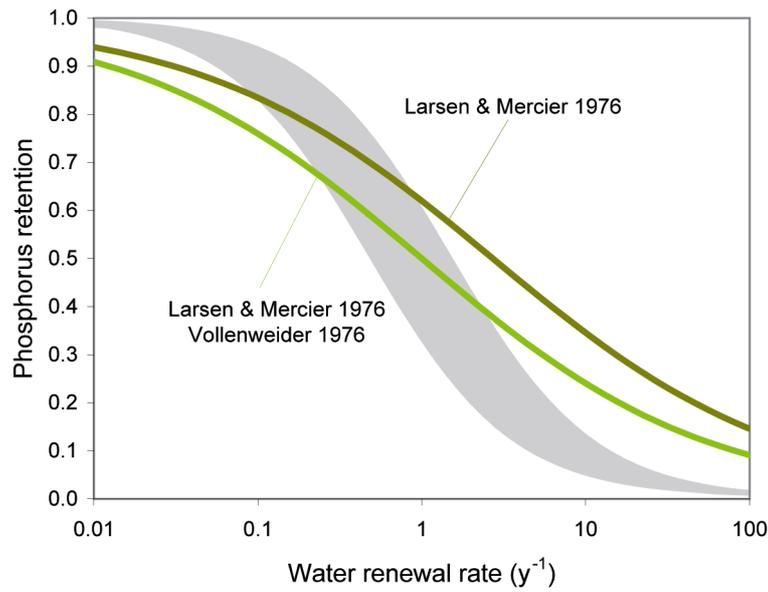
Figure 8.2 Comparison of 2 models for phosphorus retention as a power function of water renewal rate (equations 6 or 7) with the earlier models from figure 1 (range indicated by shaded area) Parameter values can be found in Table 1.
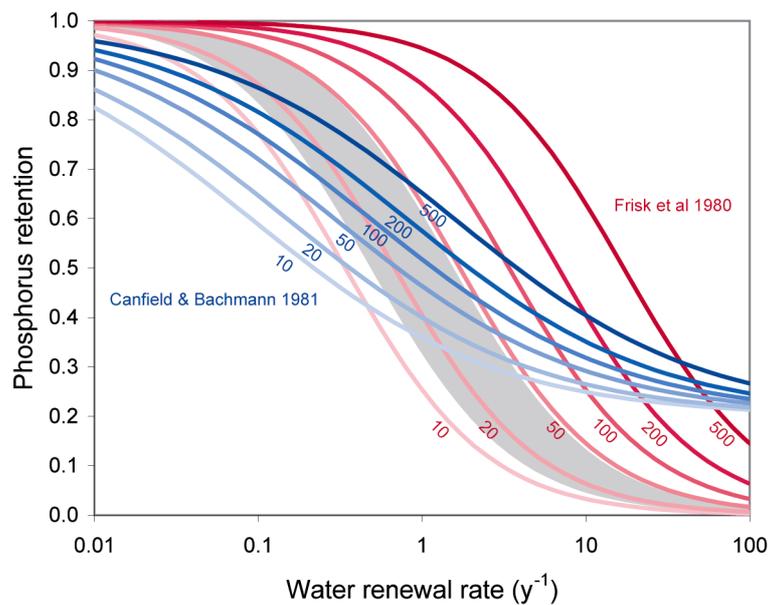
Figure 8.3 Comparison of 2 models for phosphorus retention as a function of water renewal rate and inflow total P concentration (equations 6 or 7) with the earlier models from figure 1 (range indicated by shaded area). Curve labels are inflow total P concentrations (P_L ; µg L⁻¹). Parameter values can be found in Table 1.

8.4   Prairie's compromise

Prairie (1988) noticed that the diversity of retention models descending from Vollenweider (1969) typically fall into two groups – those that describe net losses as function of lake content and those that

describe it in terms of loading. Vollenweider (1969, 1975) and Larsen and Mercier (1976) serve as examples of the first approach, while Reckhow (1979) and Canfield and Bachmann (1981) represent the second. Prairie (1988) presented a simple solution that unifies the two by assuming that net P loss rate (S_P) can be decomposed into two terms: one representing the net sedimentation of lake content, and the other representing a fractional loss of the volumetric loading before it actually reaches the lake (load decay)

$$S_P = c_P P + R_L \left(L_P / \bar{z} \right) = c_P P + \rho R_L P_L$$

where c_P represents the net sedimentation loss rate, as before, while the dimensionless parameter R_L represents the load decay – i.e., the fraction of the external loading that is lost before it enters the lake. If we substitute this expression into the mass balance equation and solve for the equilibrium situation, we get the following relationship between retention and water renewal rate

$$R_P = \frac{\sigma_P + R_L \rho}{\sigma_P + \rho}$$

This expression has a strong resemblance to the original Vollenweider model, the main difference being that R_P no longer asymptotically approaches zero when the water residence time becomes very short ($\rho - \infty$). Instead, the retention process becomes dominated by load decay in lake with very short residence times. Load decay is usually interpreted as being related to sedimentation of coarse particles and nutrient uptake by macrophyte beds as water enters the lake. The importance of such processes has also been inferred from the typical discrepancy found between retention calculated by mass balance and sedimentation loss measured by sediment traps (e.g. Edmondson and Lehman 1981).
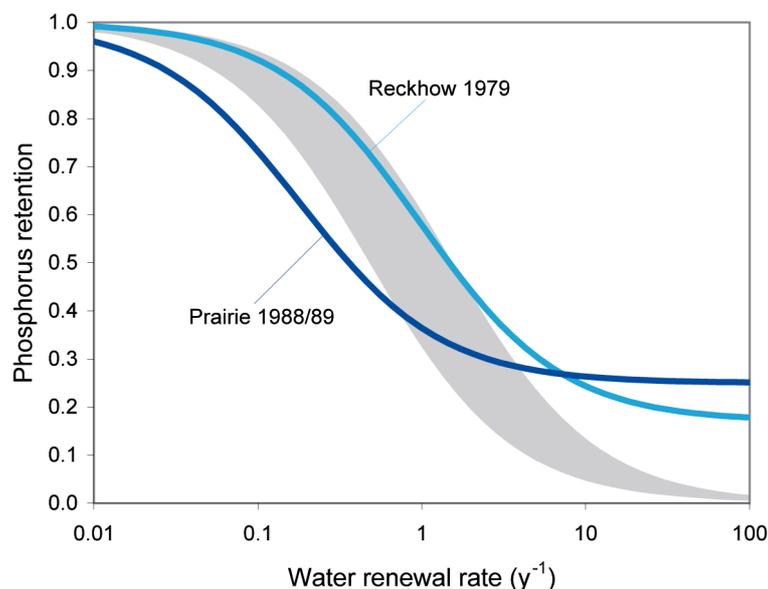
Figure 8.4 Comparison of 2 models for phosphorus retention as function of water renewal rate with a load decay term (equations 1.z or 1.w) with the earlier models from figure 1 (range indicated by shaded area) Parameter values can be found in Table 1.

The predictive power of such a relationship can be illustrated (figure above) by a data set, also compiled by Prairie (1988), comprising 120 lakes in Europe and North America covering a wide range of hydrological and trophic conditions. The Prairie model certainly captures the general trend of this data set, and it is particularly noticeable how the implied non-zero retention at very high water renewal rates is reflected by the data.
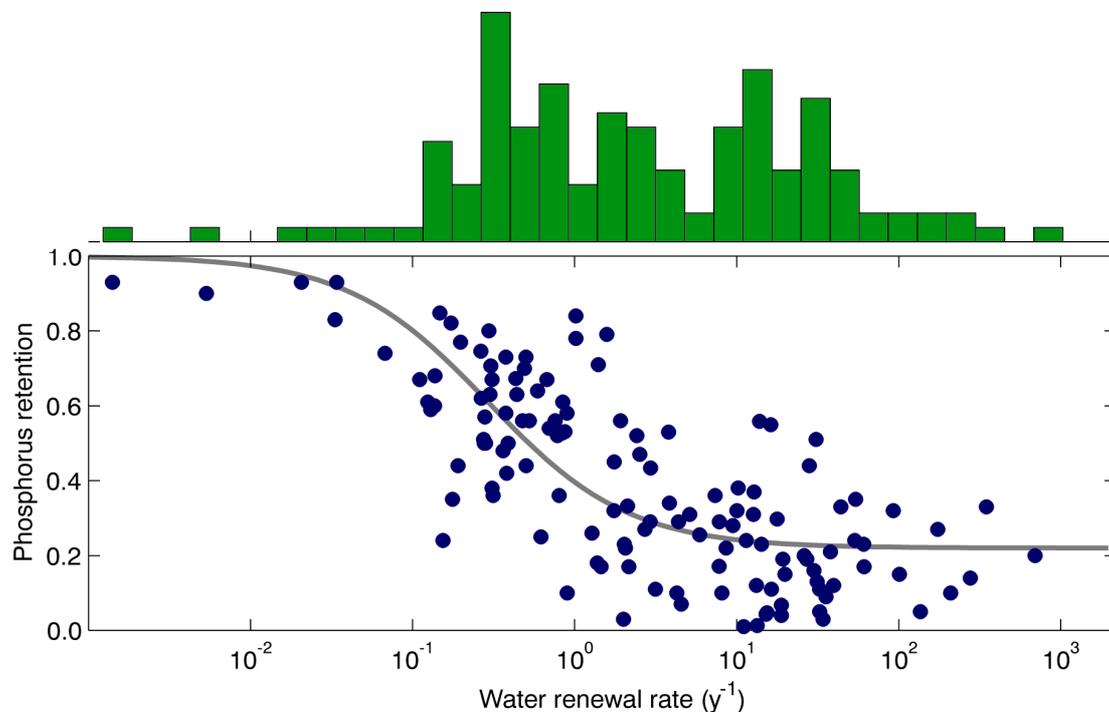
Figure 8.5 The model of Prairie (1988/89) Parameter values can be found in Table 1.

On the other hand, the figure also points out the inherent limitations of this approach. The unexplained variance is substantial, especially for the most frequent lake types in this data set – those with renewal rates from 0.2 – 20 y^{-1}. In this range, the P-retention can vary by more than an order of magnitude between lakes with practically identical residence times. It is quite unlikely that this variance can be reduced very much by any other predictor based solely on morphometrical and hydrological parameters. Most probably, these differences reflect differences between the biological communities of lakes, and the ways they may affect nutrient retention.

For example, the relative importance of planktonic vs. littoral primary producers may influence the degree to which nutrients are regenerated in the littoral zone or buried in the deep sediments. Apparently, dominance of littoral macrophytes or planktonic microalgae represents alternative stable states in shallow lakes, although their occurrence seem highly unpredictable (Scheffer 1998). Likewise, the contrasting properties of fast-sinking diatoms and buoyant cyanobacteria indicate how the composition of the phytoplankton community may affect sinking losses. A substantial part of lake total phosphorus is commonly located in organisms from higher trophic levels. The actual distribution of phosphorus between groups of invertebrates and fish has been shown to strongly influence cycling and retention of phosphorus in lakes (Brabrand *et al.* 1990, Reinertsen *et al.* 1990, Vanni *et al.* 1997, Andersen 1997).

Hardly any of these aspects of community structure can be predicted from hydrological and morphometrical lake properties alone. It is also doubtful if the present state of ecological system models will be capable of predicting such phenomena with the necessary level of confidence. Thus, it

appears that direct measurements of nutrient input-output balance may actually be the most cost-efficient way of estimating nutrient retention if there is need for a level of precision beyond what is offered by simple Vollenweider type models.

9.   Nutrient retention in streams and rivers – a review

9.1   Introduction

Direct measurement of different retention and loss processes is only possible at certain locations and in research projects (Svendsen & Kronvang, 1993). Even though riverine P-retention has been measured in many studies, a general evaluation on an annual or seasonal base is still extremely difficult. This is because many processes are seasonally dependent, thus P retained (mostly during summer) in one or the other pool (plants, sediment) is often remobilised in winter, when, for example, higher runoff occurs and the sediment is not covered by macrophytes.

In additional, upscaling of such measurements requires knowledge of the distribution of the identified driving parameters along the whole river system. Therefore, some authors tried to calculate P-retention by comparing the sum of emission from the catchment with the measured river load. From several studies it is known that a significant discrepancy exists between the measured nutrient load at the river outlet and the nutrient input in the upstream river network (Probst, 1985; Hilbricht-Ilkowska, 1988, Svendsen & Kronvang, 1993, Behrendt, 1996, Tonderski, 1997). This could be caused by either uncertainty in the emission calculations or in the measured river load.

The major driving force for P-retention seems to be flow velocity. But in addition, many other factors have been investigated to identify their influence on the retention (e.g. macrophyte biomass, extent of riparian zones and concentration of nutrients, length, slope, availability of Fe-and Al-oxide, transient storage areas, etc). On a river system scale the crucial point still is to find and finally to measure the driving forces governing these processes. Hilbricht-Ilkowska (1993), for example, could not identify relations between the retention and driving forces (lakes: depth, trophic state, flushing rate, area covered by littoral vegetation, or length of shoreline, rivers: length, flow) for a Polish lake-river system. De Klein (subm.) did not find a clear seasonal pattern in phosphorus retention either, although discharge is low in summer and high in winter. No relation was found between P-retention and specific runoff. Although many authors found indications that P-retention occurs at lowflow conditions and during overbank floods, the calculated net retention on an annual basis varies considerably among authors, study sites and methods applied. P-retention values in the literature range from almost negligible (e.g. De Witt, 1999; Svendsen *et al.*, 1995; Schulz *et al.*, in press) to a major part of the measured load (e.g. Behrendt & Opitz, 2000; Pöthig, in prep.).

In the following chapter the different processes and their driving forces are discussed and the retention rates found by different authors and studies are collated and compared. Finally, some approaches to model P-retention are introduced.

9.2   Mechanisms and processes related to phosphorus retention

In the literature the following processes have generally been accepted as being relevant for phosphorus retention in rivers:

– adsorption on suspended solids and the sediment

– deposition of particulate matter on the sediment

– resuspension and remobilisation

– P-uptake by algal and aquatic plants

–   Sedimentation on inundated areas during floods.

Adsorption onto bed sediments is thought to be a major mechanism for P-retention (Hill, 1982 and Nichlos, 1983) as is uptake by algae and aquatic macrophytes (Probst, 1985, Hilbricht-Ilkowska, 1988, Svendsen-Kronvang, 1993, Van der Perk, 1996).

Variation in catchment land use was not a major determinant in P-retention in summer, but stream hydrology and hydraulics, such as discharge and transient storage (backwaters, deep pools and the hyporheic zone, i.e. deep alluvial sediments where surface water and ground water often mix) were regulating factors (Haggard *et al.*, 2001). In general it can be assumed that the absolute loss [kg/yr] in a river segment increases in downstream direction, because the total nutrient river load increases in downstream direction. Yet, the relative loss (1-tf) will decrease in downstream direction, because the ratio between the volume of a river segment [m³] and the surface of a river bed [m²] generally decreases in downstream direction (De Witt, 1999). Kronvang *et al.* (1999) found similar results in a Danish lowland river, where particulate P in stream bed sediments and marginal bank zones increased with increasing stream order up to 3rd order streams and decreased going from 3rd order to 4th order streams. This trend followed the observed mean slope of the different stream orders.

Behrendt & Opitz (2000) concluded from their studies that phosphorus retention is higher for smaller catchments, especially in the range of low specific runoff and low hydraulic load. This phenomenon could be attributable to the fact that smaller river basins, especially those with low specific runoff, possess larger areas where submerse and emerse macrophytes can grow. These macrophytes expand? the area with low-flow velocities and influence directly the sedimentation of particles.

By subtracting point source P-discharge from the river load at low-flow conditions, Svendsen *et al.* (1995a) calculated negative balances.. This relation between low runoff (baseflow, which also means low specific runoff and low hydraulic load) and increased sedimentation rates was confirmed by many other studies (Keup, 1968; Rigler, 1979; Doroiz *et al.*, 1989; Triska *et al.* 1989).

9.3   Transformation processes

Chemical precipitation of P might occur in groundwater-fed rivers (stretches), and lead to increased sedimentation rates. Under anaerobic conditions high concentrations of soluble bivalent iron ions can be found in groundwater. When in contact with oxygen, soluble iron binds dissolved phosphorus and precipitates as dark brown iron ochre (iron oxide). Under such conditions Pöthig *et al.* (in prep.) determined increased sedimentation rates. A total net annual retention of 1.2 [g P/(m²·yr)] was determined in this brook (taking other processes into account too).

A large part of P is adsorbed onto suspended sediments, in contrast to N of which the major part in the surface water is dissolved (De Witt, 1999). According to Walling *et al.* (1997) and Meybeck (1984), sediment-associated nutrient transport contributes up to 75% or 95%, respectively, of the total N and P flux. Transport of P compounds (dissolved and particulate P) exposed a seasonal pattern, which is highly effected by flow conditions, in-stream processes, as well as point and non-point sources. Particulate P transport in the Gelbæk stream constituted 56% and 75% of annual total P transport during ? two years compared with 77% and 75% in River Gjern Å (Svendsen *et al.*, 1995a).

Walling *et al.* (2001) found for four rivers in the UK that the TP content in suspended sediments is dominated by non-apatite inorganic P (NAIP) (60-70%) which in turn accounts for alagal available P (AAP) representing a substatntial proportion (48-59%) of the TP content. For NAIP and AAP, TP and TN significant differences between the rivers were found, which could partly be explained by the size of the suspended sediments. Large temporal differences in the nutrient content in the four rivers were

measured. Walling *et al.* tried to explain these differences by temporal variations of four properties (TOC, cation exchange capacity (cec), oxalate extractable irion (Fe_o) and percentage of particles smaller than 2 µm) of the suspended sediments. TOC appears to exert the strongest control over the nutrient content of the samples. (For larger catchments) the grain size did only have limited influence on the nutrient content. Nevertheless, the influence of suspended sediment's properties on this temporal variability is most evident for smaller catchments, as in this case a clear association between the spatial origin of sediments and the individual sample could be made. This relationship might explain the differences in P content in suspended solids, but not the inter-annual differences.

Walling *et al.* (2001) also used hydro-meteorological parameters to explain the seasonality?? in nutrient contents (suspended sediment concentration, discharge at sample time, mean discharge during previous seven days and a seasonal index). The seasonal index shows a significant positive relationship with six out of seven parameters for each of the rivers (AAP, NAIP, apatite P, organic P, inorganic N, TN, but not TP). The results indicate that nutrient concentrations are highest in summer and lowest in winter. This result is confirmed by Svendsen *et al.* (1995a). Discharge at the time of sampling, antecedent flow conditions, and time of year were all shown to significantly influence the nutrient content or suspended sediment.

Haggard *et al.* (2001) found similar differences in ?? SRP concentration between summer and winter in three 3rd or 4th order streams on the Ozark Plateau, Oklahoma. The authors suggested that the lack of seasonal difference between P concentrations in these streams could be explained by the dominance of physical processes, such as sorption and desorption in regulating the P concentration. This means that P is subject to both abiotic and biotic processes. Phosphorus was retained during summer injections, but no significant retention could be measured during winter. This was explained by reduced biological activity, resulting from a temperature decrease of 10°C between summer and winter. Furthermore, abiotic sorption was not significant during winter, most likely because bentic sediment P buffering capacity and exchangeable P were lower in winter than in summer, and the coverage of fine sediments was low (Haggard *et al.*, 2001; Popova, 2000).

Sedimentation of particulate matter is considered to be the most important process to retain phosphorus. But when sedimentation was measured, an equally high remobilisation of this matter was very often also observed. Nevertheless, there is evidence that on an annual basis, both net sedimentation and net remobilisation may occur. Good examples of this are rivers that build up riverside soils or such, thereby cutting deeper into the ground from year to year.

De Witt (1999) also considered sedimentation within the river as a temporary sink, which is probably of minor importance when analysed on an annual basis. Svendsen *et al.* 1995a concluded for a Danish lowland river that the pool of retained P must be recognised as the major source of P during storm events, at least until the pool is exhausted.

Svendsen *et al.* (1998) found that retention by deposition in summer amounted to 12% of the total nutrient export in a lowland river system. The authors measured a marked reduction of the retained P pool on the stream bottom during August and September 1987. In the Gelbæk stream, resuspension occurred during summer because of the absence of macrophytes and in the main channel of the River Gjern Å, following weed cutting in September (Svendsen & Kronvang, 1993). Kronvang *et al.* (1999) also found that most of the retained P (80%) in the same river was resuspended during storm events in autumn and winter (1994-1995), following a decline in protective cover providing submerged and emergent macrophytes.

Schulz *et al.* (in press) examined the influence of macrophytes on the sedimentation in a lowland river in north-east Germany. Dense vegetation was found at shallow banks as well as in the centre of the river profile, where depth and flow velocity were high. Water residence time within the stand was increased by a factor of 18 in comparison to the unvegetated area of the river. They found that flow patterns, sedimentation, and therefore retention due to deposition are dependent on the shape of macrophytes, and therefore the retention by deposition is dependent on the species composition

(Table xx). Similarly, in a stock of S. sagittifolia with great longitudinal extension, a gradient was evident from low trapping rates upstream (17.5 [g/(m^{2}d)]) to high rates downstream (47.5 [g/(m^{2}d)]). High trapping rates were measured in the centre of a stock of N. lutea (30 [g/(m^{2}d)]). Rates were lower upstream, downstream and beside the stand. In general, high trapping rates were measured at the upstream margin of the vegetated area, where flow velocity was decreased.

Between May and September, phosphorus was retained by deposition by as much as 12.2% (% of total load). Macrophytes contributed considerably to the total monthly load-weighted P-retention (up to 25%) by increasing deposition of particulate organic matter.

Table 9.1 Mean monthly retention of nitrogen and phosphorus by deposition in stands of three macrophyte species during the vegetation period.

Macrophte species	Nitrogen	Phosphorus
	[g m^{-2} month^{-1}]	
Sagittaria sagittifolia	2.3-0.9	1.5-0.6
Nuphar lutea	1.6-0.6	0.8-0.3
Potamogeton pectinatus	1.4-0.5	0.8-0.3

Schulz *et al.* (in press) found at the end of their study period that the complete organic surface layer deposited during the vegetation period in summer had disappeared short time after the senescence and abrasion of macrophytes in the entire investigated river reach, except for dead zones and downstream of wood debris. Additionally, organic layers of river substrates at greater sediment depth indicated incomplete erosion of organic substrates during autumn and winter.

Pöthig *et al.* (prep.) measured P content in sediments in a lowland river in north-eastern Germany. During early spring a P-content of 0.4-3 g P/kg dry sediment and N-content of 5.6-7.4 kg N/kg dry sediment were measured. With the macrophyte harvesting in October 2001 also the upper sediment was removed. During the study period 8.1 kg P and 32 kg N was accumulated in the sediment within 6 months after harvesting (until spring 2002). During low-flow conditions and river loads less than 50 g/d P-sorption led to enrichment in the sediment, or new material precipitated on the sedimentation. During the dry period in summer no runoff was measured. Following this dry period high rainfall and run-off occurred in September, and still high retention rates were measured. Finally, negative retention was measured at the end of the wet period, but a total positive net retention of 2.75 kg (60 % of the total P input) was nevertheless determined for 2001.

On the other hand, Svendsen *et al.* (1999) reported high P transport during storm events, especially during months following prolonged periods with low flow. This was explained by resuspension of retained P in the sediments. Moreover, slightly increased DRP levels were measured during the rising limb of storm hydrographs. Harm *et al.* (1978) reported increased DRP concentration during storm events as a result of the release of interstital water from resuspended sediment, and Casey & Farr (1982) found that sediment release increased during an artificial spate.

Table 9.2 Phosphorus and nitrogen content in sediments measured in different sections of the Bsuchgraben (Pöthig *et al.* (prep.).

River section	Spec. P content	Spec. N-content	Total P-content	Total N-content
	[gP/kg DW]		[kg]	
B1	1.48	5.63	0.19	0.74
B2	1.72	7.44	1.24	5.34
B3	3.00	7.06	1.39	3.27
B4	2.77	7.14	0.83	2.14
B5	2.88	7.21	2.36	5.90
B6	0.42	6.68	0.40	6.47
B7	1.32	6.17	1.72	8.00
Mean*/total**	1.73*	6.79*	8.10**	32.00**

Beusekom & De Jonge (1998) measured continuously increasing TP load with increasing discharge, due to enhanced resuspension and transport of particles, which accounted for 61% of the TP load. Dissolved inorganic P (DIP) was not related with river discharge.

Nutrient retention by aquatic plant uptake only occurs during the vegetation period and is only temporally as stored P is decomposed to DRP or DOP after the senescence (and abrasion). Therefore, nutrient retention due to biomass uptake and following deposition of plant matter is often considered to be of little importance in comparison with sedimentation (Körner, 1995).

Svendsen at al. (1995a) could explain the DRP retention partly by a biological P uptake in benthic algae and partly by adsorption to Fe and Al oxides and hydroxides (long residence time favours adsorption reactions). The maximum P content in algae was found to be 0.64gP/ m². Casey & Clark (1986) documented that P uptake by algae can be of great importance as it corresponded to 50% of DRP transport in April in their study. The main part of the biomass is decomposed and released within a few days, but as the main residence time in the River Gjern Å watershed is only 6 to 12 hours, resuspended algae could easily escape as POP before being decomposed to DRP or DOP.

In some lowland rivers macrophytes are removed from the river, which means a real loss of nutrients from the river system. Pöthig *et al.* (in prep.) measured the N and P content in submerged and emerged aquatic plants (Table 9.3).

Table 9.3 Specific P and N content in macrophytes measured in Buschgraben and Uppstallgraben.

Plant name	spec. P-content [g/kg DW]	spec. N-content [g/kg DW]
Buschgraben		
Praghmites australis	0.89	13.35
Carex acutiformis	1.47	12.20
Glyceria maxima	1.79	8.22
Typha latifoglia	2.82	13.51
Berula erecta	3.19	28.47
Glyceria fluitans	2.04	12.69
Sparganium erectum	1.60	12.58
Mixed plant communities	1.68	13.10
Mean	1.30	12.74
Uppstallgraben		
Mixed Phalaris arundinacea & Urtica dioica	4.01	26.22
Phalaris arundinacea	3.55	26.20
Mixed Phalaris arundinacea & Mentha aquatica	3.58	27.70
Phragmites australis	2.33	36.00
Carex acutiformis	1.51	19.50
Glyceria maxima	2.74	22.30
Mentha acquatica	3.65	32.30
Mean	3.29	27.01

9.4   Methods applied in phosphorus retention studies in streams

The retention rate of phosphorus is described in several different ways. On one hand, figures found in the literature are related to different processes and substance. On the other hand, different units and calculation approaches are used. In most cases the information provided in the publication is not sufficient for transferring the figures in one comparable unit. Great difficulties also occur when comparing TP retention with SRP uptake length. SRP is usually transferred to POP or PIP but with

this it is not removed from the water column. Additionally, because of the strong relation of P-retention to seasons, investigations are often only conducted in summer.

- The most common way is to calculate the retention as percentage of the river load or the emissions.

- Especially for tracer experiments, retention is given as uptake length in [m]. Unfortunately, the uptake length is not calculated consistently. Marti & Sabater (1996) defined it as nutrient uptake rate [1/s]/flow velocity. Haggard *et al.* (2001), on the other hand, calculated the uptake rate as –1 divided by the slope of the line of the proportion of nutrients remaining in the water versus distance downstream. Both papers also give the linear uptake rate, but consequently they were also defined differently:

$$U = \frac{C \cdot Q}{S_W \cdot W} 60 \quad [\mu g/(m^2 \cdot min)] \qquad\qquad U = \frac{C \cdot Q}{S_W} \quad [mg/(m^2 \cdot s)]$$

Marti & Sabater (1996)   Haggard *et al.* (2001)

with: C   = background concentration [mg/l]

            Q   = stream discharge [l/s]

            SW   = uptake length [m]

            W   = average river width [m]

Sedimentation rates are given in these two units [g/m²] or [g/kg], whereas sediment surface area or mean density are not always given in the paper.

9.5   Reported nutrient retention rates

Haggard *et al.* (2001) examined the relationship between transient storage zones (backwaters, deep pools and the hyporheic zone, i.e. deep alluvial sediments where surface water and ground water often mix) and nutrient retention. Cherokee Creek, constrained with shallow bedrock underneath bentic substrates, had the smallest transient storage cross-sectional area and the longest uptake length. In agreement with Valett *et al.* (1996) an exponential decrease in uptake length with increasing transient storage size was shown. The SRP uptake rate (U) decreased with increasing flow velocity but increased with increasing ambient SRP concentration. Mean flow velocity and transient storage size were important determinants of SRP retention in these rivers.

Table 9.4: Hydrologic parameters in Cherokee Creek, Cloud Creek and Dry Creek.

Date	Q [l/s]	A_s [m²]	SRP [mg/l]	S_w-SRP [m]	U [mg/(m·s)]
			Cherokee Creek		
27 July 99	140	0.2	0.030	900	4.7
3 Aug 99	125	0.5	0.028	580	5.7
19 Aug 99	115	0.8	0.032	200	17.9
14 Jan 00	135	0.3	0.028	-	-
			Cloud Creek		
19 July 99	140	4.6	0.029	339	12.8
27 July 99	110	1.4	0.032	257	13.8
6 jan 00	135	3.1	0.032	-	-
21 Jan 00	80	0.6	0.027	-	-
			Dry Creek		
19 July 99	140	1.8	0.006	371	2.1
3 Aug 99	110	3.4	0.012	248	5.1
6 Jan 00	130	2.9	0.011	-	-
14 Jan 00	85	2.7	0.010	-	-

Q = discharge; A_s= absolute transient storage zone, dispersions coefficient,   = transient storage exchange coefficient ; Length = length of study reach, T_m=median travel time or time required to reach one-half of plateau.

Svendsen and Kronvang (1993) measured P-retention in the River Gjern Å in summer. It amounted to 8.4 kg P/day (June, July and August 1987) and 5.4 kg P/day (June, July and August 1988). Likewise, Doroiz *et al.* (1989) measured a retention of 9 kg P/day in the Redon river of France during a steady flow period. Svendsen *et al.* (1995) conducting in situ measurements (retention in sediments) of P content in sediments found that the maximum amount of P stored in the Gelbæk brook during summer (June to August) was 22 g P/m² (1988) compared with 27 g P/m² (1987) in the River Gjern Å. On an annual basis instream retention was found to be negligible (400 kg P; 3.5 %) compared with the P-export (11640 kg P) from the whole watershed

Schulz *et al.* (in press) measured particulate P-retention with plate traps ranging between 0.5 and 192 µg P m^{-2} d^{-1}, demonstrating a high heterogeneity of seston sedimentation. However, concentration of seston (dry weight l^{-1}) had only a moderate impact on sedimentation (r²= 0.39).

Salvia *et al.* (1999) studied phosphorus and nitrogen concentrations and fluxes during stable low-flow conditions in the transnational upper Sûre watershed (428 km², Belgium-Luxemburg) applying the 'Snapshot' sampling method. Sampling was undertaken within 12h at 50 sites throughout the basin after a period of two weeks without any rainfall. As to point sources, the slaughter house stands out because of its high P-concentrations (input from the sl. house is about 2.5 kg TP/day). 2 km downstream TP had already decreased by 60%. For the other river stretches, no significant retention could be observed.

9.6   Models describing phosphorus retention

Ziegler *et al.* (2000) developed and applied a model on sediment transport dynamics for the upper Hudson River. The model was applied to sediment-related PCB transport, but is probably suitable for other substances too. The model implies different sub-models for sediment transport, deposition processes, cohesive and non-cohesive resuspension processes, river bed properties and a hydrodynamic model. The model is described quite explicitly and some of the approaches and ideas could also be transferred to P-retention.

De Klein (subm.) delivers a conceptual approach to describe the seasonal variation of riverine nutrient retention. It was developed and tested for 4 Dutch lowland rivers with a catchment size ranging between 48 and 336 km². Monthly emissions from point and diffuse sources were compared with the river load from 1998-1999.

From the annual emission monthly emissions are derived using:

$$M_{i,sw} = \frac{Q_i}{Q_t} * L_D + \frac{L_P}{12}$$

where: $M_{i,sw}$ = monthly emission to surface water (kg/ha), i =index for month

Q_i = average monthly discharge (m³)

Q_t = average annual discharge (m³)

L_D = total annual diffuse emission (kg/ha)

L_P = total annual point source emission (kg/ha)

The river load was calculated as:

$$M_{i,c} = M_{i,sw} - \left(M_{i,sw}\right)^a * R_i$$

where: $M_{i,c}$ = catchment export mass load in month i (kg/ha)

R_i = retention coefficient (-)

a = coefficient for mass load-weighted retention (-)

The nitrogen retention coefficient can be calculated from:

$$R_i = Rb * AR_i^{\,b} * K^{Ti-20} * c$$

where: Rb = normalised retention coefficient (-)

AR_i = area specific runoff (= Q_i / catchment area) (m3/s/ha)

K = temperature coefficient (-)

T_i = average monthly temperature (ºC)

b = calibration coefficient

c = unit correction (value set as1)

The phosphorus retention was assumed to depend also on the slope and flow length:

$$R_i = Rb * AR_i^{\,b} * K^{Ti-20} * c * \left(\frac{LM}{SL}\right)^d$$

where:　　　　　LM = length of the river main stream (km)

　　　　　　　　SL = average slope of the river main stream (m/km)

　　　　　　　　d = calibration coefficient

Behrendt and Opitz (2000) found that the mean annual transport or load of nutrients in a river system (L_P) within a certain time period is the result of the sum of all point (E_{point}) and all diffuse ($E_{diffuse}$) emissions (EP) reduced by the sum of all nutrient and retention and losses (R_P):

$$L_P = E_P - R_P = \sum E_{point} + \sum E_{diffuse} - \sum R_P$$

Because the river basins differ in size, it is essential to eliminate the influence of the catchment area when comparing river basins. Behrendt (1996) has shown that the use of the ratio of load to the sum of emissions is one possible way of normalisation:

$$\frac{L_P}{E_P} = \frac{1}{1 + R_{LP}} \quad \text{or} \quad R_{LP} = \frac{E_P}{L_P} - 1$$

where:

　　　　　　　　R_{LP} = transport-weighted sum of all retention and losses (R_P divided by L_P)

The load-weighted nutrient retention can be described with the following statistical model:

$$R_{LP} = a \cdot x^b$$

with:

　　　　　　　　x　　　　= driving force (specific runoff q)

　　　　　　　　a, b　　= model coefficients.

Using the solver tool from Excel following coefficient were derived:

$$L_P = \frac{1}{(1 + 26.6 \cdot q^{-1.71})} E_P.$$

The regression analysis shows that the specific runoff has the highest influence on the total variance for phosphorus. About 80% of the variance of the phosphorus retention is explained by the dependency on specific runoff. Hydraulic load only explains 61%. Therefore, phosphorus retention is practically only controlled by specific runoff.

De Witt (1999) used the local drain direction map (LDD) to route the nutrients through the river system. The LDD is a representation of the drainage network that can be used to model the transport of material from upstream cells to downstream cells. In each cell that has to be traversed a certain fraction of the nutrient load is lost. It appeared that the flow regime is a major factor affecting N- and P-losses in the river network. The fraction (*tf*) that is transported from one cell to the lowest neighbouring cell is therefore estimated as a function of discharge, slope (taken from a DEM) and occurrence of lakes.

If the discharge is zero, *tf* must be zero too and it is assumed that *tf* approaches 1 with increasing discharge.

$$tf = 1 - \frac{1}{1 + ((rn_1 \cdot ((1000 \cdot slope) + 1)) \cdot q_d{}^{rn_2})}$$

where

> tf = transport fraction: output to downstream cell/total input to the cell [-]
>
> q_d = average discharge in the cell [m³/s]
>
> $slope$ = slope derived from 1 km²-elevation map [km/km]
>
> rn_1 = parameter to describe the loss in the river network [s/m³]
>
> rn_2 = parameter to describe the loss in the river network [-].

The exact values of rn_1 and rn_2 were estimated by calibration using 5-year mean N- and P-loads from monitoring station all over the river Rhine network (1970-1995).

The model parameter rn_1 is used to quantify the change of the value *tf* through the river system, whereas rn_2 is used to quantify 'basic' loss in a segment of the river network. Discharge (q_d) in lakes is estimated as the discharge at the outlet of the lake divided by the area of the lake (derived from the land cover map). This implies that *tf* is smaller in lakes than in rivers. Moreover, *tf* decreases with increasing size of the lake. It can be assumed that the absolute loss [kg/yr] in each river segment (1km) increases in the downstream direction, because the total nutrient river load increases in downstream direction. Yet the relative loss (1-tf) will decrease in downstream direction, because the ratio between the volume of a river segment [m³] and the surface of a river bed [m²] in general decreases in downstream direction.

10. Review of nutrient retention in wetlands and on riparian floodplains

10.1 Nitrogen removal in floodplains

Natural systems – internation studies

Many international studies have shown that nitrogen removal takes place in different systems ranging from riparian forest, bogs, marshes, fens and wet meadows (Table 10.1). These systems receive nitrate with groundwater discharging from recharge areas that are often cultivated and therefore enriched in nitrate content. Moreover, many riparian natural wetlands systems receive an input of nitrate from rivers during inundation of the floodplains during high flow periods. In some catchments, nitrogen removal in natural wetlands during either the passage of groundwater or during inundation with river water can be of great importance (Table 10.1).

Table 10.1 Nitrogen retention in different riparian meadows, fens, bogs and marshes.

Type	Area ha	Fraction of N	Load	Leachin	Reten.	Reten %	Water balance	Reference
			----kg N ha^{-1} y^{-1} ----					
Bog	3.24	Ammonium	2.249	0.706	1.543	69	Precip,	Verry & Tim-
Picea mariana,		Nitrate	2.041	0.278	1.763	86	surface	mons, 1982
Sphagnum		Organic	8.407	5.388	3.019	36	water,	
		Total N	12.696	6.374	6.322	50	groundwater uncertain	
Floodplain,	90.5	Nitrate	9.246	0.351	8.895	96	Calculated with assump-tions, uncertain	Yates & Sheridan, 1993
Hardwood, Juncus sp								
Riparian,	470	Precipitation	12.2				Precipitation,	Lowrance *et*
hardwood,		Total N, gw	29.0			68	surface water	*al.*, 1983, 1984
Acer rubrum, Liriodendron t.,		N-fixation	10.6				and ground-	
Nyssa sylvaticus,		Denitrific		34.5			water,	
Magnolia virgiana		Sum N	51.8	13.0	38.8	75	uncertain	
		Sum N + d	51.8	44.5(+d)	73	14		
Deciduous forest, riparian,	5.9	Precipitation	14.2				Precipitation,	Peterjohn &
hardwood		Ammon$_u$, s			0.219	78	surface water	Correll, 1984
Liriodendron tulipifera, Fagus		Organic-N$_p$, s			11.2	86	and	
grandifolia, Acer rubrum,		Nitrate, s			2.71	79	groundwater	
Liquidambar styraciflua,		Ammon$_o$, s			0.827	73	Description	
Nyssa sylvaticus, Quercus		Organic-N$_o$, s			0.568	62	missing	
falcata		Total N, s	32.2	2.3	29.9	93		
		Nitrate, gw			45.5	94		
		Ammon, gw			-0.917	-480		
		Organic-N, gw			-0.194	-144		
		Total N, gw	51		44.1	86		
		Sum N	83.2		74	89		
Bog, Acer rubrum,	?	Ammonium	3.31	4.04	-0.73		Only runoff	Peverly, 1982
Phalaris arundinacea		Nitrate	80.3	78.66	1.64	0.2	surface water	

Table 10.1 continued

Type	Area ha	Fraction of N	Load	Leaching	Reten.	Reten %	Water balance	Reference
			---kg N ha^{-1} y^{-1} ----					
Marsh Typha sp	156	Nitrate				51	Only runoff surface water	Fetter *et al.*, 1978
Marsh, Carex sp Typha, grasses	640	Nitrate				61	None,only conc.	MacCrim-mon, 1980
Rich fen, Carex diandra Caltha palustris Menyanthes trifoliata Potentila palustris Equisetum fluviatile	0.32	Precipitation inorganic,s Organic,s N-fixation Denitrificat. Inorganic,gw Organic,gw Sum N	42.0 0.2 1.1 12.7 17.0 2.6 75.6	6.6 14.3 (1.1) 0.1 0.2 21.2	-6.4 13.2 16.9 24 54.4	72	Complete all parameters measured	Koerselman *et al.*, 1990
Fen transitional, Phragmites australis, Carex acutiformis, Sphagnum sp	0.15	Precipitation inorganic,s Organic,s N-fixation Denitrificat. inorganic,gw Organic,gw Sum N	43.7 1.2 6.1 2.1 0.0 0.0 53.1	1.9 7.4 (1.4) 0.2 0.8 10.3	-0.7 -1.3 -0.2 -0.8 42.8	81	Complete, all parameters measured	Koerselman *et al.*, 1990
Wet meadow, grasses	48.6	Precipitation Total N, s Total N, gw Sum N	11.3 20.3 671.4 703.0	552	151	22	Surface water, ground-water, complete	Novitzki, 1978
Wet meadow, Poa pratensis, Alopecurus p., Ranunculus repens, Phalaris arundinacea, Glyceria maxima	0.25	Precipitation Ammon, gw Nitrate, gw Denitrific. Sum N	21.3 6.9 32.1 60.3	1.9 0.005 (31.1) 2.0	5.0 58	72 96	Complete all para-meters measured	Hoffmann et al, 1993

Table 10.1 continued

Type	Area ha	Fraction of N	Load	Leaching	Reten.	Reten %	Water balance	Reference
			----kg N ha^{-1} y^{-1} ----			%		
Beaver pond	3.81	Precipitation	9.8				Complete	Devito *et al.*,
Sphagnum sp		Ammonium	2.4	5.5			all	1989
Labrador tea		Nitrate	3.4	4.0			parameters	
		Organic N	18.4	23.1			measured	
		Sum N	34.0	32.6	1.4	4		
Conifer swamp	1.13	Precipitation	9.8				Complete	Devito *et al.*,
Picea mariana		Ammonium	0.2	0.4			all	1989
Alnus sp		Nitrate	9.8	8.5			parameters	
Sphagnum		Organic N	16.6	27.5			measured	
		Sum N	36.4	36.4	0.01	<1		
Conifer swamp	2.12	Precipitation	9.8				Complete	Devito *et al.*,
Picea mariana, Thuja		Ammonium	0.0	0.1			all	1989
occidentalis		Nitrate	0.2	1.6			parameters	
Alnus sp,Ilex verticillata,		Organic N	5.1	13.3			measured	
Sphagnum		Sum N	15.1	15.0	0.01	1		
Sedge fen	0.1	Precipitation	9.9				Complete	Devito *et al.*, -
Carex sp		Ammonium	0.5	2.6			all	1989
		Nitrate	30.5	27.0			parameters	
		Organic N	63.9	69.8			measured	
		Sum N	104.8	99.4	5.4	5		
Wet meadow, grasses	0,16	Nitrate	707	317	390	55	Surface water	Brüsch & Nielsson, 1990

Natural systems – Danish experiences

In Danish natural freshwater wetlands receiving groundwater recharge (i.e. minerotrophic wetlands), nitrogen removal varies from 57 kg N to >2100 kg N ha^{-1} yr^{-1}. The relative removal varies only from 56-97%, without any clear correlation between loading and efficiency (Table 10.2 and 10.3). Thus, there is a huge capacity of Danish freshwater wetland soils for nitrogen removal through denitrification. The nitrogen loading to the wetlands reflects upland characteristics such as land use, precipitation surplus, drainage conditions, soil type, the groundwater flow pattern, etc. Some of the overall factors characterising wetlands recharged by groundwater and examples on their ability to remove nitrogen will be given in this section.

At the River Stevns, the concentration of nitrate in recharging groundwater to the meadow varied from 15–30 mg NO_3^--N l^{-1}. Nearly 74% of all upland groundwater was discharged directly into River Stevns through drainage pipes. Only 57 kg N was retained in the meadow, of which 31 kg N ha^{-1} y^{-1} was denitrified, while on average 89 kg N were removed from the meadow through haymaking. Thus, nitrogen removal from the meadow was higher than the input to the meadow (total input: 60 kg N - total output: 120 kg N).

The wet meadow at the Rabis brook is recharged by nitrate-rich groundwater, which at the valley slope breaks through to the soil surface and irrigates the meadow naturally (Table 10.2). This is possibly the reason why the relative nitrogen removal is so low (56%), since the nitrate has to move by advective flow or by diffusion to the active denitrification sites close to the soil surface.

Wetlands with different hydraulic regimes have been studied for several years in the River Gjern catchment area (Table 10.2). Nitrogen turnover has been studied intensively in a 73-metre wide water-covered fen (area B, Table 10.2), and particularly high rates of denitrification have been found in the area around the river valley slope. Over a distance of only 13–17 m, the nitrate concentration decrease from approx. 25 to 0.01 mg NO_3^--N l^{-1}, corresponding to a denitrification rate of 1-5 g N m^{-2} d^{-1}, depending on where in the zone of enhanced denitrification sampling is undertaken (Blicher-Mathiesen, 1998; Hoffmann, 1998a; Hoffmann et al., 2000b). Only a few other studies have hitherto reported denitrification rates of this magnitude, e.g. Cooper (1990)(8.1 g N m^{-2} d^{-1}), Haycock and Burt (1993) (0.74 g N m^{-2} d^{-1}), Haycock and Pinay (1993) (up to 10 g N m^{-2} d^{-1}) and Jørgensen et al. (1988) (2.1 g N m^{-2} d^{-1}).

Table 10.2 Nitrate removal in different riparian wetlands with groundwater recharge (flow through). %: percentage of incoming nitrate loading removed (From Hoffmann, 1998).

Locality	Nitrate removal rates (kg NO_3^--N ha^{-1} $year^{-1}$)	Reduction (%)
River Stevns, meadow	57	95
Rabis brook, meadow	398	56
River Gjern:		
A, meadow	140	67
B, fen (1993)	2100	97
B, fen (5 years)	1079	97
C, meadow (5 years)	541	96
D, meadow (5 years)	398	97

Rehabilitation of fens, wetlands and wet meadows in floodplains

In most European countries, watercourses has been modified by man for various purposes, for example flood control, drainage of surrounding land, navigation, etc. In countries like Denmark with an intensive agricultural production, more than 90% of the total river network has been regulated to some extent (Iversen et al., 1993). Watercourses were straightened and channelised to ensure sufficient drainage of the floodplains.

Nowadays we restore many of our rivers by reinstating their former meandering course (Kronvang et al., 1998). Hence, former fens, wetlands and wet meadows are reinstated in our river valleys by re-meandering the river channel, elevating the river bed and disconnecting drains and ditches and this also leads to increased nitrogen removal (Table 10.3). Table 10.3 shows the nitrogen removal rates obtained at two river restoration sites in Denmark. Considerable variation in the groundwater flow pattern was found both along the river and from riverside to riverside, implying that nitrogen transport and removal vary significantly (Hoffman et al., 1998; Hoffmann et al., 2000a).

Table 10.2 Examples of nitrogen removal rates measured in two Danish river valleys with groundwater recharge following re-meandering of the river channel. Both studies were conducted in the first year following the river restoration (1995/96). (From Hoffmann *et al.* 1998, 2000a).

Locality	Kg NO_3^--N ha^{-1} $year^{-1}$	%
River Brede, large-scale, meadow (63 ha)	92	71
Headwaters of River Gudenå, large-scale, meadow (57 ha)	8.4	57

Irrigation of meadows with drainage or river water

Experiments involving irrigation of meadows and reed forests with drainage water or river water have also yielded promising results with respect to nitrate reduction. The extent of nitrate removal depends primarily on the amount of water infiltrating the soil. Therefore, the size of the area to be irrigated needs to be adjusted to the amount of water it is expected to receive. In an irrigation experiment alongside the River Stevns, where all the water input to the area infiltrated the soil, 99% of the nitrate was denitrified in the uppermost 2 cm of the soil profile (Table 13) (Hoffmann *et al.*, 1993). In the same study, nitrate reduction was also measured on a plot of the meadow that had been fed with tile drainage water for approx. 100 years via a drainage conduit terminating on the river valley slope. Over a distance of 45 metres, the nitrate concentration fell from 11.3 mg NO_3^--N l^{-1} at the conduit outflow to 0.1 mg NO_3^--N l^{-1} midway into the meadow, i.e. a reduction of 99% (Hoffmann *et al.*, 1993).

When part of the irrigation water is discharged as surface runoff, the relative nitrate removal decreases to between 48% and 72% according to the studies hitherto undertaken at Syv Bæk brook (Hoffmann, 1991), Lake Glumsø (Hoffmann, 1986; Jørgensen *et al.*, 1988) and the River Storå (Fuglsang, 1993; 1994) (Table 4.3), this being attributable to the fact that denitrification does not occur in the surface water due to the prevailing oxic conditions. Any nitrogen removal occurring in the surface water must therefore takes place through algal uptake, uptake into the microbial pool or sedimentation of particulate nitrogen.

Irrigation of riparian areas with tile drainage water can only be undertaken during periods when water is flowing in the drains. In consequence, the operational period highly depends on local conditions such as the amount of precipitation, soil type etc. The annual rates given for the meadows at the River Stevns and Syv brook shown in Table 13 are thus calculated for the period during which they were actually irrigated by drainage water, i.e. 120 and 200 days, respectively.

A short-term irrigation and flooding study at the lower reaches of the River Gjern shows that nitrate reduction occurs in the uppermost part (0-2 cm) of the soil in areas subjected to regular flooding or irrigation events (Hoffmann, 1996; Hoffmann, 1998b). Although the infiltration capacity is low at the Gjern study site, the results show reduced nitrate values even during short-term flooding/irrigation events. It means that apart from being important for sedimentation, naturally meandering rivers and their riparian areas serve as a functional unit and a stabilising ecological factor for the aquatic environment.

Table 10.3 Nitrate removal by irrigation with time drainage water or stream water. The removal rates obtained during irrigation with tile drainage water take into account the periodicity of tile drainage runoff (in Denmark, highest runoff in winter and spring: October to May).

Locality	Kg NO_3^--N ha^{-1} year^{-1}	%
Glumsø, reedswamp§	520	65
Glumsø, reedswamp§	975	62
Glumsø, reedswamp§	2725	54
Glumsø, large-scale, reedswamp§	569	94
River Stevns, meadow*	350	99
River Stevns, meadow with drainage pipes!	(conc.) 11.3	99
Syv brook, meadow	300	72
River Storå, restored meadow	530	48
River Gjern, meadow*§ (min)	34	88
River Gjern, meadow*§ (max)	200	98

* Short-term experiment.

§ Different hydraulic loading and different nitrate loading.

! Concentration given in mg NO_3^- -N l^{-1}.

10.2   Phosphorus storage on inundated floodplains

Asselmann (1997) reported a net loss of sediments from the river system due to overbank sedimentation. She showed that during an extreme flood event in 1993, 19% of the total sediment load transported be the River Waal (tributary of the Rhine in the Netherlands) had been deposited in the floodplain. Heusch *et al.* (1993) analysed erosion and accumulation of sediments in a floodplain section along the River Sieg (tributary of the Rhine) and concluded that erosion and sedimentation were almost balanced.

Investigations by Svendsen *et al.* (1995a) on the mass balance of P for the main river channel of the River Gjern revealed that on an annual basis it acted as a net P source. Bank erosion was shown to explain a large part of residual of the mass balance (30-100%). Therefore bank and bed erosion should be regarded as a major P source in lowland rivers. It is probable that PP is stored in overbank deposits during floods and deposited interstitially in coarse bank material during the rising limb. The contribution of soil erosions, although unmeasured, was almost certainly insignificant.

By comparing the concentrations measured in the river with those at the outflow of the floodplain Kronvang *et al.* (2003) concluded that 81% of the suspended sediment and 40% of its particulate phosphorus content are retained on the floodplain.. Gross and net sedimentation in the inundated floodplain were nearly identical, indicating either no re-suspension or no sedimentation of very small particles, which would easily be re-suspended. Reduced efficiency of the floodplain to retain particulate phosphorus was explained by the enrichment of phosphorus in fine particles that easier escape the deposition process. Increasing phosphorus content in the deposited material with increasing distance from the river (0.41% at 20 m to 0.72% at 60 m) supports that idea. Re-suspension seemed only to occur close to the river channel in the in- and out-flow area of the floodplain. This can be explained by the higher flow velocities in these areas (30-50 cm/s) compared with an average flow velocity of 3.2 cm/s in the entire flooded area. This, in turn, corresponds with an exponential decrease in the deposition rate of suspended sediment with increasing distance from the river channel during overbank flooding. Comparison of the entrapment efficiency of the floodplain with the transport of suspended sediments in the river reveals a retention rate of 5.6-23.9% (1.18-6.50% of the P river load) during the 3 overbank floods. The maximum measured sedimentation rate was 3,000 g sediment m^{-2} and 6.5 g P m^{-2} during a 19-day over bank flooding. A mean annual deposition of sediment and particulate phosphorus of 2,1000 g DW/m² and 8.2 gP/m² was calculated for a 10-year period, which

is within the same range as the sedimentation rate of 3,000 gDW/m² reported by Walling *et al.* (1996) in the floodplain of the River Culm, UK.

11.　References

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