MTT REPORT 94

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Jari Koskiaho, Markku Puustinen, Kauko Koikkalainen, Tapio Salo, Kristjan Piirimäe

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# Maatalouskosteikkojen ja valumavesien aktiivisten puhdistusmenetelmien kustannustehokkuuden arviointi ja mallintaminen

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## Tiivistelmä

Suomessa ja Virossa tutkittiin pieniin kosteikkoihin tai ja pelto-ojiin asennettavien kemikaalikäsittelyjen (aktiivikosteikko) toimivuutta maataloudesta peräisin olevan fosforin pidättämisessä. Tässä Active Wetlands -hankkeen osaraportissa mallinnettiin koelaitteistojen erikokoisilla sijaintivaluma-alueilla saavuttamia fosforin pidättämistuloksia, ja verrattiin tuloksia samoille valuma-alueille tehtyjen kosteikkosimulaatioiden ("perinteiset" maatalouden vesiensuojelukosteikot) kanssa. Lisäksi arvioitiin aktiivi- ja perinteisten kosteikkojen kustannustehokkuutta.

Mallinnus tehtiin viidelle kohdealueelle Suomessa ja yhdelle koealueelle Virossa. Käytetyt mallit olivat päivittäistä aika-askelta käyttävä prosessipohjainen SWAT, empiirinen VIHMA ja paikkatietoon perustuva RasterMode malli. Mallien lähtötietoina käytettiin saatavissa olevaa GIS- ja muuta valuma-aluetietoa ja niiden parametrit valittiin aikaisempien tutkimusten ja tässä hankkeessa tehtyjen kokeiden tulosten perusteella.

SWAT mallilla tehty kosteikkojen sijoittelustrategian simulointi osoitti, että useiden kosteikkojen perustaminen valuma-alueen eri osiin oli selvästi tehokkaampaa kuin rakentaa yksi suuri kosteikko valuma-alueen purkupisteeseen. Molemmissa tapauksissa kokonaiskosteikkoala valuma-alueella oli samansuuruinen. Myös kemikaaliannostelijan kustannustehokkuuteen sijoituspaikan valinnalla on ratkaiseva merkitys. Korkean fosforipitoisuuden valumavesiä käsiteltäessä niin luontaisten prosessien kautta pidättyvän kuin kemikaalilla saostetunkin fosforin määrä on huomattavasti suurempi kuin silloin, kun valumaveden fosforipitoisuus on alhainen. Siten niin rakennetut kosteikot kuin kemikaalikäsittelytkin tulisi sijoittaa mahdollisimman lähelle kuormituslähteitä. Tässä suhteessa "hotspot" kuormittajiin, kuten navetat, maitohuoneet, hevostallit jne. kannattaa kiinnittää erityistä huomiota. RasterMode malli osoittautui käyttökelpoiseksi kosteikkojen suunnitteluapuvälineeksi ja hyödylliseksi myös arvioitaessa fosforin pidättymistä. Tulosten perusteella sekä perinteiset rakennetut kosteikot että aktiiviset toimenpiteet ovat kustannustehokkaita vesiensuojelumenetelmiä sillä edellytyksellä, että ne on suunniteltu ja toteutettu huolellisesti ja sijoitettu oikeisiin paikkoihin.

**Avainsanat:**
*fosfori, mallinnus, kustannustehokkuus, kosteikot, kemiallinen käsittely, saostuminen, pidättyminen, maatalous, valumavedet, rehevöityminen*

# Modeling, assessments and cost-effectiveness analysis of constructed wetlands and active methods for the treatment of runoff from agricultural areas

**Jari Koskiaho[1), Markku Puustinen[1), Kauko Koikkalainen[2), Tapio Salo[3), Kristjan Piirimäe[4)**

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## Abstract

In this project—conducted in Finland and Estonia—we studied different applications i.e. active measures, that can be used to boost the retention of dissolved phosphorus (P) in agricultural wetlands and field ditches. In this report, we show results from the catchment-scale modeling and assessments to estimate the cost-efficiency of active measures and constructed wetlands in retaining the P escaped from agriculture.

Modelling was conducted in five target areas in Finland and one in Estonia. The used models included process-based catchment scale SWAT model using a daily time step, empirical VIHMA model and catchment scale RasterMode model calculating annual P concentrations in surface waters. Available GIS- and other data from the catchments were used as input and parameters for the model were set according to the previous studies and P retention results of this project.

Wetland location strategy, as studied by SWAT model, showed that establishing several constructed wetlands on the upper reach of a catchment was much more effective than constructing one large wetland at the outlet of the same catchment. In both cases the total area occupied by constructed wetlands was equal. In terms of active measures, doser site selection was also crucial to cost-effectiveness. With diluted waters P precipitation will be substantially lower than with waters rich in P. Thus, locating constructed wetlands and active wetlands near the sources of loading is highly recommended. In this respect, "hotspots" such as cowsheds, milk houses, horse stables etc. should be of special interest when sites are selected. RasterMode model was observed as a useful tool for wetland planning and for estimating P retention of the selected measures.

Both traditional constructed wetlands and active measures, when decently implemented and wisely located, are cost-effective alternatives for water protection and thus worth serious consideration. However, because their cost-effectiveness depends greatly on suitable places, they cannot be recommended everywhere.

**Keywords:**
*phosphorus, wetlands, modeling, cost-efficiency, chemical amendments, phosphate retention, agriculture, runoff, eutrophication*

# Contents

# 1 Introduction

Modern agricultural production with efficient field drainage, soil tillage and fertilizing has led to increased loadings of suspended solids, nitrogen (N) and phosphorus (P) from arable areas. Consequently, this trend has induced negative impacts on the environment, such as the degraded quality of surface waters. In Finland, the most widely recognized problem has been the eutrophication of the Baltic Sea. Constructed and restored wetlands (CWs) are regarded as a potential tool for intervening in the nutrient leakage from arable land and the Baltic Sea water basin. CWs not only retain eroded soil and nutrients from incoming water, but also improve species biodiversity as well as the landscape by creating habitats different from the neighbouring fields. In CWs through-flowing waters are exposed to the natural water purifying mechanisms. Consequently, the building, or re-establishment, of wetlands restores some of the lost capacity of agricultural watersheds to retain floods, erosion and nutrient transport. In Estonia, the protection of existing natural wetlands is an important issue to maintain their beneficial effects on biodiversity and water protection. CWs disperse and slow down the inflowing water thus promoting the settling and deposition of suspended particles. Wetlands are also highly productive ecosystems in which plants and microbes break down, assimilate and cycle nutrients, organic matter and associated pollutants transforming them into less harmful forms. The soil of a CW may be beneficial for the chemical binding of P. Thus, the retention mechanisms in CWs can be categorized to physical, biological and chemical processes.

Although the nutrient retention processes are not at their most effective in low temperatures, there are encouraging experiences of wetland treatment in cold conditions. Hence, even in the Finnish climate CWs were regarded as a promising tool for the treatment of agricultural runoff in 1995 when Finland joined the EU and the first period of the Finnish Agri-Environmental Protection scheme (FAEP) was launched. Finnish research results (Koskiaho et al. 2003 and 2009, Koskiaho and Puustinen 2005) have revealed that such expectations were not unrealistic, and high annual retentions (up to 70%) were indeed measured in some cases. However, these studies also suggested that the prerequisite for the good functioning of a CW was a high CW-to-watershed area ratio. In Finnish CW design guidelines (Puustinen et al. 2007) based on our studies as well as international experiences, it was recommended that if 1-day residence time of water during mean annual maximum flood is the target, this ratio should be at least 1% if the upstream field percentage is low and at least 2% if it is high. However, in the present FAEP stipulations for CWs to be eligible for subsidy, the ratio is only 0.5% and in real-world planning cases even such a low ratio is often hard to achieve (Eskola et al. 2009). This dilemma is due to the typical situation in Finnish agricultural watersheds; the fields and thus favourable sites for CWs are often located near larger streams in their lower reaches, which means that the upstream watershed is in many cases large, even tens of square kilometers. On the other hand, farmers are understandably reluctant to convert very large field areas into CWs for fear of economic losses. Meanwhile in upper reaches where the above watershed and thus required CW area would be smaller, there are often no – or very few– farms with fields. For these reasons, Finnish agri-environmental CWs tend to be small in relation to their upstream catchments and their nutrient retention efficiency is presumably rather poor.

The Active Wetlands Project identified possible solutions to this drawback. The project concentrated especially on testing the potential improvement of phosphorus (P) retention in small-sized wetlands with chemicals commonly used in wastewater treatment plants to precipitate solids, organic matter and P (Work Package 2, WP2). In addition to on-site testing, the project also conducted catchment-scale modeling and assessments to estimate the cost-efficiency of, not only the tested active measures, but also CWs in general in retaining the P escaped from agriculture (Work Package 3, WP3). Derived from the results of these work packages, one of the objectives of the Active Wetlands project was to conclude and recommend how to incorporate agricultural wetlands and their active measures in the current water management policies, including the FAEP scheme. In this report, the results of modeling and assessments (WP3) are presented.

# 2 Material and methods

## 2.1 Modeling and assessment tools

### 2.1.1 SWAT

The SWAT model (Soil and Water Assessment Tool, Arnold et al. 1998, 2009) is a continuous time model that operates on a daily time step at catchment scale. It can be used to simulate water and nutrient cycles in agriculturally dominated large catchments. The catchment is generally partitioned into a number of sub-basins based on the threshold area which defines the minimum drainage area required to form the origin of a stream. The smallest unit of calculation is a unique combination of soil, land use and slope overlay, referred to as a hydrologic response unit (HRU). SWAT is partly a process-based model and partly a distributed model, including many empirical relationships. The water quantity processes simulated by SWAT include precipitation, evapotranspiration, surface runoff and lateral subsurface flow, ground water flow and river flow. Water quality processes are calculated with various well-known equations. For example, erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE, Williams 1977). In terms of P, the primary mechanism of soluble fraction movement in the soil is by diffusion. Organic and mineral P attached to soil particles may be transported by surface runoff to the main channel. For channel flow simulation, SWAT uses Manning's equation coupled with variable storage or the Muskingum routing method. Interactions and relationships of the QUAL2E model (Brown and Barnwell 1987) are used as in-stream water quality processes.

In terms of CWs, SWAT regards them as water bodies located within subbasins that receive inflow from a fraction of the subbasin area. The water balance for a CW is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad (1)$$

where

$V$= the volume of water in the CW at the end of the day ($m^3$)
$V_{stored}$ = the volume of water stored in the CW at the beginning of the day
$V_{flowin}$= the volume of water entering the CW during the day
$V_{flowout}$= the volume of water flowing out of the CW during the day
$V_{pcp}$ = the volume of precipitation falling on the CW during the day
$V_{evap}$= the volume of water removed from the CW by evaporation during the day
and
$V_{seep}$ = the volume of water lost from the water body by seepage

When calculating nutrient transformations in a CW, SWAT assumes that the system is completely mixed. In a completely mixed system, nutrients are instantaneously distributed throughout the volume as they enter the water body. The assumption of a completely mixed system ignores stratification and intensification of phytoplankton in the epilimnion. The initial amount of N and P in the water body on the given day is calculated by summing the mass of nutrient entering the water body on that day with the mass of nutrient already present in the water body. The initial concentration of nutrients in the water body is calculated by dividing the initial mass of nutrient by the initial volume of water. Nutrient transformations simulated in CWs are limited to the removal of nutrients by settling. Transformations between nutrient pools (Org.N ➔ NH4-N ➔ NO2-N ➔ NO3-N) are ignored.

Settling losses in the water body can be expressed as a flux of mass across the surface area of the sediment-water interface (Chapra 1997). The mass of nutrient lost via settling is calculated by multiplying the flux by the area of the sediment-water interface.

$$M_{settling} = v \cdot c \cdot As \cdot dt \quad (2)$$

where $M_{settling}$ is the mass of nutrient lost via settling on a day (kg)

v is the apparent settling velocity (m/day)

c is the initial concentration of nutrient in the water ($kg/m^3$)

$A_s$ is the area of the sediment-water interface ($m^2$)

and dt is the length of the time step (1 day).

The settling velocity is labeled as "apparent" because it represents the net effect of the different processes that deliver nutrients to the water body's sediments. The water body is assumed to have a uniform depth of water and the area of the sediment-water interface is equivalent to the surface area of the water body. The apparent settling velocity is most commonly reported in units of m/year and this is how the values are input to the model. For natural lakes, measured P settling velocities most frequently fall in the range of 5 to 20 m/year although values less than 1 m/year to over 200 m/year have been reported (Chapra 1997). Panuska and Robertson (1999) noted that the range in apparent settling velocity values for man-made reservoirs tends to be significantly greater than for natural lakes. A negative settling rate indicates that the reservoir sediments are a source of N or P and vice versa; a positive settling rate indicates that the reservoir sediments are a sink for N or P.

A number of inflow and CW properties affect the apparent settling velocity for a water body. Factors of particular importance include the form of P in the inflow (dissolved or particulate) and the settling velocity of the particulate fraction. Within the CW, the mean depth, potential for sediment resuspension and P release from the sediment will affect the apparent settling velocity (Panuska and Robertson 1999). Water bodies with a high internal P release tend to possess lower P retention and lower P apparent settling velocities than water bodies with low internal P release (Nürnberg 1984). Table 1 summarizes typical ranges in P settling velocity for different systems.

SWAT input variables that pertain to nutrient settling in CWs are listed in Table 2. The model allows the user to define two settling rates for each nutrient and the time of the year during which each settling rate is used. A variation in settling rates is allowed so that the impact of temperature and other seasonal factors may be accounted for in the modeling of nutrient settling. To use only one settling rate for the entire year, both variables for the nutrient may be set to the same value. Setting all variables to zero will cause the model to ignore settling of nutrients in the CW.

Table 1. Recommended apparent settling velocity values for phosphorus in different types of water bodies (Panuska and Robertson 1999).

| **Water body type** | **Range in settling velocity values (m/year)** |
|---|---|
| Shallow water bodies with high internal P loading | $v \leq 0$ |
| Water bodies with moderate internal P loading | $1 < v < 5$ |
| Water bodies with minimal internal P loading | $5 < v < 16$ |
| Water bodies with high P retention capacity | $v \geq 16$ |

Table 2: SWAT input variables that control nutrient settling constructed wetlands (CW).

| Variable | Definition |
|---|---|
| IPND1 | Beginning month of mid-year nutrient settling period for the CW modeled in subbasin |
| IPND2 | Ending month of mid-year nutrient settling period for the CW modeled in subbasin |
| PSETLW1 | Phosphorus settling rate in CW during mid-year nutrient settling period (*IPND1* ≤ *month* ≤ *IPND2*) (m/year) |
| PSETLW2 | Phosphorus settling rate in CW during time outside mid-year nutrient settling period ( *month* < *IPND1 or month* > *IPND2*) (m/year) |
| NSETLW1 | Nitrogen settling rate in CW during mid-year nutrient settling period (*IPND1* ≤ *month* ≤ *IPND2*) (m/year) |
| NSETLW2 | Nitrogen settling rate in CW during time outside mid-year nutrient settling period ( *month* < *IPND1 or month* > *IPND2*) (m/year) |

After nutrient losses in the CW are determined, the final concentrations of nutrients in the CW are calculated by dividing the final mass of nutrient by the initial volume of water. The concentration of nutrients in outflow from the CW is equivalent to the final concentration of the nutrients in the CW for the day. The mass of nutrient in the outflow is calculated by multiplying the concentration of nutrient in the outflow by the volume of water leaving the CW on that day.

Assuming that the volume of the water body remains constant over time, the processes described above (inflow, settling, and outflow) can be combined into the following mass balance equation for a well-mixed water body:

$$V \cdot (c/dt) = W(t) - Q \cdot c - v \cdot c \cdot A_s \qquad (3)$$

where $V$ = the volume of the system ($m^3$)
$c$ = the concentration of nutrient in the system ($kg/m^3$)
$dt$ = the length of the time step (1 day)
$W(t)$ = the amount of nutrient entering the water body during the day (kg/day)
$Q$ = the rate of water flow exiting the water body ($m^3$/day)
$v$ = is the apparent settling velocity (m/day)
and $A_s$ = the area of the sediment-water interface ($m^2$)

In this work, SWAT was used to assess the nutrient retention effects of CWs with different locating strategies in three target areas (Jokioinen and Paimelan Myllyoja catchments and Paimionjoki river basin). The two scenarios (see Figure 1) were

strategy a) One CW with 1% CW-to-subcathcment area ratio at the outlets of every subcatchment
strategy b) One CW with 1% CW-to-catchment area ratio at the outlet of the entire catchment

In other words there were many smaller CWs in the upper reaches of each catchment in strategy a) and one large CW located at the outlet of each catchment and in strategy b) (see Figure 1). The total acreage occupied by CWs for each catchment was equal in both strategies. Total P and total N loadings at the outlet point were calculated separately with these two strategies and compared with the corresponding loadings simulated for the same target areas without any CWs (0-scenario). Lieto catchment was so small that SWAT did not form any subcatchments. Thus, simulations of CW locating strategy were not applied there.

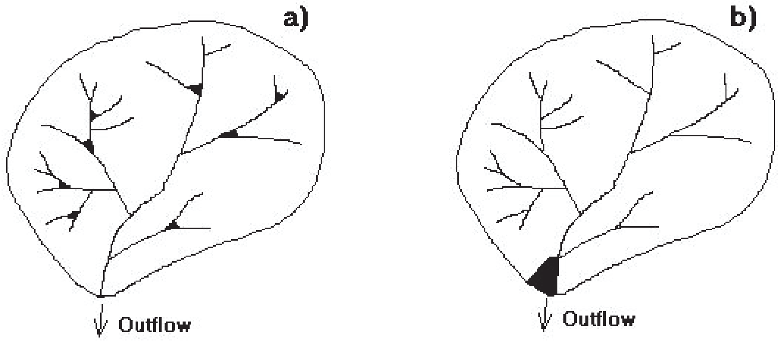



Figure 1. Two different location strategies of locating constructed wetlands. Several small wetlands in the upper reaches and along tributaries (a) and one large wetland at the outlet of the catchment (b).

### 2.1.2 VIHMA

The basic principle of the VIHMA tool is to integrate information on cultivation practices and characteristics of agricultural fields at the catchment-scale with the specific loading values based on the studies on various agricultural management practices and mitigation measures in Finnish experimental fields (Puustinen et al. 2010). In the first step, VIHMA calculates the initial loading to recipient waters according to existing characteristics (listed below) of the target catchment that are given as model inputs. Next step, the user can change the field management practices (tillage intensity and timing) and/or add off-field mitigation measures (CWs and buffer zones) in the target catchment.

Characteristics of a target catchment (VIHMA inputs) are as follows:

Tillage intensity (6 classes)

- Intensive autumn tillage (normal moldboard ploughing)
- Reduced autumn tillage (cultivator tillage or shallow stubble tillage)
- Winter-time vegetation cover (ploughing followed by winter wheat or winter rye)
- Winter-time stubble (tillage in spring)
- No-till (direct sowing in spring or in autumn)
- Permanent vegetation cover (grass ley)

Slope (5 classes)

- <0.5%
- 0.5–1.5%
- 1.5–3%
- 3–6%
- 6%

P status (3 classes)

- <8 mg $l^{-1}$
- 8–14 mg $l^{-1}$
- >14 mg $l^{-1}$

Soil type (4 classes)

- Clay (Ø<0.002mm, share >30%)
- Silt (Ø 0.002–0.02mm, share >50% and Ø<0.002mm share <30%)
- Coarse (remaining mineral soil)
- Organic

Of the above inputs, tillage intensity, slope and soil type are given as hectares distributed into the above classes of these three characteristics so that there are matrix tables of tillage intensity and slope in each of the soil type classes, which have their own tabs (sheets) in an Excel-file. P status is given as a percent distribution in the target catchment. By changing the initial distribution of tillage intensity, the user can make scenarios, such as how much the loading is reduced if intensive autumnal tillage in the steepest field plots is replaced by direct sowing. In terms of CWs, the user gives the field-hectares upstream the simulated CWs, for which he/she can choose different CW-to-catchment area ratios between 0.05% and 5% describing the dimensioning of CWs. In VIHMA, CWs with area ratios less than 0.3% are titled sedimentation ponds.

In this work, VIHMA was not only used to assess the overall nutrient loading from agriculture in the target catchments, but also to assess the CW effects at the catchment scale as a supplementary tool with SWAT. For this work, field-parcel level data of cultivation practices was available from so the TIKE database maintained by the Ministry of Agriculture and Forestry. P status was obtained at the municipal-level from the database maintained by Viljavuuspalvelu (Soil Analysis Service) of Finland. In terms of soil type and slope (land elevations), the data was available in the GIS-database of Finnish Environment Institute (SYKE). As for slope distributions, instead of the five above presented classes of VIHMA, three classes (<1.5%, 1.5–6% and >6%) were used in this work. For determination of CW effects, 1% CW-to-catchment area ratio was applied for the total field area in every target catchment.

### 2.1.3 RasterMode model

The aim of this modeling work was to determine the potential of constructed wetlands (CW) and active filters in the removal of excess phosphorus. The working hypothesis was that an extensive deployment of wetland measures could significantly improve the state of Estonian waterbodies.

For the modelling of the Vända ditch, the Ministry of Environment's principal calculator (2006) was used. To the worksheet ‘retention/internal load’, a column of wetland measures was added. For the modeling of Porijõgi valgla, a RasterMode model was worked out, based on PCRaster GIS software, pixel size of 10 x 10 $m^2$, facilitating map algebra. The model predicts annual average phosphorus concentrations for every ten metres of all surface waters in the catchment area, using, for the prediction of runoff, the elevation map, maps of surface waters (including drainage systems) as well as a discharge module, calibrated on the basis of the measured runoff (Figure 2). The load was predicted according to emissions, using mostly landcover, soil texture, slope and point sources as well as retention, determined by runoff and slope, calibrated with measured concentrations.

The work area of constructed wetlands (CW) was defined for the catchment areas where phosphorus pollution was predicted, while its main factor was agriculture and, at the same time, high nature value areas (habitats of salmonids, landscape protection areas, Natura areas, etc.) or high consumption value (recreation, etc.) areas due to significant runoff. Areas suitable for open CWs were considered in mostly grasslands and pastures, located on clay or peat soils, neighbouring for a certain distance streams with a certain runoff range, small slopes, originating from mostly agricultural land (Figure 3). CWs were planned for areas with a small elevation difference but high catchment size ratio. In addition to common CWs, active filters (AW) were also planned for the catchment area for the stream segments with a suitable runoff range as well as a long low slope (Figure 4). Also, erosion protection measures were planned for large areas with steep slopes, that were intensively cultivated, and neighbouring waterbodies.

The model also predicted the reduction of emissions due to erosion protection. Further, the model predicted increased retention due to the application of CWs and AWs. From that, the model predicted reduced a phosphorus load and concentration. Finally, the model predicted stream segments and catchment area parts where requested phosphorus concentration will be achieved (success areas) as well as not achieved (failure areas) (Figure 4). These maps facilitated mapping of perspective measures. The model also analysed the cost-efficiency of the measures in euros per kilogramme of phosphorus removal, calculating, among other things, the volume of earth to be removed from the open wetlands.

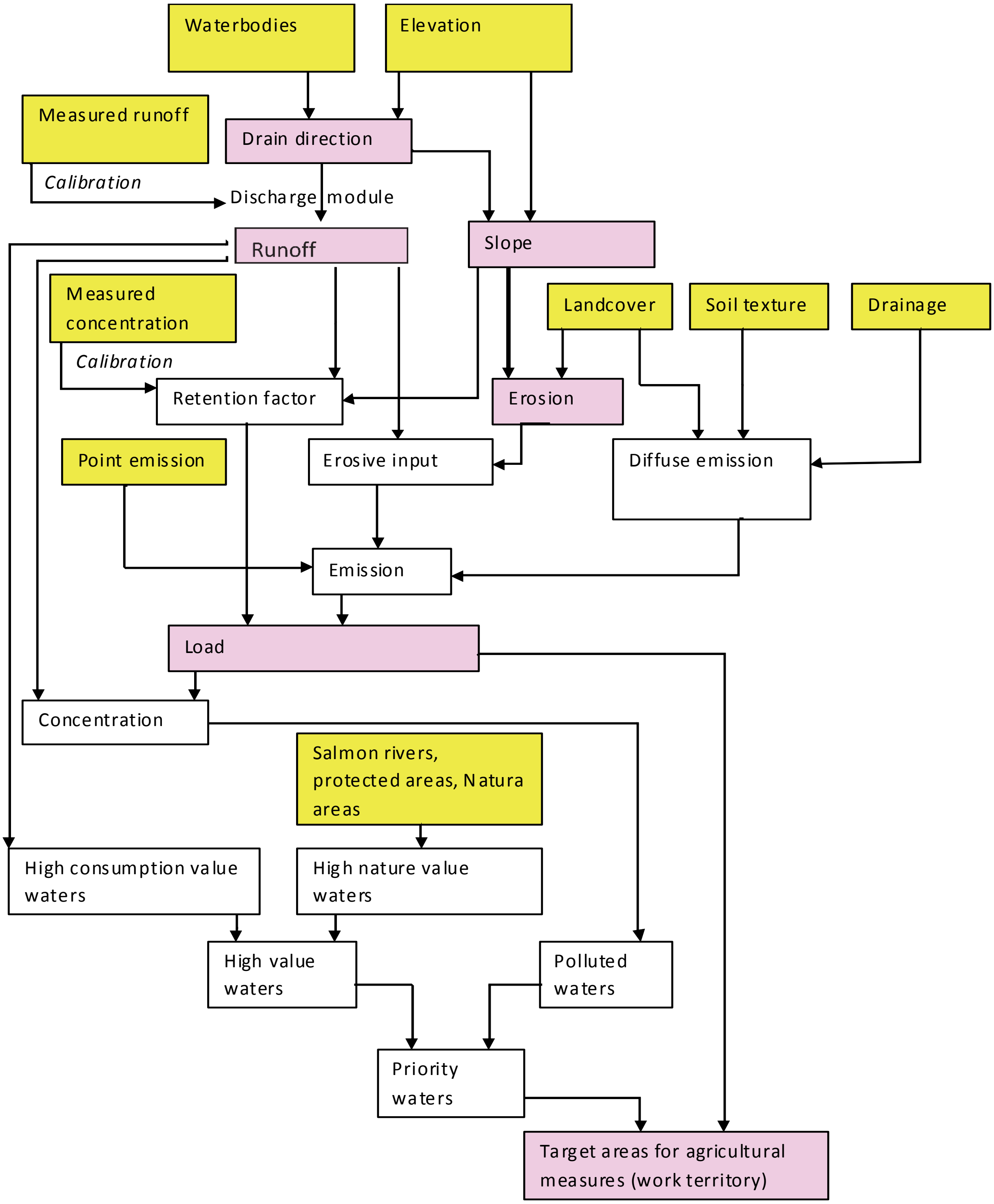



Figure 2. Master planning of measures, reducing agricultural pollution, using a RasterMode model. Yellow indicates data; pink indicates maps to be used in the next model stage.

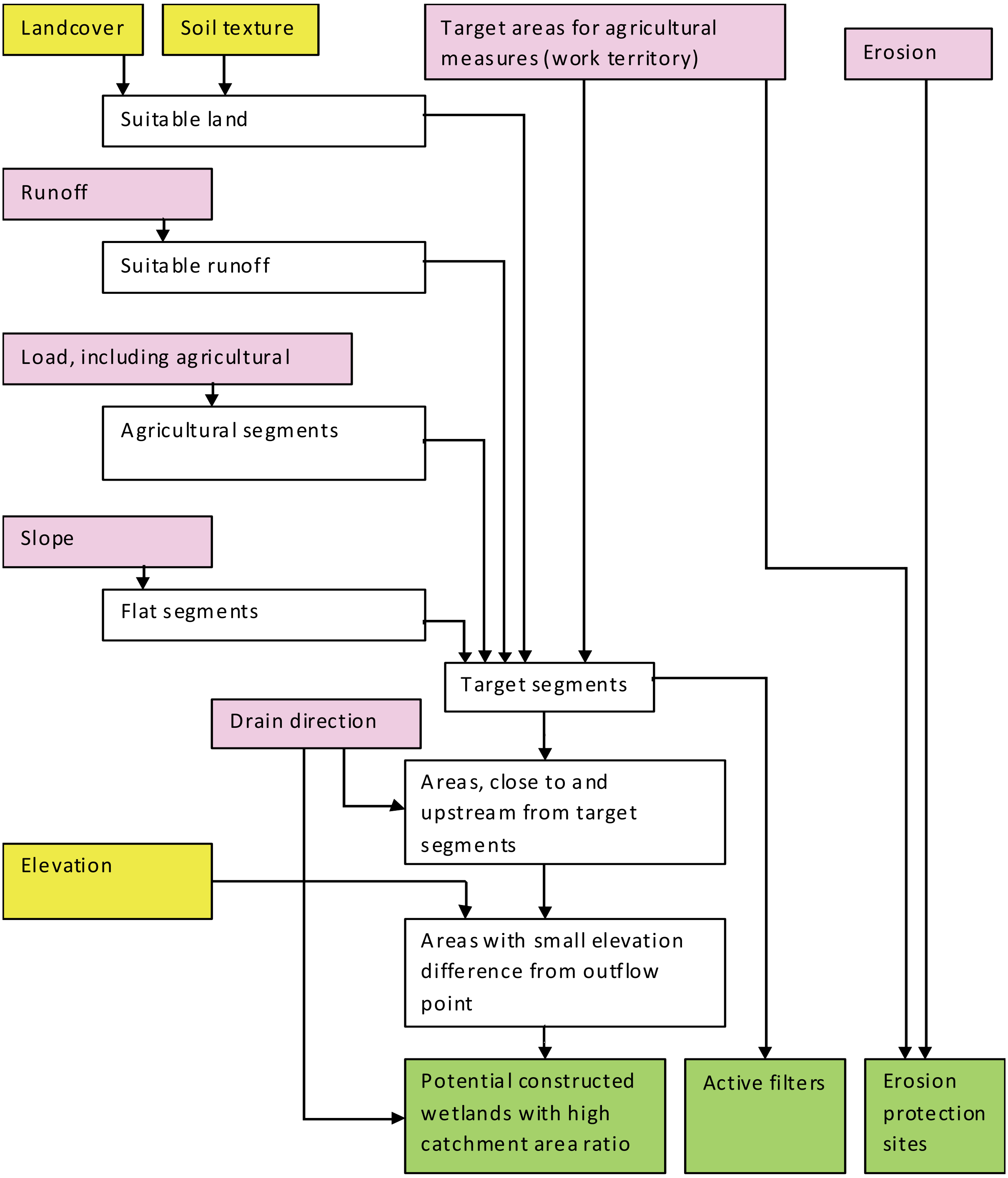



Figure 3. Master planning of measures, reducing agricultural pollution, using a RasterMode model. Yellow indicates data; pink indicates maps, worked out in the previous model stage; green indicates worked out measures.

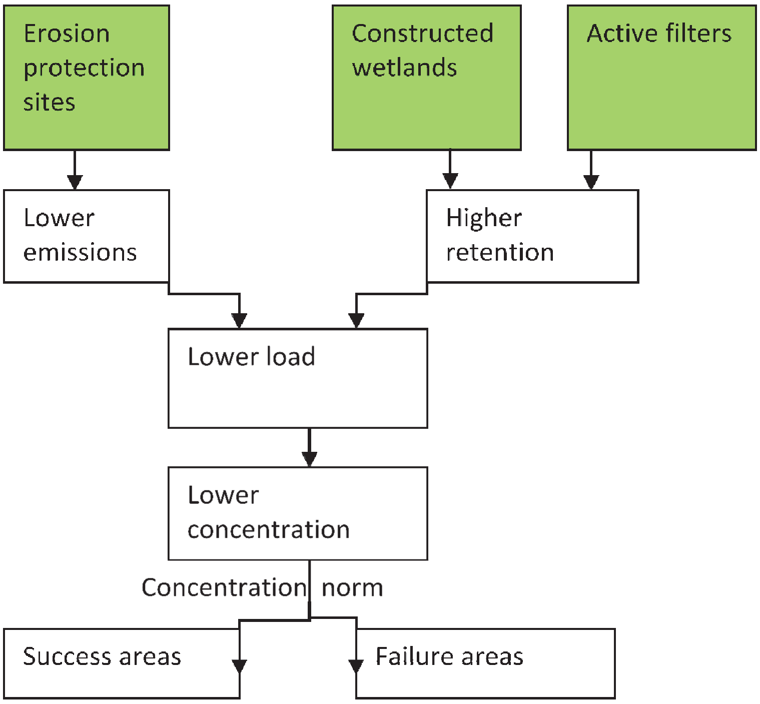



Figure 4. Prediction of measures to reduce agricultural pollution, using RasterMode model. Green colour indicates planned measures.

For the planning and design of open active wetlands, following parameters were applied. Maximum allowed distance of edge of active wetland from stream: 200 metres. Required annual average runoff in ditch: 3.5 - 14 l/s. Phosphorus concentration limit in surface water: 0.08 mg/l (Riigi Teataja, 2010). Minimal annual average discharge rate concerning pollutant concentration: 50 l/s. Minimal share of agricultural load from total load in a potential stream to consider construction of a wetland: 75%. Maximal allowed relative slope in streams: 0.02 metres of elevation change per metre of distance. Maximal elevation difference between a constructed wetland cell and its outflow point cell: 2 m. Construction price = price of digging earth: 0.8 € / $m^3$.

The assumed rate of P removal in an active filter or doser was 50% and estimated using the results of WP2 of this project (Uusitalo et al. 2013). The annual cost of one active filter or doser was EUR 281 (see Table 12).

The rate of removal of slope erosion in erosion protection sites was 100%. The slope threshold to apply the erosion multiplicator was 4%. The additional erosion, appearing in these steep agricultural slopes was 0.29 kg/ha (Kronvang et al., 2000). The ratio between discharge (l/s) and catchment ($km^2$) was 7.

## 2.2 Target areas

The locations of the Finnish target areas, i.e. the catchments listed here as Jokioinen, Lieto, Nuutajärvi and Paimelan Myllyoja catchments and Paimionjoki river basin are presented in Figure 5. In all target areas, except for Paimelan Myllyoja, chemical experiments of WP2 were carried out. Except for Lieto, there may be nutrient loading also from scattered settlements as well as from some minor point sources in the catchments, not to mention the large river basin of Paimionjoki. However, in this report only agricultural diffuse loading which, after all, is the major source of loading in all target areas, is dealt with. Estonian test site, Rahinge ditch, is part of the Ilmatsalu catchment, which is flowing to the River Emajõgi as the target area, River Porijõgi.

### 2.2.1 Jokioinen

The Jokioinen catchment (58 $km^2$) is located in the headwaters of the River Loimijoki, which is a tributary of one of the largest Finnish rivers, i.e. the River Kokemäenjoki discharging into the Bothnian Sea through the city of Pori (Figure 5). Agriculture is the primary form of land use in the Jokioinen catchment, 39% of which is under field cultivation and 10% covered with pastures and meadows. The rest of the catchment is covered with forests (28%) and urban areas (21%) and lakes (2%). The dominant soil type is, as typical for this part of the country, clay (67%) with lesser portions of coarser mineral soils (25%), rock (5%) and peatlands (3%).

### 2.2.2 Lieto

The Lieto catchment is by far the smallest (0.68 $km^2$) of the target catchments and it is located adjacent to the River Aurajoki some 20 km from Turku at which the river discharges into the Archipelago Sea (Figure 5). Agriculture is the major source of nutrient loading transported by the River Aurajoki to the Archipelago Sea. In the Lieto catchment, the major form of land use is agriculture (67%) and the dominant soil type is clay (90%).

### 2.2.3 Nuutajärvi

Like Jokioinen, the Nuutajärvi catchment (Figure 5) is also part of the Kokemäenjoki river basin. Of the catchments (apart from the Paimionjoki river basin) dealt with in this study, Nuutajärvi is the largest (95 $km^2$). In terms of land use, forested areas dominate (70%), while agricultural areas occupy around 20% of the catchment. Soil in the Nuutajärvi area mostly consists of moraines (46%), while clay areas cover 23% of the catchment. However, the bulk of the agricultural areas is located on these clayey soils. In the Nuutajärvi catchment organic soils (peatlands) occupied a lot higher percentage (19%) of the area than in the other target catchments.

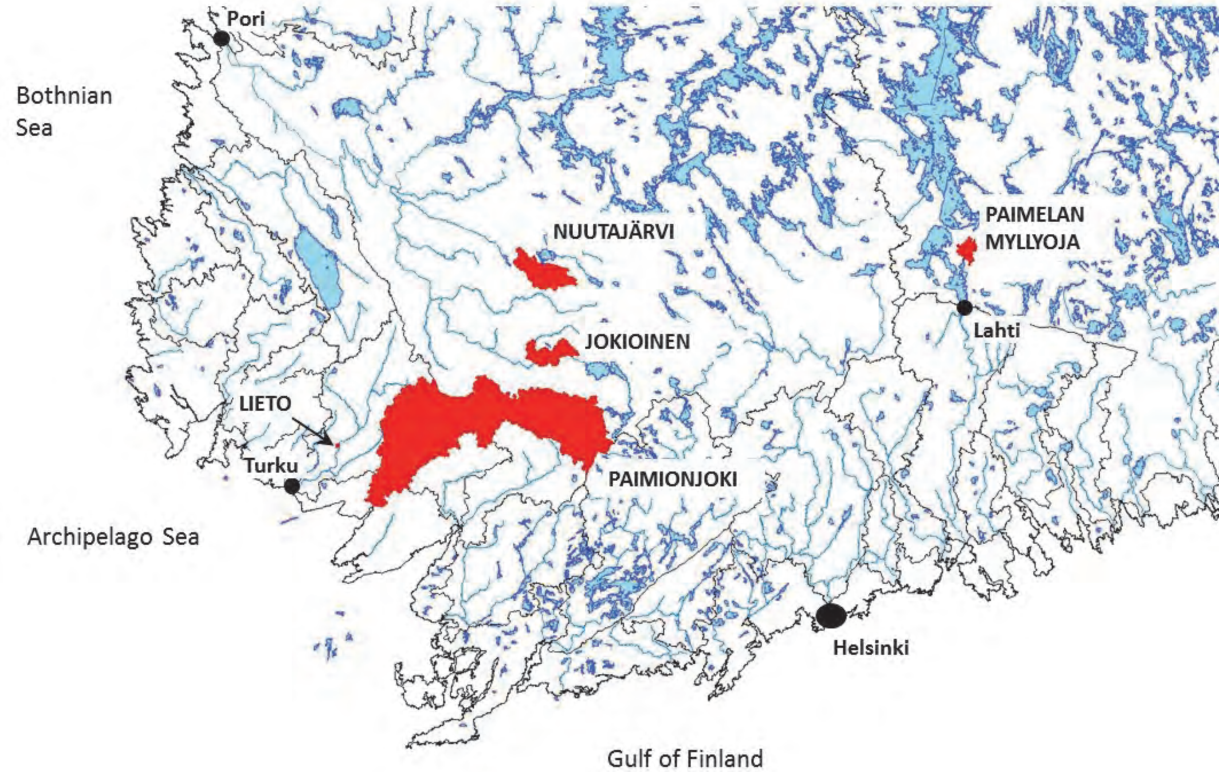



Figure 5. Locations of the target catchments.

### 2.2.4 Paimelan Myllyoja

The Paimelan Myllyoja catchment (21 $km^2$) is located on the eastern shore of Lake Lahden Vesijärvi some 20 km from the city of Lahti (Figure 5). The catchment discharges into the narrow bay Paimelanlahti. The primary land uses in the Paimelan Myllyoja catchment are forestry (45%) and agriculture (43%). As in most of the target catchments, in Paimelan Myllyoja the most common soil type is also clay (47%).

### 2.2.5 Paimionjoki river basin

The Paimionjoki river basin is by far the largest (1088 $km^2$) of the target areas dealt with here. It is situated in southwestern Finland and discharges into the Paimionlahti bay of the Archipelago Sea not far from the city of Turku (Figure 5). Of the almost 70 major river basins of Finland, the Paimionjoki basin is perhaps the most agriculture-dominated in terms of land use. Almost 45% of the basin is under field cultivation and 8% of it is pasture and meadow. Clay is the dominant soil type in the Paimionjoki river basin with a 2/3 share, the rest being mostly moraines.

The Paimionjoki river basin was included in the target areas of the Active Wetlands project in such a late phase of the project that the VIHMA model, which requires a lot of data-gathering work, was not employed there. Instead, agricultural loading was estimated with the readily available VEPS tool (Tattari and Linjama 2004) developed at the Finnish Environment Institute (SYKE). The fundamental difference with the VIHMA tool is that in VEPS the results are scaled not only to the information from experimental field plots, but also to the data obtained from monitoring programmes of larger research basins, where land uses other than agriculture also exist and retention thus occurs. Because the Paimionjoki river basin is so much larger than the other target catchments, the use of VEPS there was reasonable and justified.

### 2.2.6 Porijõgi catchment

In the first phase, as a pilot area, we used the Vända ditch catchment area (ca 5 $km^2$). In the second phase, we worked in the River Porijõgi catchment area (ca 292 $km^2$). The runoff rate at the mouth of Porijõgi is ca 2000 l/s. The length of the river is 38 km. The major tributary rivers are Peeda and Tatra. The largest lake in the catchment area is Pangodi, with an area 91.4 ha, and a maximum depth 3.9 m. Porijõgi flows to the River Emajõgi. The southern part of the catchment area, feeding the upper course, is situated mostly on the hilly Otepää highland, where natural landscapes prevail. In the area of the lower course, a flat agricultural area prevails. Before the mouth, Porijõgi receives wastewaters from the city of Tartu, including approximately 13 t of phosphorus per year.

The middle course of Porijõgi as well as the mouths of the tributaries Peeda and Tatra serve as habitats for salmonids. The largest protected areas in the catchment area are the landscape reserves of the Pangodi and Aardla lakes. The catchment area is rich in non-official bathing sites.

Phosphorus pollution was found in the Vända ditch, while in Porijõgi the concentration of phosphorus remains within the allowed limit of 0.08 mg $l^{-1}$. The catchment area has several waterbodies which are polluted or on the brink of becoming polluted: Lake Pangodi, River Tatra, Sipe ditch, Lake Aardla.

GIS data were acquired as indicated in Table 3. The areal export of P from various land cover and soil texture types was interpreted from Iital (2007) as shown in Table 4. The slope erosion of P was estimated, based on Kronvang et al. (2000). The efficiency of removal of P by open constructed wetlands was taken from Puustinen and Jormola (2005).

Table 3. Used spatial data sources

| Data | Source |
|---|---|
| Landcover | EEA, 2006 |
| Elevation | Estonian Land Board, 2012 |
| Point sources | EEIC, 2012 (a) |
| Monitored concentrations of P | EEIC, 2012 (b) |
| Soil texture | Estonian Land Board, 2000 |
| Drainage systems | Estonian Agricultural Board, 2012 |

Table 4. Applied emission parameters depending on various landcover types (according to Iital, 2007)

| Landcover | Emission of P, kg ha$^{-1}$ |
|---|---|
| Artificial surfaces | 0.25 |
| Arable land | 0.4 (clay soils: 0.8) |
| Permanent crops | 0.12 (clay soils: 0.24) |
| Pastures | 0.2 (clay soils: 0.4) |
| Complex cultivation patterns | 0.3 (clay soils: 0.6) |
| Land principally occupied by agriculture | 0.2 (clay soils: 0.4) |
| Forests | |
| Sandy and loamy soils | 0.06 |
| Peat and clay soils | 0.1 |
| Shrub and/or herbaceous vegetation associations | 0.12 |
| Open spaces with little or no vegetation | 0.12 |
| Inland marshes | 0.11 (coastal reed belts: 0) |
| Peat bogs | 0.09 (peat mines: 0.38) |

## 2.3 Evaluation of the effects of chemical amendments

In the Active Wetlands project, two different approaches of chemical amendments (Ferix-dispenser and Sacthofer granules) were tested in the Jokioinen, Lieto and Nuutajärvi catchments in Finland and in Rahinge near Tartu in Estonia. The objective of the measurements and monitoring conducted in WP2 was to obtain information how many kilograms of (dissolved) P could be retained annually with these methods. Here in WP3, our aim was to assess these results together with catchment-scale P loading figures, and thereby make evaluations of the significance and cost-effectiveness of the chemical amendments. The catchment-scale effects of each chemical amendment system were dealt with only within the respective catchment where the system was located. Since the functioning and efficiency of the systems were not uniform, this should be kept in mind when interpreting the catchment-scale results.

In the Nuutajärvi catchment only the spring flood period of the year 2012 was monitored and in the Paimionjoki river basin only the autumn flood period of the same year was measured. For these sites the results were extrapolated to cover the whole year 2012. For Lieto and Jokioinen, of which the measurement periods covered more than one year, annual means were used. The experimental sites with chemical amendments are hereafter referred to as active wetlands (AWs) to distinguish them from constructed wetlands without chemical amendments (CWs).

### 2.3.1 Ferix-dispenser

One solution was to use a chemical dispenser that consists of a container with a piece of pipe led through its bottom, and a cone-shaped netting bag attached to the end of the pipe (Figure 6). The container is filled with granular ferric sulphate (e.g. Ferix-3 manufactured by Kemira Chemicals Ltd.), that dissolves from the cone at a rate that depends on the surface area exposed to water, i.e., on the water level in front of a v-notch weir. The dispenser can be scaled up and down by simply changing the size of the pipe and/or the netting cone. The Ferix-dispenser is primarily meant for treating high-P waters, because the economy of chemical stripping is strongly dependent on the P concentration in runoff.

Ferix-dispensers were tested in the Lieto catchment from 18 April to 23 November 2011 and from 20 March through 30 October 2012. In the Nuutajärvi catchment, Ferix-dispensers were used at nine experimental sites during the spring flood period (13 March to 16 April) of 2012. In Rahinge, Ferix applications were tested between April and December in 2012. Detailed results of these experiments are reported in Uusitalo et al. (2013).

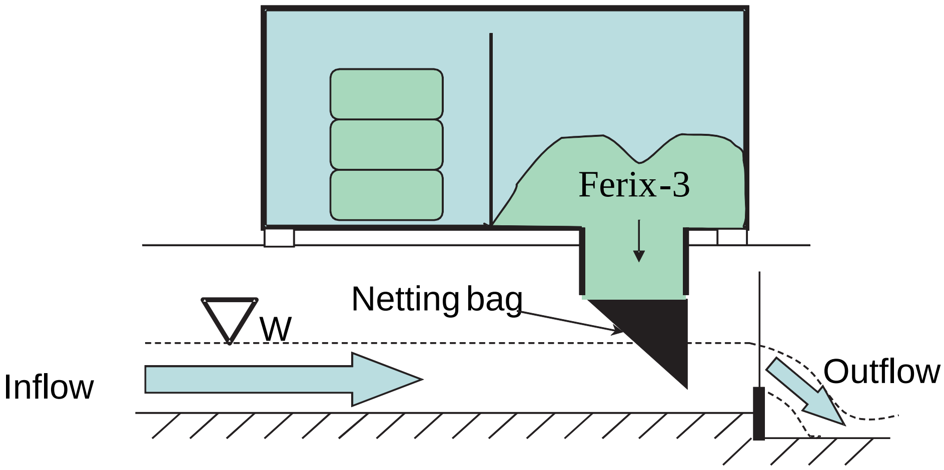



Figure 6. A schematic figure of Ferix-dispenser.

### 2.3.2 Sachtofer PR granules

Another approach is to use a barrier of Sachtofer PR granules (manufactured by Sachtleben Pigments Oy) that form a permeable barrier at the outlet of a wetland. The inflow into this prototype buffer is from below, through the granule mass, and out of the buffer via a v-notch weir (Figure 7). The buffer between the dam structures is filled with 6–7 $m^3$ (about 9 tn) of Sachtofer PR granules, and the theoretical P retention capacity of this granule volume exceeds 60 kg of phosphorus. If the granule buffer works as well as the laboratory tests suggest, this buffer would have an effective life-cycle of up to ten years.

In Finland, the Sachtofer-granules system was experimented with at the Ojainen site in the Jokioinen catchment from 23 September 2010 to 31 December 2012 (Uusitalo et al. 2013). In Rahinge, Estonia, more portable systems of Sachtofer-granules were tested in 2011 and 2012 (Uusitalo et al. 2013).

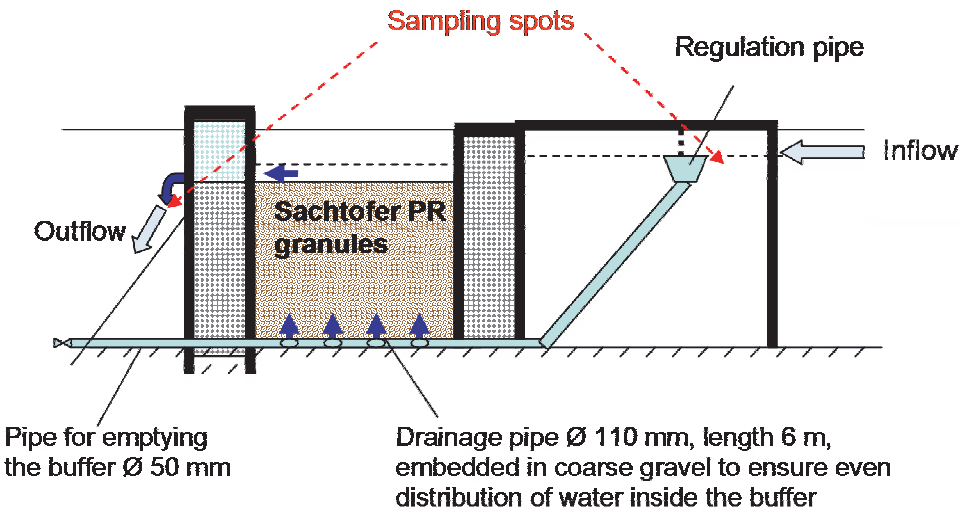



Figure 7. A schematic figure of a barrier of Sachthofer PR granules.

## 2.4 Economical assessments

In this project we estimated the cost-efficiency of the tested AWs. CWs in general in retaining the P escaping from agriculture were also evaluated in this respect. In the discussion part of this report, cost-effectiveness was compared to other agricultural water protection methods. In total equipment costs per one chemical dispenser i) the timber needed for the supporting elements of the dispenser, ii) the dispenser itself, iii) the dam supplies, iv) the chemical containers delivered to the site and v) the amount of the chemical were taken into account. In addition, the amount of work needed for the construction, maintenance and monitoring, as well as other necessary expenses (such as transit costs) were taken into account in cost evaluations. The results based on individual experiments are presented as the average annual cost for one dispenser. The lifetime of a dispenser was evaluated to be 10 years and the interest rate used was 5%.

The cost-effectiveness of AWs was calculated by dividing the annual average costs (EUR) by the annual amount of precipitated P (kg) as evaluated from the results of WP2 experiments. These results (EUR per kg of P) were compared with the cost-effectiveness calculated for the CWs modeled in this study, as well as with other water protection measures (Ahopelto and Hjerppe 2012)

# 3 Results

## 3.1 Agricultural nutrient loading and wetland effects

Nutrient loading as simulated by the VIHMA model in the four target catchments is presented in Figure 8. These loading figures were used as inputs in the modeling of CW effects and locating strategies.

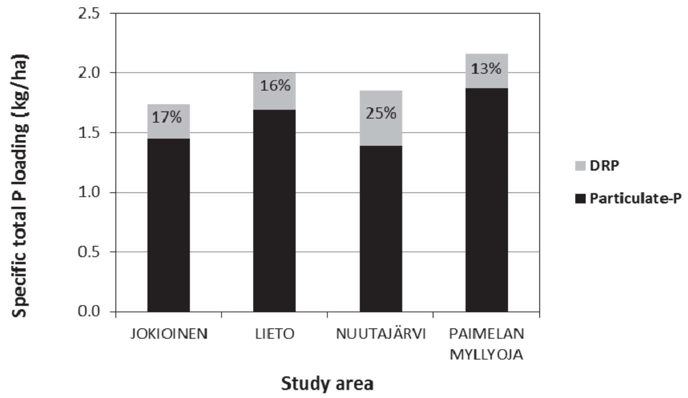
### 3.1.1 Jokioinen

Agricultural practices and slope steepness are distributed in Jokioinen as presented in Table 5. Up to 70% of the 2.26 $km^2$ total field area is under intensive autumnal tillage. In terms of slope, there is not any clearly dominant class, but the area is rather evenly distributed between the three categories the middle (1.5–6%) being most common (40%) (Table 5).

Table 5. Distribution of characteristics of agricultural land in the Jokioinen catchment.

| | Slope | | | |
|---|---|---|---|---|
| Cultivation practice | <1.5% | 1.5–6% | >6% | Total |
| Intensive autumn tillage | 25% | 28% | 17% | 70% |
| Grass | 9% | 11% | 7% | 27% |
| Winter cereals | 1% | 1% | 1% | 3% |
| Total | 35% | 40% | 25% | **100%** |

According to VIHMA, annual nutrient loading from agriculture in the Jokioinen catchment was 4 000 kgP and 36 800 kgN. In specific terms the loading in Jokioinen (1.7 kgP $ha^{-1}$ $yr^{-1}$ and 16 kgN $ha^{-1}$ $yr^{-1}$) was the lowest of the examined catchments (Figure 8).



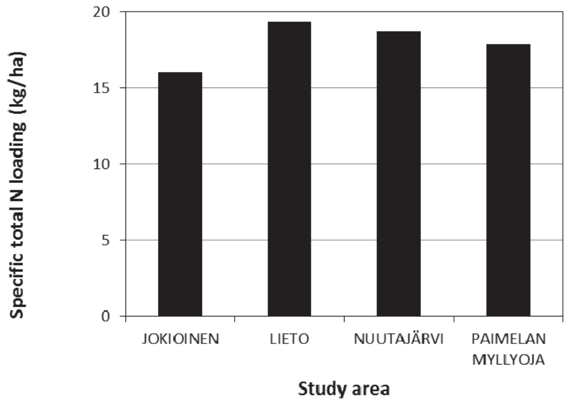




Figure 8. Specific total phosphorus (P) (upper graph) and nitrogen (N) (lower graph) loading from the cultivated fields in four target areas as estimated by the VIHMA model. The percentage of dissolved P (DP) of the total P loading is marked in the bars of the upper graph.

When a CW with 1% CW-to-catchment area ratio was input to the VIHMA assessment case of Jokioinen, the estimated retentions were 21% for total P and 11% for total N. Meanwhile SWAT estimated 12% total P and 13% total N retentions when every one of the 11 SWAT-subcatchments was covered with a CW occupying 1% of the subcatchment. The average per cent retentions of the two modeling approaches mean that with this acreage of CWs, some 660 kg of P and 4 300 kg of N could be annually retained in the Jokioinen catchment.

### 3.1.2 Lieto

Distribution of agricultural practices and slope steepness classes in the Lieto catchment are presented in Table 6. Of the arable area 91% is under intensive autumnal tillage the rest being under grass. Slope distribution was very similar to that in the Jokioinen catchment.

Table 6. Distribution of characteristics of agricultural land in the Lieto catchment.

| | Slope | | | |
|---|---|---|---|---|
| Cultivation practice | <1.5% | 1.5–6% | >6% | Total |
| Intensive autumn tillage | 31% | 37% | 23% | 91% |
| Grass | 3% | 4% | 2% | 9% |
| Total | 34% | 41% | 25% | **100%** |

VIHMA estimated 91 kg annual total P loading and 887 kg annual total N loading for the Lieto catchment. The specific total P loading in Lieto (2.0 kgP $ha^{-1}$ $yr^{-1}$) was between those of Jokioinen and Paimelan Myllyoja while the specific total N loading (19 kgN $ha^{-1}$ $yr^{-1}$) was highest (Figure 8).

In the Lieto catchment, the VIHMA-estimation of CW effects yielded similar nutrient retentions (21% for total P and 11% for total N) to those found in Jokioinen. In terms of SWAT simulation, the Lieto catchment was so small that the model did not create any subcatchments. As a result, only one 0.7-ha-CW (1% of the upstream catchment) was simulated to be placed at the outlet. With this set-up, SWAT estimated higher retentions (for total P 25% and for total N 19%) than VIHMA. When the averages of the outputs produced by the two models (23% for total P and 15% for total N) were used, the results suggested 21 kg total P and 130 kg total N retention in the CW at Lieto.

### 3.1.3 Nuutajärvi

The distribution of agricultural practices and slope in the Nuutajärvi catchment are presented in Table 7. Agricultural land use in Nuutajärvi is quite different from the other target catchments with only 5% under intensive autumnal tillage, which should lead to lower erosion and nutrient loading. On the other hand, however, the share of steep terrain is high, as two thirds of the catchment falls into the category of >6%.

Table 7. Distribution of characteristics of agricultural land in the Nuutajärvi catchment.

| | Slope | | | |
|---|---|---|---|---|
| Cultivation practice | <1.5% | 1.5–6% | >6% | Total |
| Intensive autumn tillage | 2% | 0% | 4% | 5% |
| Grass | 13% | 2% | 30% | 44% |
| Winter cereals | 15% | 2% | 34% | 50% |
| Total | 29% | 4% | 67% | **100%** |

The simulations with VIHMA suggest that annually 3 680 kg of total P and 37 300 kg of total N is transported from the cultivated areas of the Nuutajärvi catchment. In specific terms, the nutrient loading (1.8 kgP $ha^{-1}$ $yr^{-1}$ and 19 kgN $ha^{-1}$ $yr^{-1}$) was close to that in Lieto. The share of dissolved P of total P (25%) as well as specific dissolved P loading (0.48 kgDP $ha^{-1}$ $yr^{-1}$) was highest in the Nuutajärvi catchment.

According to VIHMA simulations, 20% of total P and 11% of total N would be annually retained in CWs occupying 1% of the catchment. In kilograms this means 730 kg total P and 3 900 kg total N retention.

### 3.1.4 Paimelan Myllyoja

Table 8 shows the distribution of agricultural practices and slope steepness classes in the Paimelan Myllyoja catchment. Intensive autumnal tillage was also the dominant cultivation practice. As in the Nuutajärvi catchment, the steepest slope class was the most common also in Paimelan Myllyoja (Table 8).

Table 8. Distribution of characteristics of agricultural land in the Paimelan Myllyoja catchment.

| | Slope | | | |
|---|---|---|---|---|
| Cultivation practice | <1.5% | 1.5–6% | >6% | Total |
| Intensive autumn tillage | 24% | 24% | 32% | 80% |
| Grass | 4% | 5% | 6% | 15% |
| Winter cereals | 2% | 1% | 2% | 5% |
| Total | 30% | 30% | 40% | **100%** |

VIHMA calculations showed that the highest specific total P loading from cultivated land (2.2 kgP $ha^{-1}$ $yr^{-1}$) was found in the Paimelan Myllyoja catchment, while the total N loading there (18 kgN $ha^{-1}$ $yr^{-1}$) was between the other target catchments. The absolute values of nutrient transport were 1 960 kg of total P and 16 200 kg of total N.

In the Paimelan Myllyoja catchment, VIHMA and SWAT simulations of 1% of the catchment covered with CWs produced almost equal total P retention estimates (VIHMA: 21% and SWAT: 22%). For total N SWAT yielded somewhat higher estimate, 15% vs. 11% with VIHMA. The use of average values of the two modeling approaches yielded 420 kg total P and 2 100 kg total N retention per year.

### 3.1.5 Paimionjoki

Agricultural nutrient loading from one hectare of field in the Paimionjoki river basin, as estimated with VEPS system, was clearly lower (0.9 kgP $ha^{-1}$ $yr^{-1}$ and 12 kgN $ha^{-1}$ $yr^{-1}$) than from the other target catchments, where the VIHMA model was used. In absolute terms, of course, this large river basin transported much more agricultural nutrients (40 500 of total P and 550 600 kg of total N) into the recipient water body than the other target catchments.

In the Paimionjoki river basin, only the SWAT model was used for the simulations of CW effects. According to the results, 8% of total P and 18% of total N loading could be retained if 1% of the whole river basin would be covered with CWs. The mass retention achieved with this water protection effort would be 3 200 kg of total P and 99 000 kg of total N.

### 3.1.6 Wetland locating strategies

The above presented nutrient retentions in Jokioinen, Paimelan Myllyoja and Paimionjoki, as simulated by SWAT, are the results of strategy a). According to the model results, it was far more efficient than strategy b) that yielded about 1% annual nutrient retentions in Jokioinen and Paimelan Myllyoja. Paimionjoki strategy b) led to slightly higher (3%) per cent retentions of both total N and total P, still clearly below those of strategy a).

Based on the modeled total P loading and the retentions achieved by strategy a), Table 9 shows how many hectares of CWs would be required to retain certain retentions of total P loading in the target catchments.

Table 9. Simulated annual total P retention (%) in constructed wetlands (CWs) covering 1% of the catchment, and the area (ha) of CWs needed for retaining different percentages of annual total P loading in Finnish target catchments.

| | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuuta-järvi | Paimion-joki | Jokioinen | Paimelan Myllyoja |
| Total P retention with 1% CW coverage % | 23 | 20 | 8 | 18 | 23 |
| Total P retention (kg $ha^{-1}$)* with 1% CW coverage | 31 | 8 | 3 | 11 | 21 |
| Area of CWs (ha) needed to retain: | | | | | |
| 5% of total P loading | 0.1 | 24 | 680 | 18 | 5 |
| 10% of total P loading | 0.3 | 48 | 1360 | 18 | 5 |
| 20% of total P loading | 1 | 95 | 2 720 | 72 | 19 |

*per hectare of wetland.

The modeled total P retention-% achieved by strategy a) clearly depended on the catchment area: the smaller the catchment, the higher the retention-% (Figure 9).

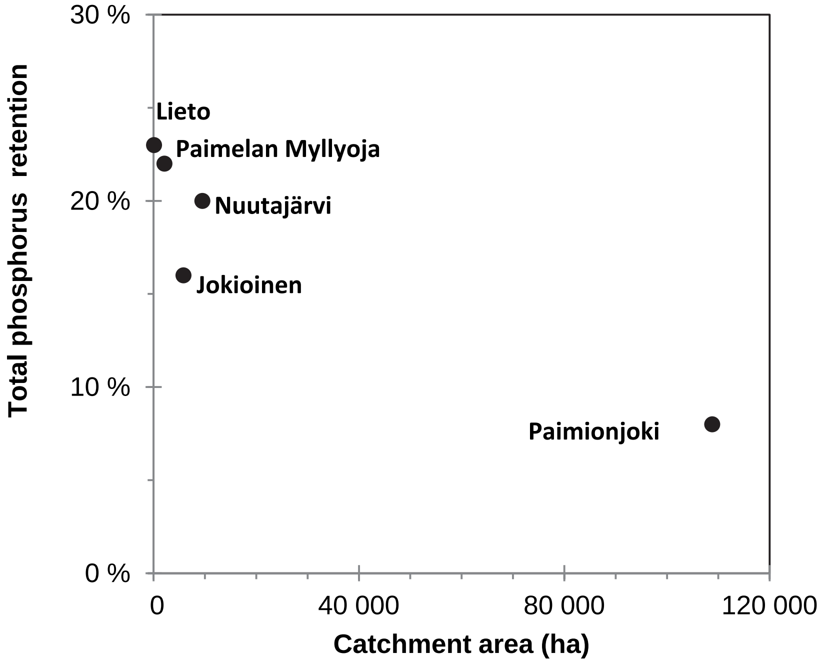



Figure 9. Dependence of total phosphorus retention (%) in CWs on catchment area (ha). In simulations 1% of each catchment was covered with CWs according to the strategy a) presented in Figure 1.

## 3.2 Chemical amendments

In this report, the effects of chemical amendments are presented as annual dissolved P retentions per one AW. The AWs did not retain much of the particulate P, which is thus not dealt with in AW calculations in this report. More detailed results with P retentions, as well as depictions of water sampling and laboratory analyses can be found in the WP2 report of the Active Wetlands project (Uusitalo et al. 2013).

### 3.2.1 Sachtofer filter in Ojainen/Jokioinen

The Sachtofer filter tested at the Ojainen/Jokioinen AW retained only 0.2 kg DP annually, which is 27% of the input dissolved P loading (Table 10). The filter system treated on average 16% of the runoff from the 15-ha upstream area, which is 0.1% of the runoff from the arable areas of the entire Jokioinen catchment. As illustrated in Table 11, such a small share would mean that very high, in practice unrealistic, number of AWs would be needed to retain any substantial portion of the agricultural P loading generated in this large catchment.

### 3.2.2 Ferix-dispensers in Lieto, Nuutajärvi and Paimionjoki

The Ferix-dispenser system in Lieto retained 11.5 kg (73%) of the input dissolved P loading (Table 10). Unlike in other target catchments, in Lieto the catchment upstream of the AW was also the target catchment. Thus, with its high retention both in kilograms and percents, the Lieto AW alone is sufficient to retain substantial amounts of P in its small catchment (Table 11).

We estimated that an imaginary AW representing the average of the actual nine experimental AWs in the Nuutajärvi area would have retained 3.8 kg (58%) of the annual input DP loading (Table 10). Table 11 shows how many of these kind of averagely functioning AWs would be needed to retain certain shares of agricultural P loading in this target catchment.

According to our estimations, a hypothetical AW representing the average of the actual three experimental AWs in the Paimionjoki area would have retained 6.5 kg (45%) of the annual input DP loading (Table 10). In such a large river basin like Paimionjoki, quite many AWs (see Table 11) would be needed for water protection effects in downstream recipient, which in this case is the Gulf of Finland. Nevertheless, with good functioning of the systems, the required numbers remained lesser than in the clearly smaller Jokioinen catchment with poorer retention in AWs.

Table 10. Estimated annual input and retention of dissolved P (DP) in Finnish experimental active wetlands (AWs).

| | Target catchment | | | |
|---|---|---|---|---|
| | Lieto | Nuutajärvi* | Paimionjoki** | Jokioinen |
| Agricultural area above the AW (ha) | 46 | 27 | 67 | 15 |
| DP input (kg) | 15.8 | 6.6 | 14.5 | 0.7 |
| DP retained (%) | 73 | 58 | 45 | 26 |
| DP retained (kg $yr^{-1}$) | 11.5 | 3.8 | 6.5 | 0.2 |

* average of 9 AWs
** average of 3 AWs

Table 11. Agricultural total phosphorus (TP) and dissolved phosphorus (DP) loading and theoretical number of active wetlands (AWs) needed for retaining different percentages of the loading in Finnish target catchments.

| | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuutajärvi | Paimionjoki | Jokioinen | Paimelan Myllyoja* |
| Agricultural area in entire catchment (ha) | 46 | 1 992 | 44 800 | 2 294 | 906 |
| Agricultural P loading from entire catchment (kgTP / kgDP) | 91/ 16 | 3 700 / 920 | 40 500 / 10 100 | 4 000 / 660 | 1 960 / 255 |
| No. of AWs needed | | | | | |
| to retain 5% of (TP/DP) loading | 1 / 1 | 48 / 12 | 313 / 78 | 1 093 / 180 | 17 / 2 |
| to retain 10% of (TP/DP) loading | 1 / 1 | 96 / 24 | 626 / 156 | 2 186 / 360 | 33 / 4 |
| to retain 20% of (TP/DP) loading | 2 / 1 | 192 / 48 | 1 251 / 313 | 4 373 / 720 | 66 / 9 |

*Average data of the AW results from Lieto, Nuutajärvi and Paimionjoki was used.

## 3.3 Economical assessments

The total yearly costs of one chemical dispenser were calculated on the base of actual total costs incurred in 13 experimental sites (Table 12). The costs were assessed for an evaluated lifetime of ten years with 5% annual interest rate. The distribution of costs is illustrated in Figure 10. The number of AWs required to achieve different desired removal rates in each of the four target catchments with experimental sites was already shown in Table 11 and the estimated costs for this are presented in Table 13. As for Paimelan Myllyoja catchment where AW experiments were not done, average values of the Ferix-3 experiments made in Lieto, Nuutajärvi and Paimionjoki were used.

The corresponding costs for CWs established by damming and excavating are presented in Tables 14 and 15. Here, also Paimelan-Myllyoja catchment, where no AW experimental sites were established, is also taken into account. In these calculations, the previously presented, modeled annual P loadings and retentions were used. Construction costs were assumed to be 4 000 EUR/ha for dammed CWs and 16 000 EUR/ha for excavated CWs, which correspond to 500 and 2 000 EUR/ha, respectively, when calculated for lifetime of 10 years and 5% interest.

Table 12. Calculated average total yearly costs (EUR) per one dispenser as calculated for an evaluated lifetime of ten years with a 5% interest rate.

| | | |
|---|---|---|
| Material costs for 13 dispensers | Timber etc. | 430 € |
| | Dispensers | 1 170 € |
| | Dam equipment | 104 € |
| | Chemical vessels delivered to the site | 2 304 € |
| | Total | 4 008 € |
| Material cost on average per dispenser | | 308 € |
| | | |
| Yearly material costs per dispenser (10 years and 5% rate) | | 39 € |
| Yearly labor cost per dispenser (14,5 €/h * 64.5 h / 13) | | 72 € |
| Yearly chemical costs per dispenser (0.27 €/kg + cargo 0.08 €/kg = 0.35 €/kg * 4850 kg /13) | | 131 € |
| Other yearly costs per dispenser (includes driving etc.) | | 40 € |
| **Total average yearly costs per one dispenser** | | **281 €** |

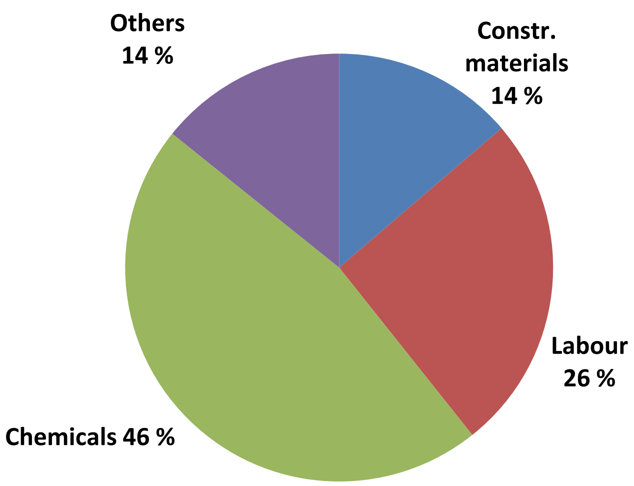



Figure 10. Distribution of yearly costs of chemical treatment in active wetlands.

Table 13. Calculated costs (EUR) of active wetlands (AWs) needed for retaining different percentages of phosphorus loading in four Finnish target catchments with experimental sites.

| Costs (€) of AWs needed | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuutajärvi | Paimionjoki | Jokioinen | Paimelan Myllyoja* |
| to retain 5% of P loading | 281 | 13 524 | 87 932 | 312 453 | 4 648 |
| to retain 10% of P loading | 281 | 27 047 | 175 863 | 624 906 | 9 297 |
| to retain 20% of P loading | 445 | 54 095 | 351 726 | 1 249 813 | 18 593 |

*Average data of the AW results from Lieto, Nuutajärvi and Paimionjoki was used.

Table 14. Calculated costs (EUR) of dammed constructed wetlands (CWs) needed for retaining different percentages of phosphorus loading in four Finnish target catchments with experimental sites.

| Costs (€) of dammed CWs needed | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuutajärvi | Paimionjoki | Jokioinen | Paimelan Myllyoja |
| to retain 5% of P loading | 74 | 11 875 | 340 000 | 9 063 | 2 386 |
| to retain 10% of P loading | 148 | 23 750 | 680 000 | 18 125 | 4 773 |
| to retain 20% of P loading | 296 | 47 500 | 1 360 000 | 36 250 | 9 545 |

Table 15. Calculated costs (EUR) of excavated constructed wetlands (CWs) needed for retaining different percentages of phosphorus loading in four Finnish target catchments with experimental sites.

| | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuutajärvi | Paimionjoki | Jokioinen | Paimelan Myllyoja |
| Costs (€) of excavated CWs needed | | | | | |
| to retain 5% of P loading | 296 | 47 500 | 1 360 000 | 36 250 | 9 545 |
| to retain 10% of P loading | 591 | 95 000 | 2 720 000 | 72 500 | 19 091 |
| to retain 20% of P loading | 1 183 | 190 000 | 5 440 000 | 145 000 | 38 182 |

The evaluated values of cost-effectiveness of AWs and CWs are presented in Table 16. In terms of AWs, the range of the values is high due to the poor cost-effectiveness of the Jokioinen site. For CWs, the variation was not as dramatic, although clear differences were found. High cost-effectiveness (i.e. low amount of EUR per kg of P) was attributed to high values of i) field-%, ii) specific P loading and iii) modeled retention-% in CWs in the target catchment (Figure 11).

Table 16. Evaluated cost-effectiveness (EUR / kg of P) of active wetlands (AWs) and constructed wetlands (CWs) as established by damming or excavating.

| | Target catchment | | | | |
|---|---|---|---|---|---|
| | Lieto | Nuutajärvi | Paimionjoki | Jokioinen | Paimelan Myllyoja |
| Cost-effectiveness of AWs | 24 | 73 | 43 | 1 561 | 47* |
| Cost-effectiveness of: | | | | | |
| dammed CWs | 16 | 65 | 168 | 45 | 24 |
| excavated CWs | 65 | 258 | 672 | 181 | 97 |

*Average data of the AW results from Lieto, Nuutajärvi and Paimionjoki was used.

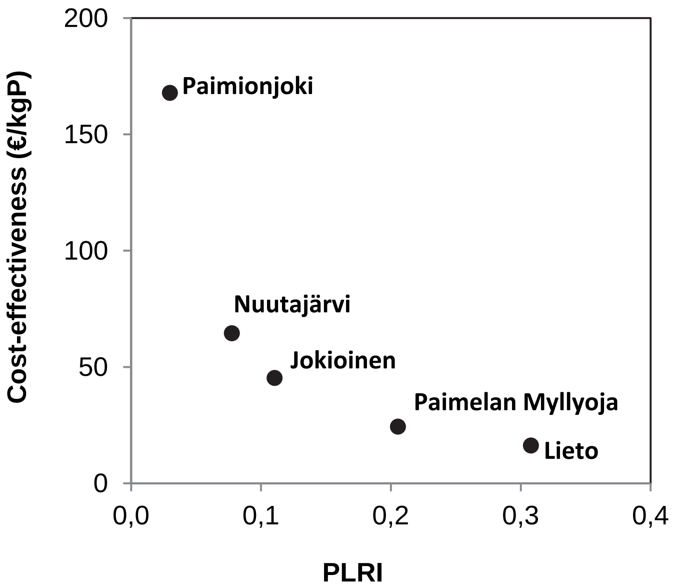



Figure 11. Dependence of cost-effectiveness of dammed constructed wetlands (CWs) on P load-retention index (PLRI) at catchment level. PLRI = field-% * specific P-loading (kg/ha) * retention-% of CWs in the target catchment. Costs of dammed CWs were estimated for a 10-year lifetime with a 5% interest rate and 4 000 €/ha initial construction cost.

## 3.4 Testing the RasterMode model in the Porijõgi catchment

Although agricultural pollution was found in the Vända ditch, no suitable place was found for the construction of wetlands. From the largest agricultural field, water flowed without ditches directly to the main ditch where pollution diluted in the cleaner water, originating from natural areas. Hence, the catchment area missed a ditch with the agricultural catchment area. In addition to dilution, the construction of a wetland in the main ditch was hindered by too high runoff and a deficit of suitable land with low value. Finally, the necessity of the purification of the Vända ditch was questionable due to the low nature and recreational value of the purified ditch, while Porijõgi, into which the ditch flows, has required phosphorus concentration.

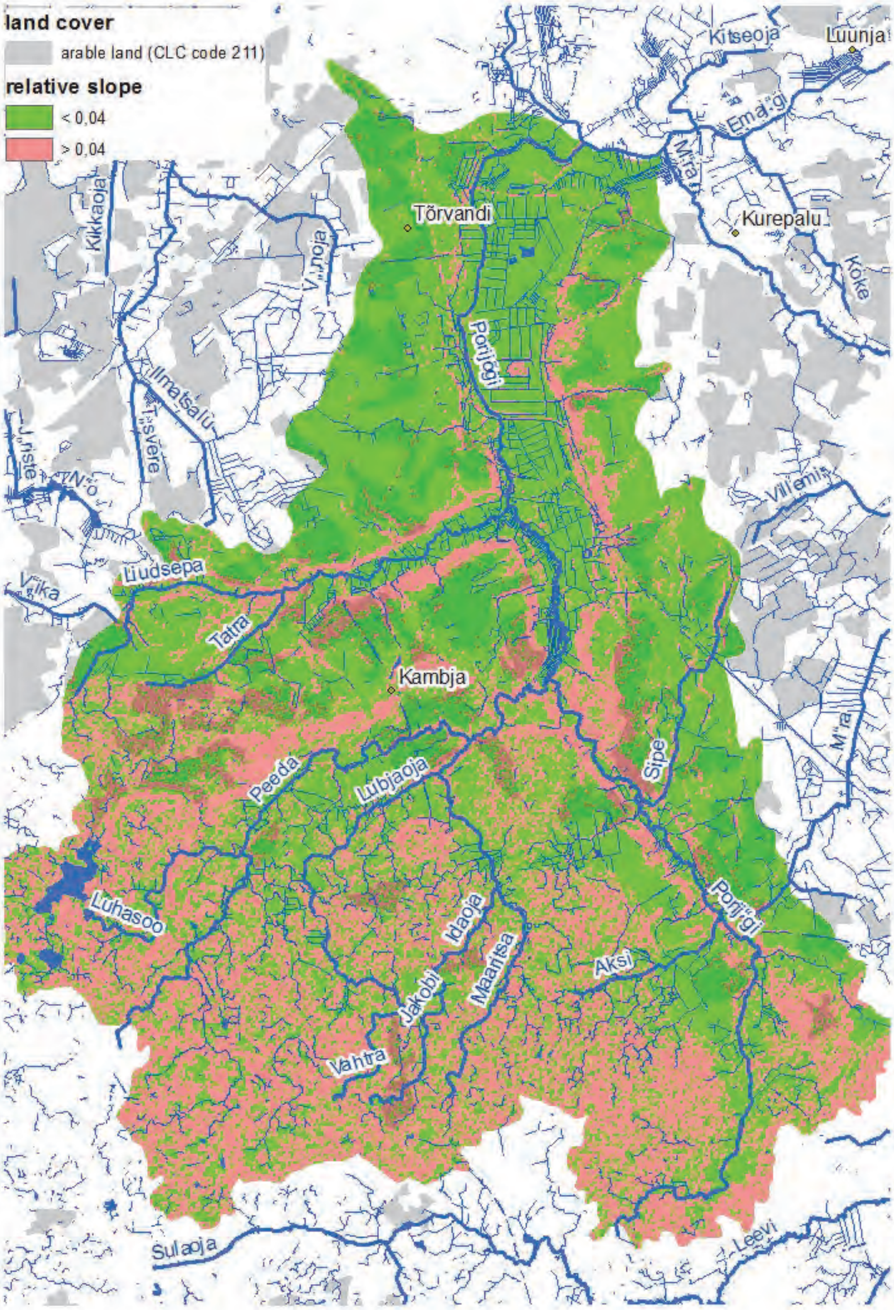



Figure 12. Erosion factors in the Porijõgi catchment area.

Defining areas with high slope erosion, the model searched for agricultural fields with a steep slope. The Porijõgi catchment area, however, divided between a steep southern part with relatively natural land cover and a flat northern part with agricultural land use (Figure 12). Erosion was predicted, mostly to the central area, particularly around the River Tatra (Figure 13).

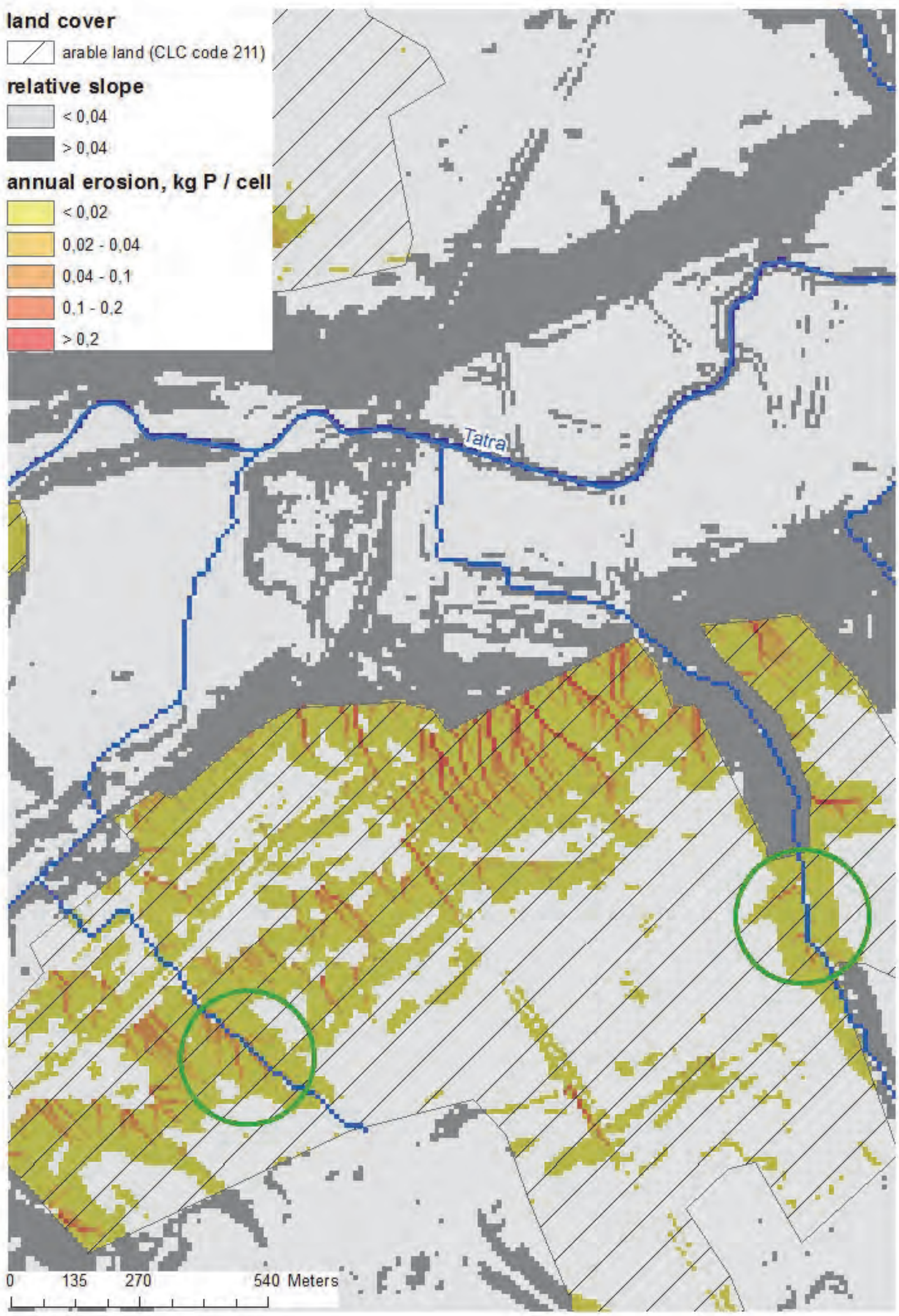



Figure 13. Erosion in a fragment of the Porijõgi catchment area. Green circles indicate places where erosive soil reaches waterbodies.

Before the inflow of the wastewater from Tartu town (13 tons per year), more than 4 tons of phosphorus flowed into the river Porijõgi of which 3 tons originated from agricultural areas (Figure 14 and 15).

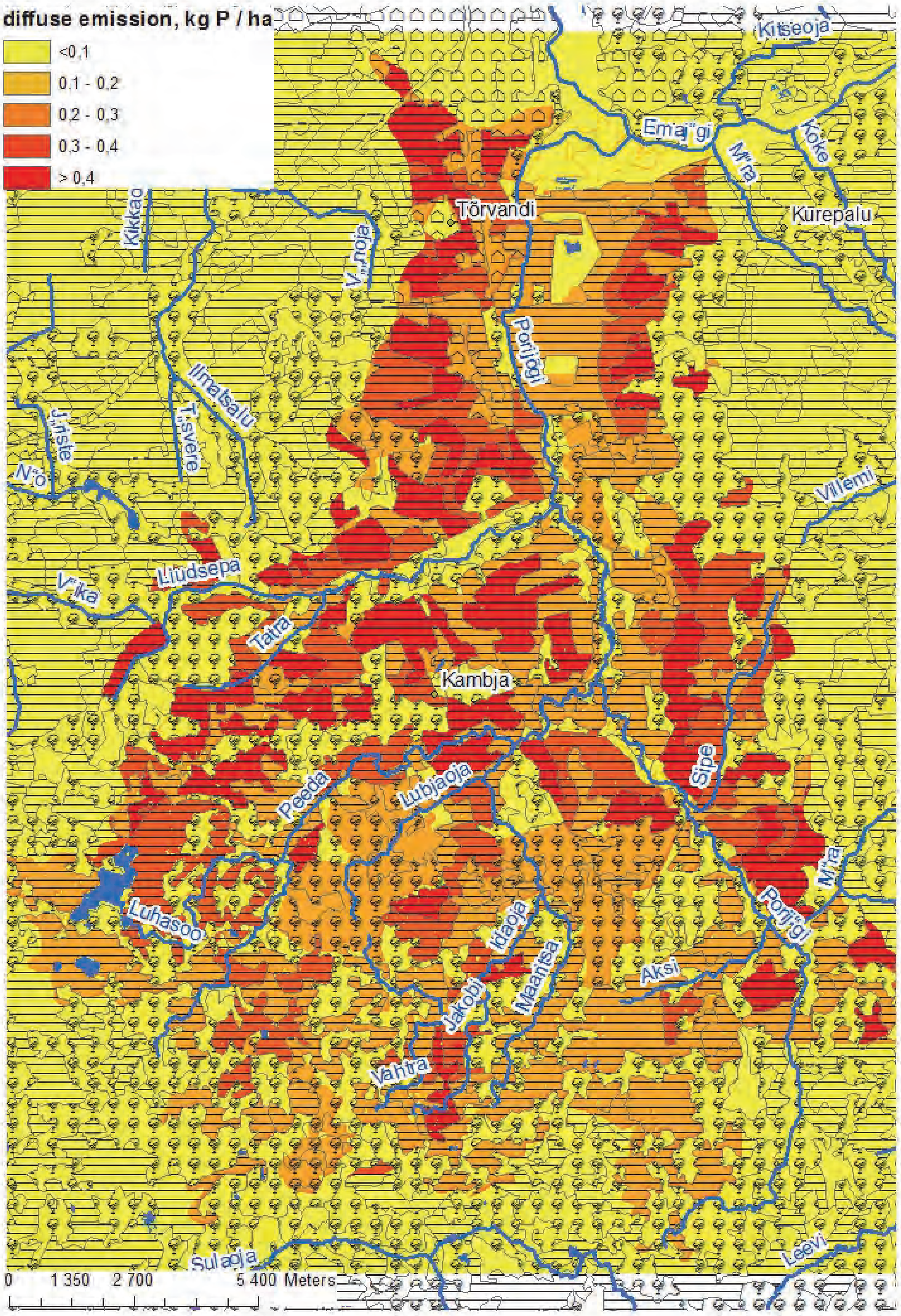



Figure 14. Diffuse emissions in the Porijõgi catchment area. Trees indicate forests; stripes – agricultural land; houses – urban land use.


Figure 15. Phosphorus load in a fragment of the Porijõgi catchment area. The red circle indicates a spot, where due to retention, the load reduces downstream under 4000 kg/yr.

As the upper course of Porijõgi gave sufficient amounts of pure water, agriculture from the southern part could not pollute it according to the Estonian water quality standard. Waterbodies with the highest nature value appeared to be Lake Pangodi, medium course of Porijõgi as well as lower courses of rivers Tatra and Preeda (Figure 16).

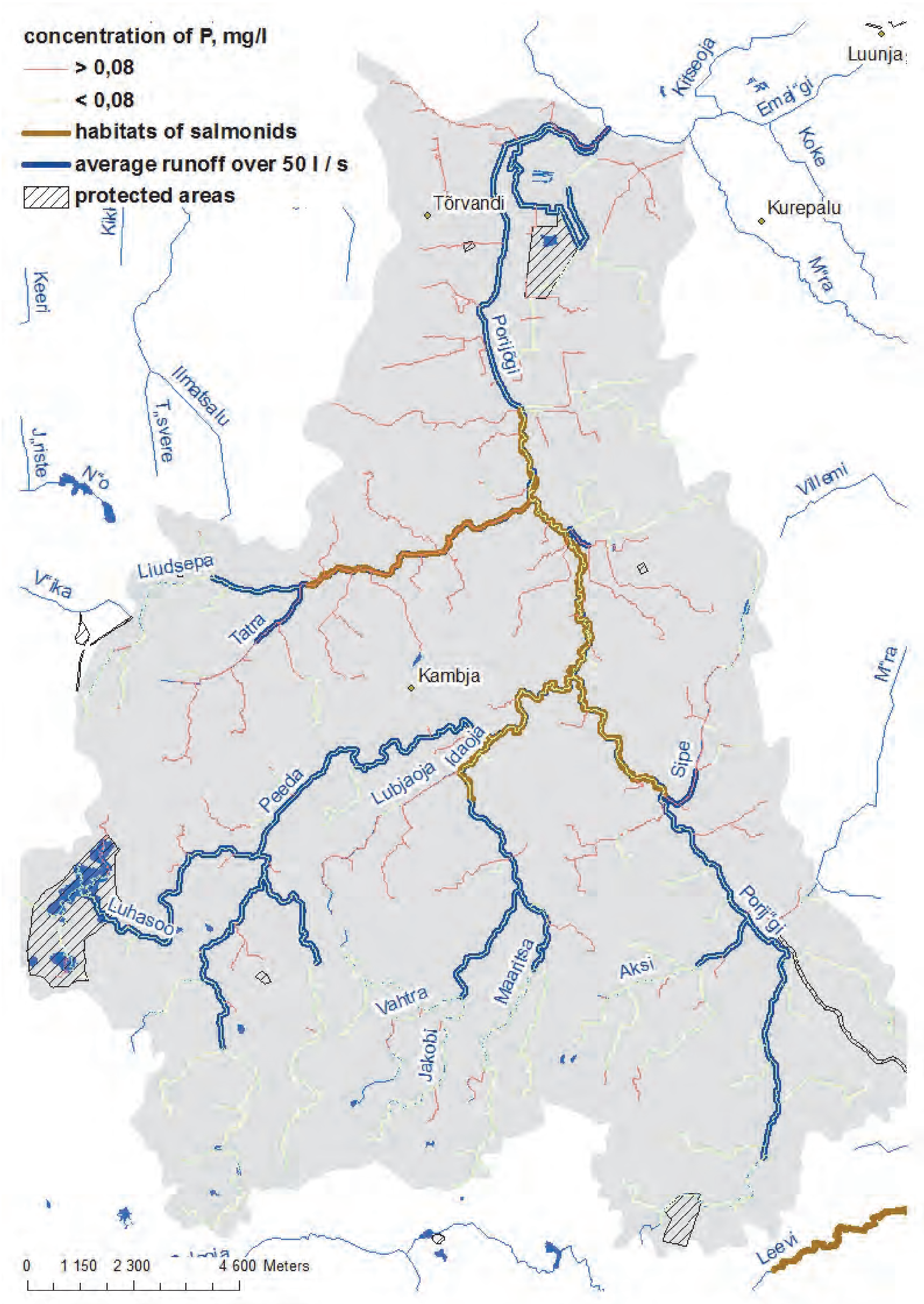



Figure 16. Pollution and values of waters of the Porijõgi catchment area.

The model defined the River Tatra catchment as the largest working territory for the planning of measures. This was followed by the Sipe ditch, the Aardla river and the northern part of the catchment of Lake Pangodi (Figure 17).

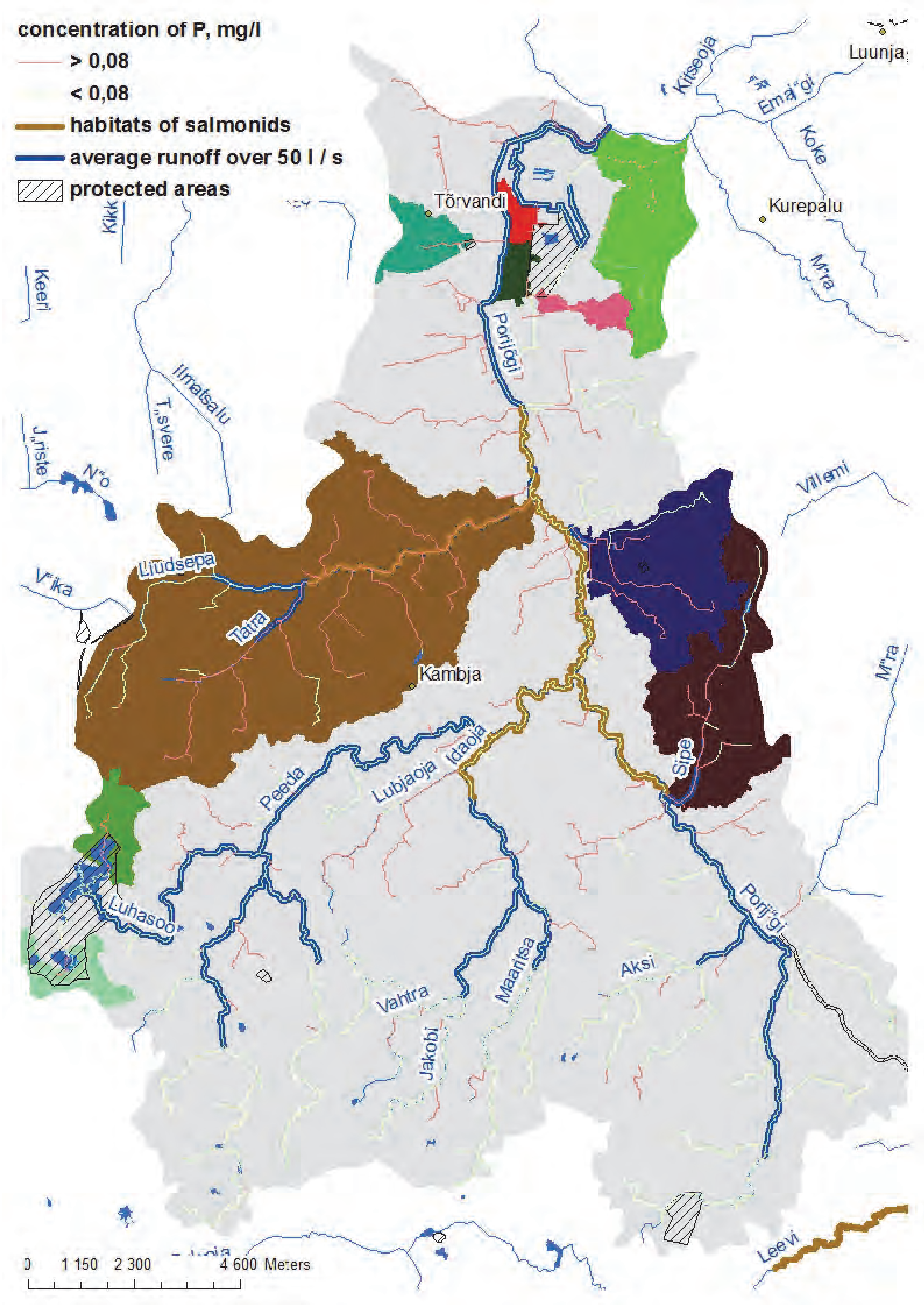



Figure 17. Master plan of agricultural measures in the Porijõgi catchment area.

Low value clay land, suitable for the construction of wetlands, appeared mostly in the southern part of the catchment area, while overlap with working territory was the largest in a small area south of Lake Pangodi (Figure 18).

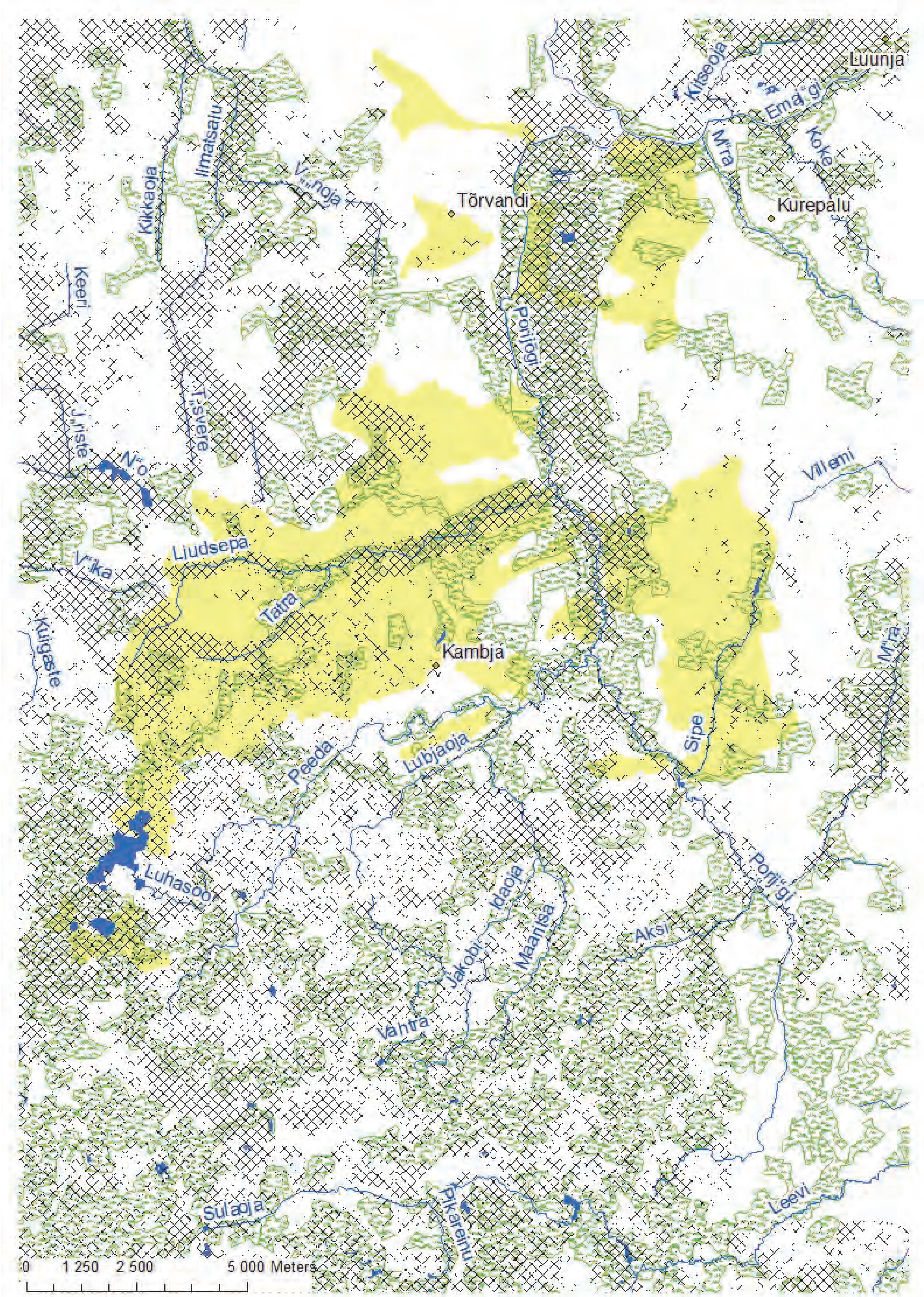



Figure 18. Land, suitable for the construction of wetlands. Yellow indicates planning areas of agricultural measures (work territory); double stripes – clay soil; green – low value land cover.

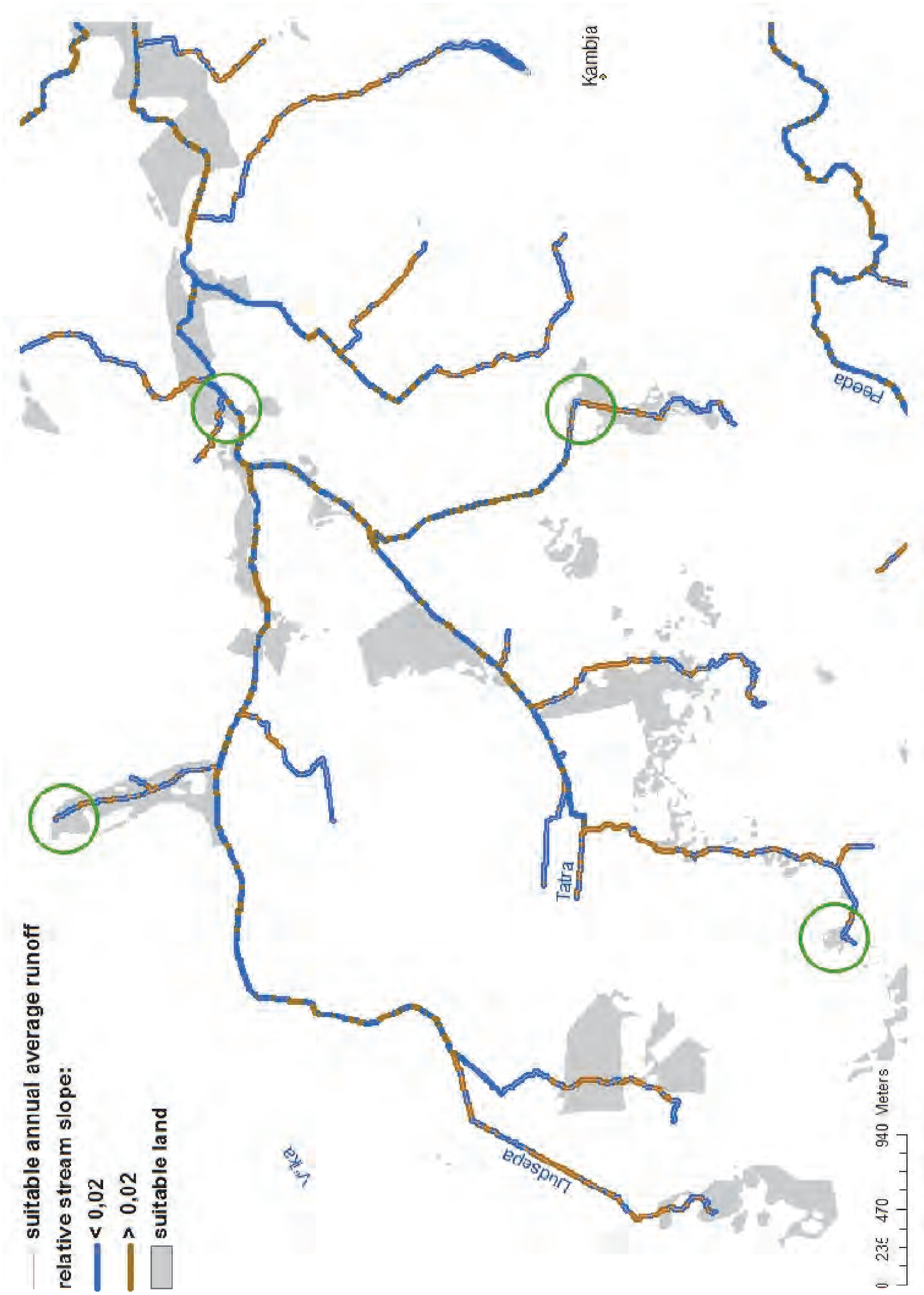



Figure 19. Preconditions for the construction of wetlands in ditches of a fragment of the Porijõgi catchment area. Green circles indicate the most suitable ditch fragment.

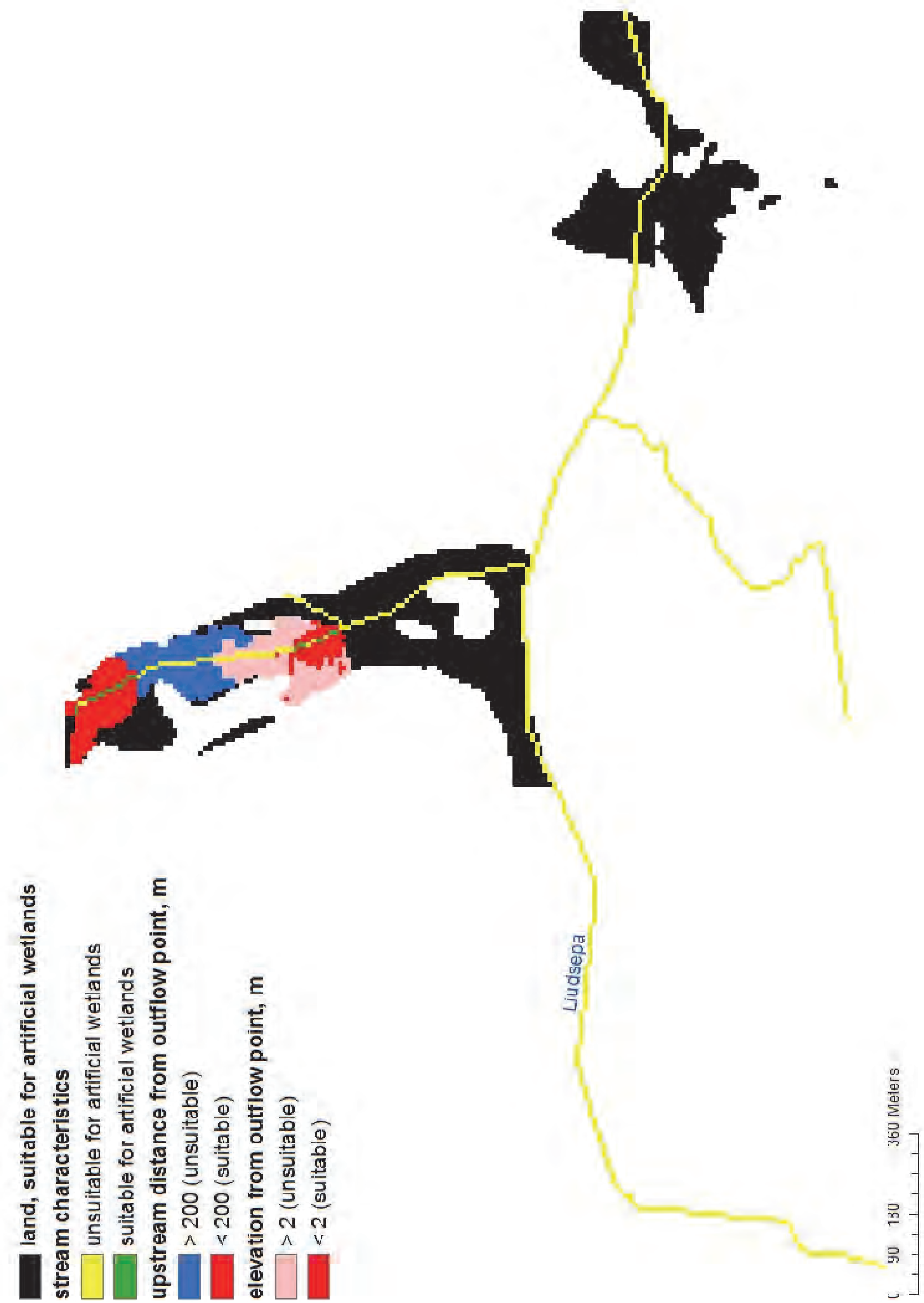



Figure 20. Detailed design of artificial wetland – example from the Porijõgi catchment area.

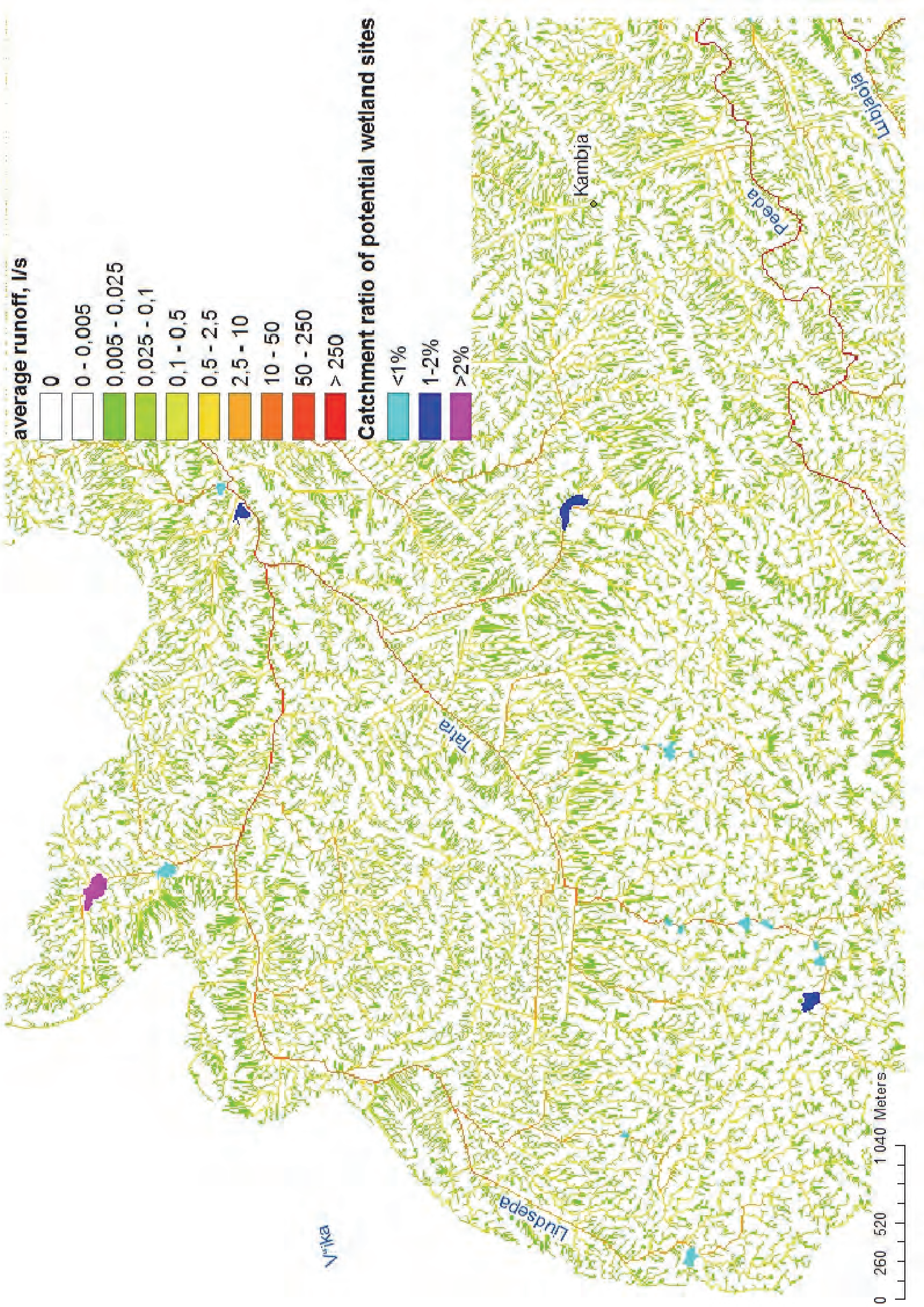



Figure 21. Catchment area size ratio of potential constructed wetlands.

Considering also other requirements for open artificial wetlands, the model planned altogether 14 wetlands mostly in the subcatchments of the River Tatra, the Sipe ditch and the River Aardla (Figures 19–21). The model also planned approximately 25 active filters in the same areas. Approximately 10 erosion protection sites were planned, mostly in the subcatchment area of the River Tatra (Figure 22).

The volume of soil and earth to be excavated fell mostly between 10 000–60 000 $m^3$ per wetland (Figure 23). Each of these wetlands would remove phosphorus of between 2–14 kg per year, with a cost-efficiency of 500–5000 € / kg / year. If we consider the exploitation time to be 20 years, without additional costs, the efficiency would be about 25–250 € / kg. In contrast, the cost-efficiency of dosers varied between only 10 and 40 € / kg. If all these measures are implemented, the concentration of phosphorus will be reduced in the target rivers by approximately 10%. The most promising measures are active filters while the least promising are erosion protection measures.

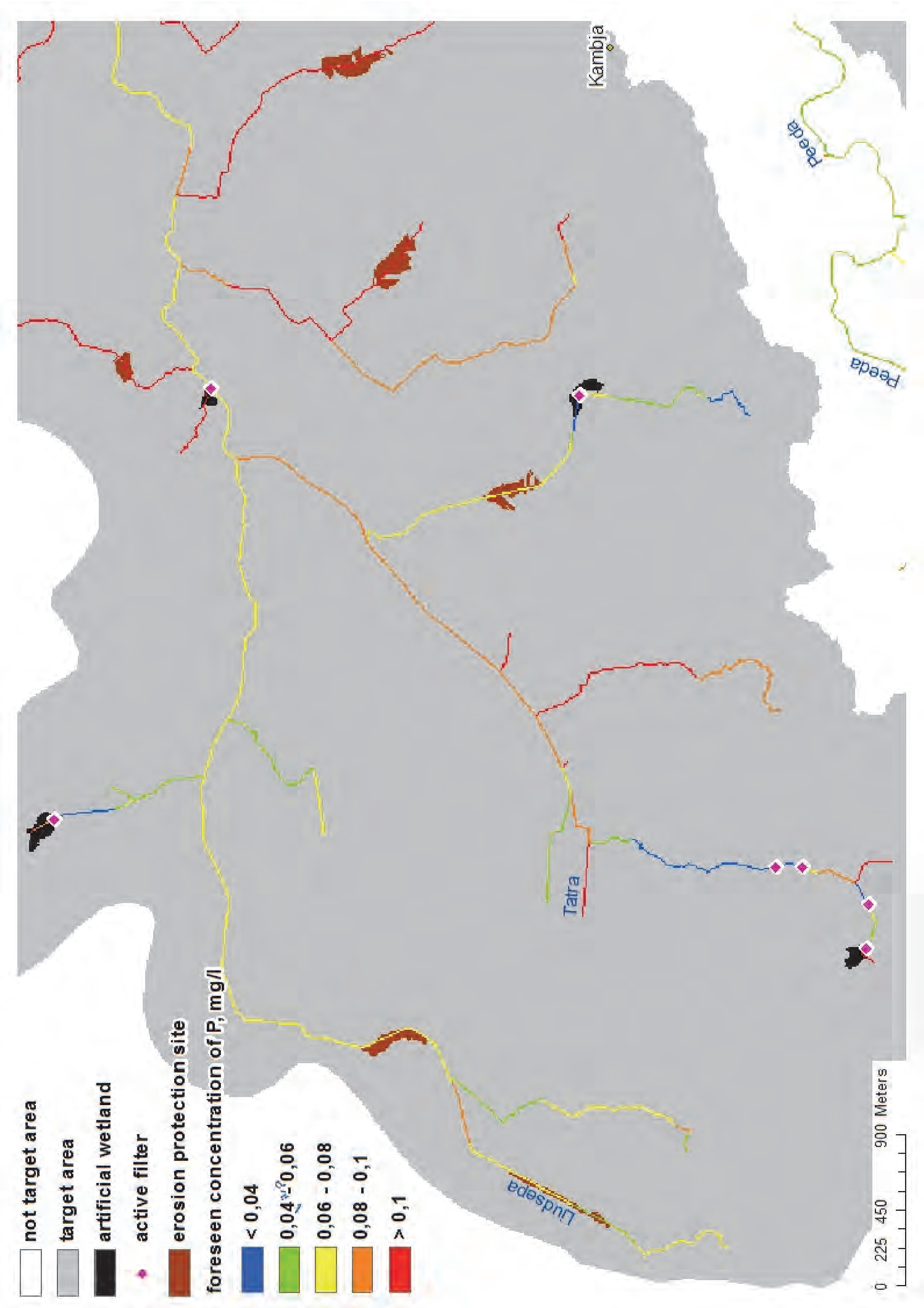



Figure 22. Location and predicted effect of the application of measures against agricultural diffuse pollution on the concentration of phosphorus.

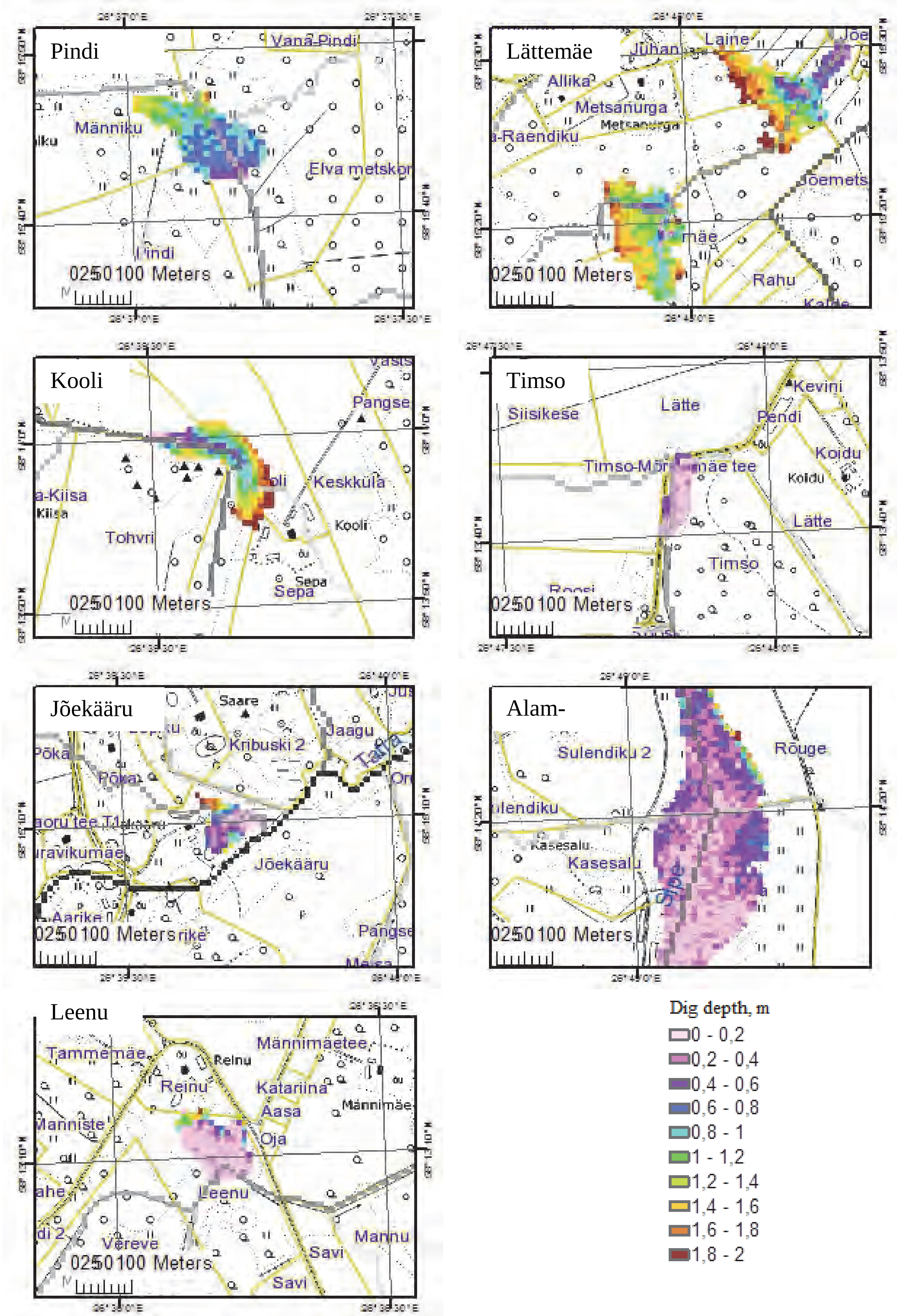



Figure 23. Dig depth of planned artificial wetlands (depth difference with outflow point).

# 4 Discussion

## 4.1 Agricultural nutrient loading from the catchments and simulated effects of constructed wetlands without chemical amendments

The catchments included in this study differed from each other not only in terms of size, but also regarding their agricultural land use, which was reflected in the specific loading figures modeled by VIHMA. The lowest specific nutrient loading of the target catchments was found in Jokioinen. This was due to the relatively low portion of intensive autumnal tillage (70%) coupled also with a low (26%) share of the steepest (>5%) slope class. In terms of P, one factor behind the low loading in Jokioinen may be the low P-status (8.1 mg $l^{-1}$) in that area.

The highest specific total N loading was simulated to take place in Lieto, probably due to the high share of autumnal tillage there. The highest specific dissolved P loading was found in Nuutajärvi in spite of the relatively low P-status (8.5 mg $l^{-1}$). In the field experiments behind VIHMA equations (Puustinen at al. 2010), organic soils were found to produce high dissolved P loading. Hence, the high share of organic soils (almost 20%) in the Nuutajärvi catchment led to high simulated dissolved P loading. In all other target catchments the area of organic soils was minor. The highest particulate- (and total) P loading was found in the Paimelan Myllyoja catchment. This was obviously related to the high shares of steep-sloped fields and autumnal ploughing, both of which are factors increasing erosion and transport of particulate nutrients in arable catchments.

In all, the specific nutrient loadings simulated by VIHMA in the target catchments of this study (1.7–2.2 kgP/ha and 16–19 kgN/ha) were higher than those from three Finnish agricultural catchments (on average 1.1 kgP/ha and 15 kgN/ha) during 1981–1995 (Vuorenmaa et al. 2002). In the same study of Vuorenmaa et al. (2002), arable areas were found to produce nutrient concentrations an order of magnitude higher than forested areas, which typically occupy the bulk of non-agricultural areas. The portion of dissolved P of total P was, partly due to the effect of the organic soils in the Nuutajärvi catchment, on average somewhat higher in the catchments of this study (18%) than in the agricultural catchments of Vuorenmaa et al. (2002); 13%.

In simulation runs with 1% of the target catchments occupied by CWs, total P retention varied between 3 and 31 kg per hectare of a CW (Table 9), i.e. 0.07–0.48 kg per a field hectare in the upstream catchment. The SWAT CW simulations in this study were based on comparison between the loading from an entire catchment without any CWs, and the loading from the same catchment with 1% of the area covered with CWs. Thus, because there was water flow in the areas outside CWs, 100% treatment of waters that does occur in a single CW, did not take place. The inverse dependence of the percent retention in the catchment area (see Figure 9) reflects the same phenomenon; although the locating strategy and dimensioning of the CWs was basically similar in all target catchments, the larger the catchment was, the more diluted were the input concentrations and thereby the lower the input loading. From practical point of view, establishing CWs on an area totalling 1% of a catchment, particularly in a larger one, may not be always realistic. However, in comparative examinations of different scenarios, like in this study, the use of this kind of simple, fixed percentage is justified.

When the results of SWAT simulations of CW locating strategies were contemplated, it soon became clear that strategy a) is more efficient than strategy b). Although the water residence time (WRT), i.e. the time there is for the purifying processes to work, should be more or less equal in both strategies, the input concentrations to CWs were, due to the closer proximity to the fields and thereby lesser dilution, obviously higher in strategy a). As previously noted, arable areas typically produce much higher nutrient concentrations than forested areas which occupied the bulk of non-agricultural land in all target catchments. And although the rate of retention, as described in SWAT by apparent settling velocity (m/day), was parameterized to be equal in the CWs in both strategies, the lower concentrations in strategy b) meant that there was less N and P to be retained.

## 4.2 Effects, potential and cost-effectiveness of chemical amendments in phosphorus retention in agricultural catchments

The lowest annual dissolved P retention by chemical amendments in both absolute (0.2 kg) and relative (27%) terms was estimated for the Sachtofer treatment system in Ojainen. The low input P loading at Ojainen was due to the small upstream catchment (15 ha) and also to the fact that on average only 16% of the runoff from the catchment was treated with the system. When there is low loading, also the retained kilograms of P remain low. With such a small amount of retained P as measured at Ojainen, an AW system cannot be a feasible method in terms of neither water protection objectives (Table 11) nor cost-effectiveness (Tables 13 and 16). However, the initially substantial reduction of dissolved P concentration observed at Ojainen (Uusitalo et al. 2013) suggests that the Sachtofer AW system is not without promise. If the problems with short-circuiting via preferential flow paths can be solved and if larger amounts of P can be input to the system, the results can be quite different than those obtained from the Ojainen experiment in this project.

In Lieto, the amount of P retained was high in both absolute (kg) and relative (%) terms. The most likely reasons behind the good result were (i) large (but not too large) upstream catchment bringing high (but not too high) amounts of water with ii) high P concentrations from agriculture-dominated (68%) catchment and of course, (iii) a well-functioning P-trapping system. Indeed, one should find an optimal amount of inflow. In general, a too high inflow volume will lead to too short contact times between the water and sorption material and thereby a poor retention result. On the other hand, a too low input (as in Ojainen) leads to negligible amounts of retained P.

In the Paimionjoki and Nuutajärvi experimental AWs, both absolute and relative dissolved P retentions were between those at Lieto and Ojainen. The retention percentage was higher in Nuutajärvi (58%) than in Paimionjoki (45%), but the clearly higher average input loading in the Paimionjoki sites led to higher amount of retained P, and thus better cost-effectiveness.

When CWs are planned, it is typical to try to avoid underdimensioning, i.e. to aim at as-long-as-possible WRT so that the water purifying processes could function effectively. To some point this is justified but, if exaggerated, this may lead to low input loading and thereby low mass (kg) retentions and not-so-good cost-effectiveness in spite of probably high relative (%) retentions. One good solution to combine long WRT and high input loading is to increase input concentrations by locating the CWs close to the sources of loading. In terms of hydraulic loading (inflow), one should find an optimal solution which combines long enough WRT, yet substantial nutrient input and moderate construction costs. The very same principles apply also to AWs. The high dissolved P retention-%:s suggest that none of the experimental AWs of this project was underdimensioned to an extent that the contact time between water and sorption material (analogous with WRT of CWs) would have become too short. Even the lowest percent retention in Ojainen (26%) was probably rather due to short-circuiting of flow via preferential flow paths than too short contact time (Uusitalo et al. 2013).

As in the case of AWs, the cost-effectiveness examination for CWs also emphasized the importance of high input loading. A comparison with AWs (Table 16) showed that if CWs can be made without expensive massive excavation, they can be as cost-effective as AWs, at least in a small agriculture-dominated catchment such as Lieto. However, it seems that when the catchment is larger and input loading to CWs more diluted, well-functioning AWs are more cost-effective than CWs. On the other hand, the example of the Ojainen Sachtofer system in the Jokioinen catchment demonstrates the collapse of cost-effectiveness (see Table 16) if an AW system fails. One definite advantage of AWs is that they don’t need large area, which is in many cases an issue with CWs. On the other hand, CWs have their own advantages over AWs. Firstly, CWs are capable of retaining also suspended solids and N and secondly, additionally to water protection they have also other benefits such as habitats for waterfowl, improvement of landscape and sometimes recreational values.

Not all costs related to either AWs or CWs were dealt with in this work. For example, CWs need maintenance during their lifetime and AWs need some kind of sedimentation basin right after the dispenser system to settle the precipitated P, which can be dug up and recycled later. However, in our view, the presented cost-effectiveness figures are comparable approximations.

In the report of Ahopelto and Hjerppe (2012) cost-effectiveness of agricultural water protection measures was approximated to vary from around 100 up to almost 2 000 EUR/kgP. Even if the costs calculated in this study were not divided into the 10 years lifetime, all AWs and simulated CWs in this study (except the AW at Ojainen and CWs in Paimionjoki) fall into the most cost-effective end of the range presented in Ahopelto and Hjerppe (2012).

# 5 Conclusions

The target catchments selected for this study represent well Finnish field-dominated catchments with their variation in cultivation practices and other characteristics as well as in area. Indeed, the range between the 0.7-$km^2$ Lieto catchment and 1 088-$km^2$ Paimionjoki river basin is huge and gives a good perspective of the different scales. Since the VIHMA model only deals with loading from field areas, the simulated specific nutrient loading in the target catchments varied according to their field characteristics. Here, the accurate, field-block level TIKE input data was very valuable and increased the reliability of the results. The nutrient loading simulated for each catchment was an important part of the assessments of the effects of both CWs and AWs.

The locating the strategy of CWs is a crucial issue regarding both water protection effects and cost-effectiveness. According to the results of this study, locating near the sources of loading is highly recommended. In terms of AWs, dispenser site selection is also crucial to cost-effectiveness. With diluted waters P precipitation will be substantially lower than with waters rich in P. Thus, the optimal dispensing point of chemical is in the immediate vicinity of agricultural production areas. In this respect, “hotspots” such as cowsheds, milk houses, horse stables etc. should be of special interest when sites for AWs (and CWs) are selected.

Both AW systems and “traditional” CWs, when decently implemented and wisely located, are cost-effective alternatives for water protection and thus worth serious consideration. However, because their cost-effectiveness depends greatly on suitable places, they cannot be recommended everywhere. Moreover, the fact that the final decision whether an AW or CW is established or not is made by the land-owning farmer, further constricts the possibilities of these water protection methods becoming more common. To increase the number of CWs and to introduce new AWs in the future, encouraging subsidy system and dissemination of information on these methods among farmers are needed.

As for AWs, a settling basin after the chemical dispensing system is highly recommended, although it somewhat increases the costs. As a deeper pond-part should be included in CWs, this kind of pond or basin should be an elemental part of an AW system. From the basin, the precipitated P can easily be dug up, which is in line with the nutrient recycling principle that, particularly regarding P, will become a globally crucial issue in the future.

Based on the study on the River Porijõgi, it can be conluded that open wetlands cannot alone clean up agricultural diffuse pollution. However, in combination with other measures, these could potentially reduce the phosphorus load in flat areas with clay and peat soils in case of the abundant availability of low value land. The cost-efficiency of measures require additional investigations. The current model lacks a nitrogen assessment as well as a number of other measures to combat agricultural diffuse load. Also, a RasterMode model has not been tested in larger areas, such as in an entire river basin where other phenomena and problems might appear.

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