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ACTION C3. Implementation for N-removal scenario for a large river basin

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Content

1. Introduction

The implementation of large scale water quality models coupled with economical models are a valuable tool to help water managers define the reduction in loading involved in reaching a good ecological status. Within action C3 (Implementation of N-removal scenarios for a large river basin), we upscaled the Vanajavesi study to the whole Kokemäenjoki river basin (27046 km^2, lake percentage 11%) by using the water quality model VEMALA v.3 (Korppoo et al., 2017). Mainly due to the variation in the weather data over the large river basin, the results of INCA-N from the Mustajoki catchment could not be upscaled. However, the VEMALA v.3 model can simulate water quality, retention and various loading scenarios over large catchments. Therefore, the implementation of INCA-N results coupled with the economical model in the Vanajavesi catchment is replaced in the Kokemäenjoki river basin by the application of VEMALA v.3 and the estimation of the cost-effectiveness of various agricultural management actions.

The Kokemäenjoki river discharges to the Bothnian Sea, which is largely N limited. The VEMALA model is an operational, national scale nutrient loading model for Finnish watersheds (Huttunen et al., 2015). The model simulates daily nutrient load from land areas, incoming loads to each lake which is larger than 1 ha, nutrients transport and processes in rivers and lakes and finally loading into the Baltic Sea. VEMALA includes field level simulation of arable land, each field plot is simulated separately taking into account slope, soil type, crop, fertilization and cultivation practices of the field. Simulation of natural background loading and loading from forestry, point sources, scattered settlements and atmospheric deposition is also included. The model simulates nutrient gross load, retention and net load from Finnish watersheds to the Baltic Sea. It includes two main sub-models, the WSFS hydrological model (Vehviläinen, 1994) and the VEMALA water quality model (Huttunen et al., 2015). The new version of VEMALA, VEMALA v.3 (Korppoo et al., 2017) has been implemented in this project. In VEMALA v.3 the nitrogen retention within the river/lake network has been improved. The river and lake nutrient processes were described in Deliverable 3.3. The state variables included in the model are oxygen, nutrients (organic nitrogen, nitrate (NO_3^-) and ammonium (NH_4^+), phosphate (PO_4^{3-}), organic phosphorus and inorganic particulate phosphorus), suspended sediments, total organic carbon and phytoplankton.

In this final report, we present the reduction of the total nitrogen loading in four separate agricultural scenarios over the Vanajavesi and Kokemäenjoki catchment using the most common agricultural management measures: accurate fertilization for different crops, direct sowing, manure injection and catch crop. The economic cost of each agricultural scenario is estimated as well as the impact on the water quality at the outlet of Kokemäenjoki over the period 2020-2029 for two scenarios: 1) all agricultural actions are implemented in the Kokemäenjoki catchment 2) Implementation of the sediment filtration system, which shall increase to 80% the final nitrogen loading reduction from wastewaters, from the present 55%. The impact of each scenario on the loading to the Bothnian Sea is evaluated.

2. Kokemäenjoki/Vanajavesi catchments

The whole Kokemäenjoki river basin is 27046 km^2 with a lake percentage of 11%. Kokemäenjoki drains to the Bothnian Sea through the city of Pori and is the fourth largest river basin in Finland (Figure 1). Lake Vanajavesi and its upstream drainage basin consist of ca. 2700 km^2, i.e. 10% of the Kokemäenjoki river basin. Lake Vanajavesi catchment includes the first-level sub-catchment 35.8 and the second-level sub-catchment 35.23, which represents about 20% of the drainage basin of the first-level sub-catchment 35.2.

In the Kokemäenjoki catchment up to 42% of the terrestrial nitrogen loading originates from agriculture, while point sources represent 17% and it characterizes 41% and 14% of the river Kokemäenjoki nitrogen load to the Bothnian Sea respectively (Figure 2). The areal nitrogen loading from arable lands is comparable in the entire catchment (Figure 3b); however, nitrogen retention varies remarkably within the Kokemäenjoki catchment. The retention of nitrogen is lowest in the downstream part of catchment, in the first level sub-catchments 35.1 and 35.9 (Figure 1 and 3a). The retention of nitrogen originating from the Vanajavesi catchment is 25%, meaning that 75% of the nitrogen load from Vanajavesi reaches the Sea.

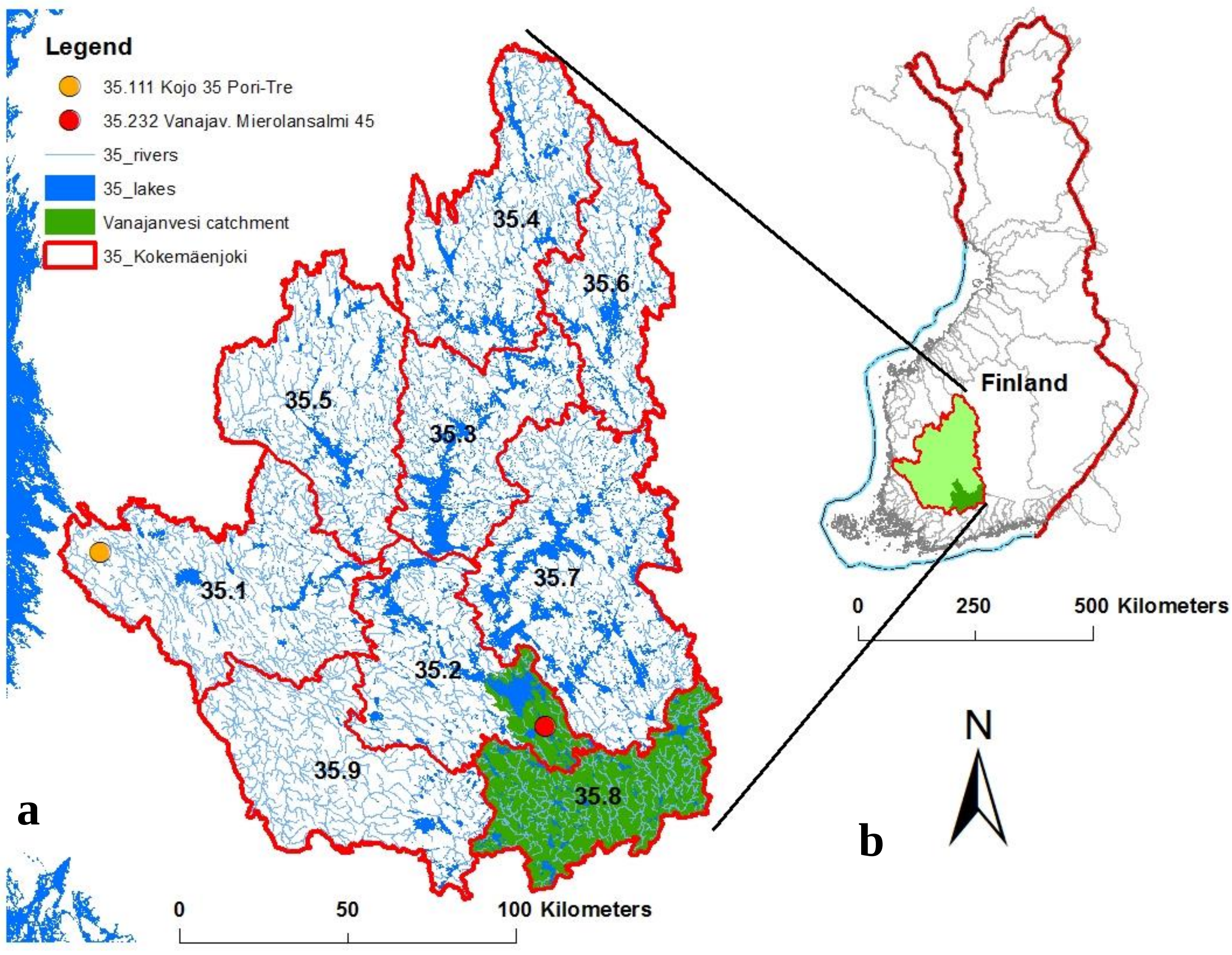

Figure 1: a- Kokemäenjoki catchment with first level sub-catchments (35.1, 35.2, 35.3, 35.4, 35.5, 35.6, 35.7, 35.8, 35.9) and Vanajavesi catchment highlighted in green (35.8 and 35.23). b- Finland with highlighted Kokemäenjoki and Vanajavesi subcatchments.

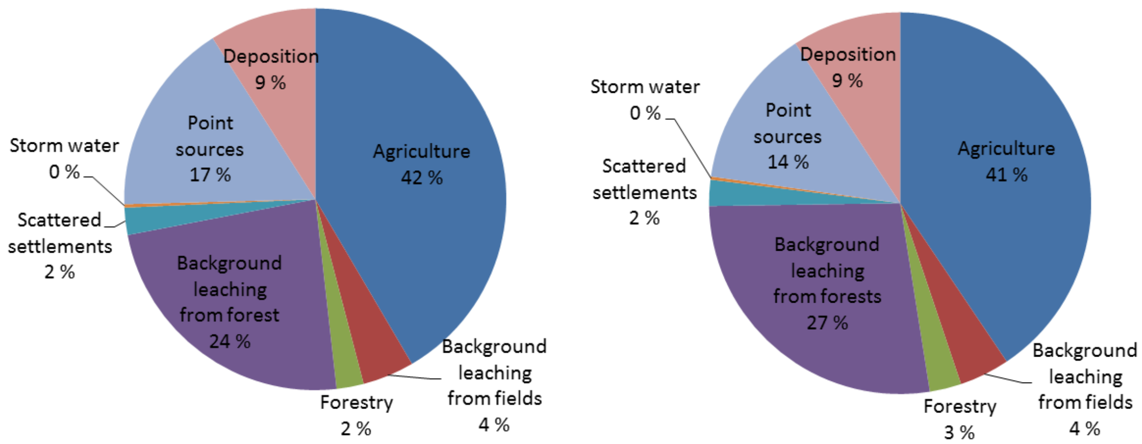

Figure 2: Nitrogen loading sources in a- in the terrestrial loading from the Kokemäenjoki catchment and b- at the outlet of the Kokemäenjoki river basin, discharging to the Bothnian Sea. Retention of loading from different sources variates due to variation of nitrogen fractions and location of the loading.

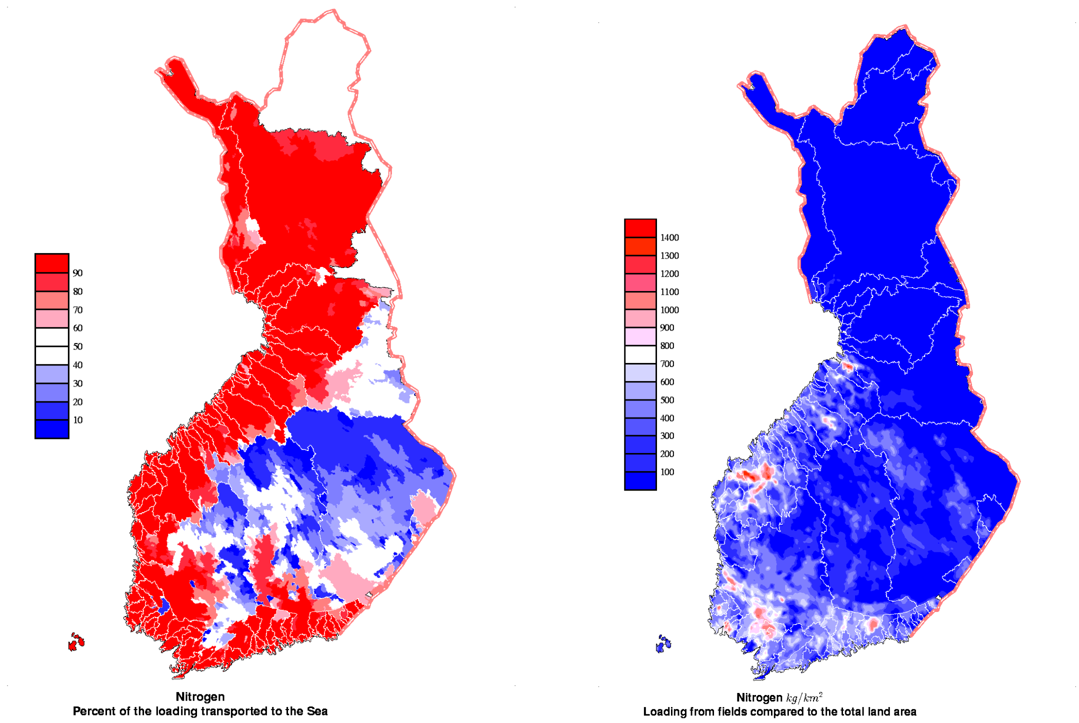

Figure 3: a) Percentage of nitrogen loading transported to the Sea. b) Nitrogen loading from fields compared to the total land area (kgN km^{-2}).

The implementation of the VEMALA v.3 model to the Kokemäenjoki river basin has been validated in Deliverable 7.3. The simulated annual loadings for total nitrogen were comparable (-18% –+15% over the period 2006-2011) to the estimated loading from the HELCOM's Fifth Baltic Sea Pollution Load Compilation (2011) to the Bothnian Sea from the Kokemäenjoki catchment (Deliverable 7.3). The average over the period 2006-2011 of the net annual loading from the Kokemäenjoki catchment to the Bothnian Sea was comparable for total nitrogen in the simulation (9502 tN yr^{-1}) than in the estimation (9743 tN yr^{-1}). The average over the period 2006-2011 of the net annual loading from the Vanajavesi catchment was 2218 tN yr^{-1}, representing about 23% of the total nitrogen load to the Bothnian Sea originating from the Kokemäenjoki catchment.

In the VEMALA v.3 simulation, nitrate and ammonium represented on average 69% and 1% respectively of the total nitrogen load to the Bothnian Sea over the period 2006-2011 (Deliverable 7.3).

3. Agricultural scenarios

By combining information about possible actions in agriculture and retention of nitrogen in rivers and lakes we can estimate the amount and location of cost effective agricultural management actions. Using VEMALA v.3 coupled with the ICECREAM sub-model that simulates various agricultural scenarios; we estimate the extent and cost of the reduction in nutrient loading to the Bothnian Sea from the Kokemäenjoki river basin over the period 2020-2029. The agricultural management actions were applied at a field level using the ICECREAM sub-model. The impact of a management action on a specific field depends on the soil characteristics (slope, soil type, P-number) and agricultural crop selected. Such measures include:

1. Accurate fertilization. This measure is applied in all fields. However, if the nitrogen balance (fertilization-yield) in the field is less than 40kgN yr^{-1}, then fertilization is not limited. If the nitrogen balance is above 40kgN yr^{-1}, the fertilization is limited and reduced by 0-10kgN yr^{-1}. Finally, if the balance is above 50 kgN yr^{-1}, fertilization is limited and reduced by 10 kgN yr^{-1}. Accurate fertilization can be implemented in practice by applying fertilizer accurately by estimating the yield together with the actions which aim at achieving good yield also during unfavorable years (upkeeping of drainage and good soil structure, adequate crop protection). Cost of action: 54 €/ha/year.

2. Direct sowing. This measure provides vegetation cover during the winter, omitting autumn plowing. Cost of action: 36 €/ha/year.

3. Manure injection. In this management action, the manure is not applied at the surface of the soil but in deeper soil layers. Cost of action: 43 €/ha/year.

4. Catch crops. Catch crops are used alongside spring cereals. Plant residues of the catch crop are either left on the ground over the winter if direct sowing is applied or are plowed in the autumn. Cost of action: 100 €/ha/year, no support for action 2 if action 4 is applied.

In this study, the costs of actions implemented originate from the River Basin Management Plan. The use of buffer zones, which is a common action, was omitted in this study since the effect on nitrogen leaching is not relevant. If both phosphorus and nitrogen reduction are targeted simultaneously, as is the normal case in Finnish catchments, buffer zones can be included.

The arable land covers about 266 000 ha (TIKE field data from 2012) in the Kokemäenjoki catchment. However, the areal extent of the application of agricultural management actions depends on the action and on the present use of the arable land. The areal extent of each measure versus the reduction in loading associated with the application is presented in Figure

4. Accurate fertilization and direct sowing can be widely spread over the whole catchment up to about 200000 ha. Catch crop is slightly limited to about 170000 ha, while manure injection can only be applied over about 66000ha in the Kokemäenjoki catchment. By applying the action over the maximum land area possible, catch crop is the action that would reduce the most nitrogen loading to the sea by about 580 tN yr^{-1}, direct sowing would reduce the loading by about 400 tN yr^{-1}, accurate fertilization by about 200 tN yr^{-1} and manure injection by about 25 tN yr^{-1}. If we consider Vanajavesi catchment alone, which includes catchment 35.8 and about 20% of 35.2, catch crop would reduce the most nitrogen loading from the catchment by 71 tN yr^{-1}, direct sowing would reduce the loading by 40 tN yr^{-1}, accurate fertilization by 23 tN yr^{-1} and manure injection by 3 tN yr^{-1}. Therefore, by applying all the actions over the maximum land area possible, the maximum nitrogen loading reduction to the Sea achievable with the agricultural scenarios in the Vanajavesi catchment is 137tN yr^{-1}.

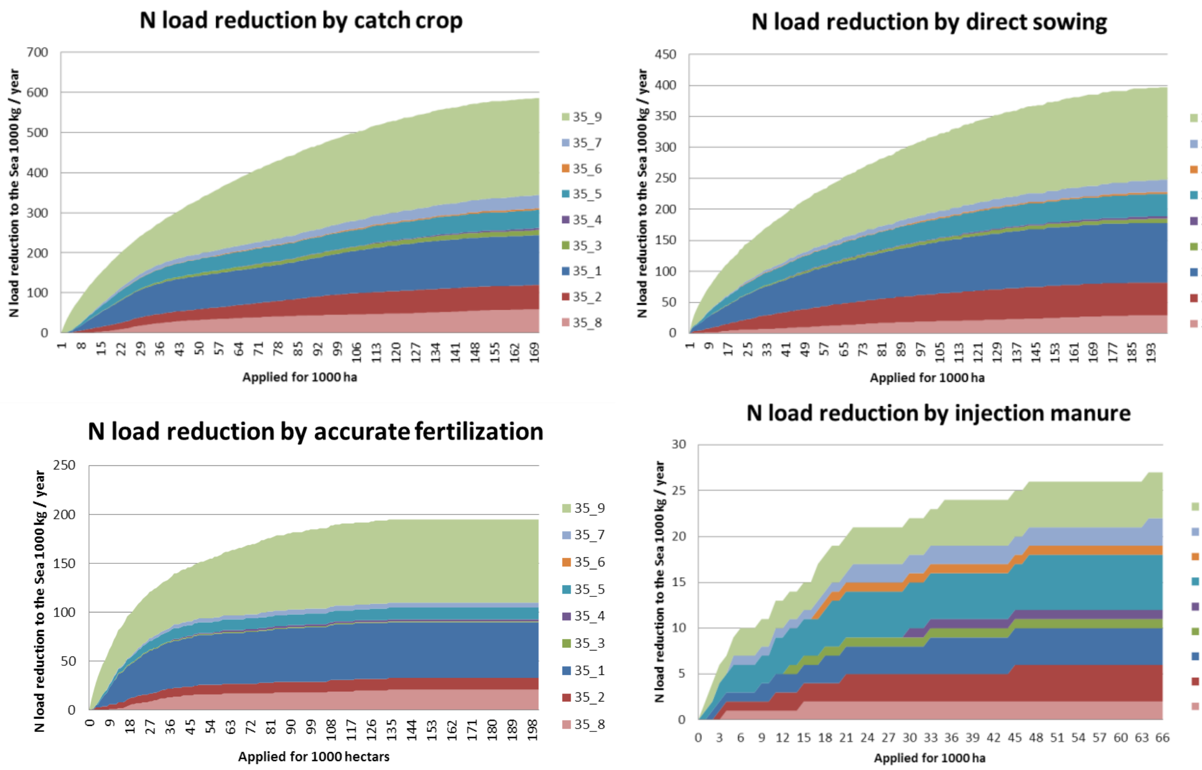

Figure 4: Total nitrogen load reduction to the Sea versus areal application for each agricultural management measure (accurate fertilization, direct sowing, manure injection and catch crop).

In Figure 5, the result of the application of all agricultural management measures over the maximum arable land area available for each action is presented in the Kokemäenjoki catchment area. The most cost-effective individual measure proved to be the catch crop (Figure 5). Indeed, by spending 20€ per kgN load reduced, with the catch crop action the total nitrogen load to the Sea can be reduced by 400 tN yr^{-1}. Direct sowing is also a cost-effective action where the total nitrogen load can be reduced by 280 tN yr^{-1}, if we limit the cost at 20 € kgN^{-1} reduced. Accurate fertilization (about 100 tN yr^{-1}) and manure injection prove to be to less effective in the Kokemäenjoki catchment. Probably the most uncertain in these estimates is the effect of accurate fertilization, because at present we have no field level fertilization or yield data for estimation of present nitrogen balance variation in different fields. The field by field variance of fertilization is first estimated and then verified by modelling nitrogen loading with the estimated fertilization and comparing loading to river and lake concentration measurements.

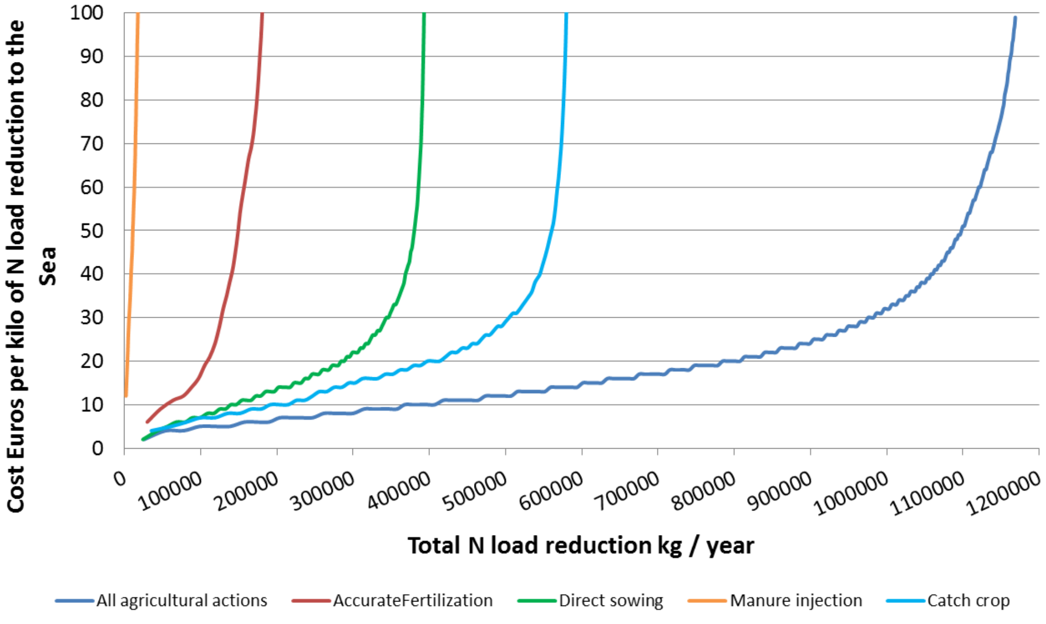

Figure 5: Cost in euros per kilo of the potential total nitrogen load to the Sea, with the total nitrogen load reduction to the Sea in kg yr^{-1}

The application of all agricultural management actions, where possible, would reduce the total nitrogen load to the sea from the Kokemäenjoki river by 1200 tN yr^{-1} and cost about 32 million € yr^{-1} (Figure 6). The goal is to reduce the nitrogen load originating from human sources (e.g. agriculture, point sources, forestry etc.) by 7% to the Bothnian Sea. The average loading from the Kokemäenjoki catchment originating from the human activities is about 6900tN yr^{-1}. Therefore, the reduction in the nitrogen load reaching the Bothnian Sea should reach about 500tN yr^{-1}. By dropping the target reduction from 1200tN yr^{-1} to 500 tN yr^{-1}, the annual cost could theoretically drop to 4 million € yr^{-1} according to our estimates and using our most efficient agricultural measures. In this scenario the whole 500tN yr^{-1} reduction is obtained by actions in agriculture only, the other sources remain on the present level. The reference level of these reduction actions is farming with present fertilization and without direct sowing, manure injection and catch crop. The reduction and costs of actions is compared to this reference level, not to the present loading. The reason for this is that the present actions are not necessarily the most cost effective ones by action type or location and we aim to present the cost and effectiveness of actions applied in the order of cost-effectiveness.

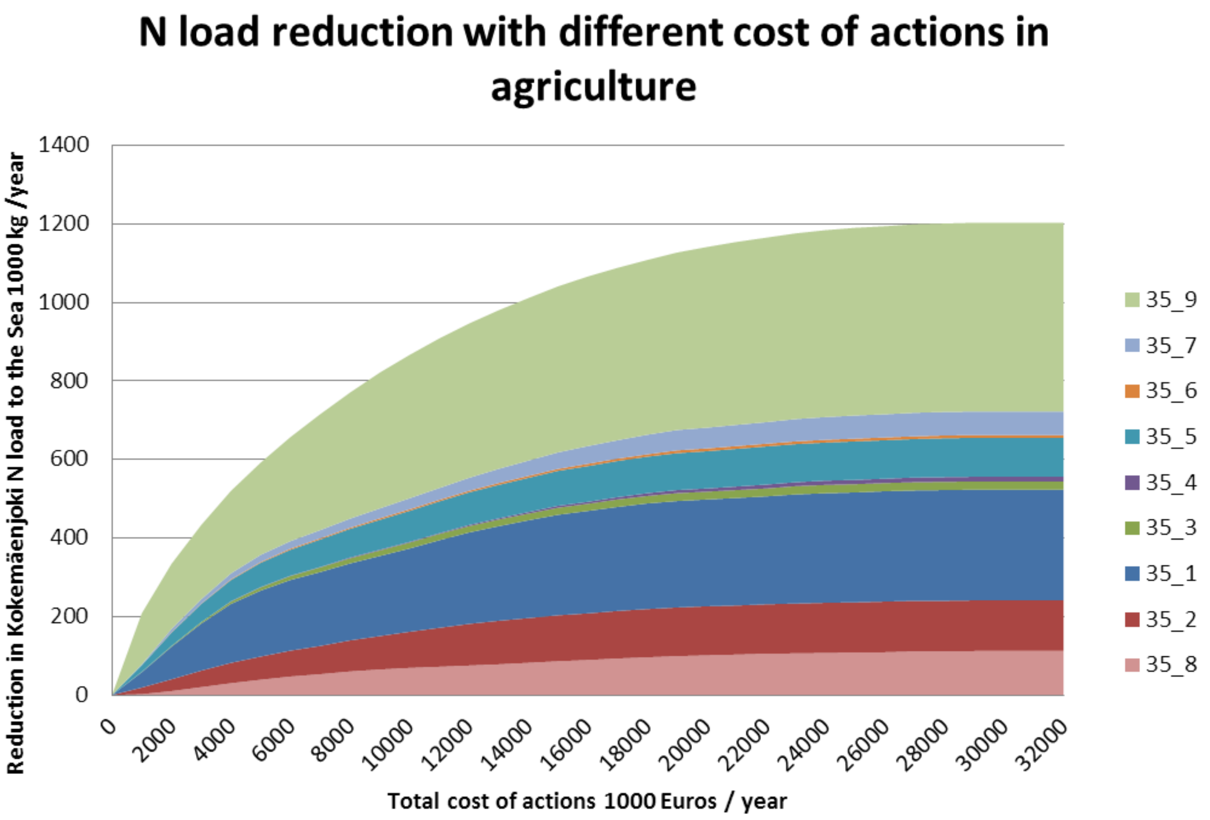

Figure 6: Cost of the nitrogen load reduction to the Bothnian Sea when cost-effective agricultural actions are applied.

4. Impact of scenarios on the nitrogen loading

The impact of two scenarios on the loading to the Bothnian Sea and from the Vanajavesi catchment is evaluated using VEMALA v.3. The first scenario (Agri) accounts for the application of all agricultural management measures, to reduce the agricultural nitrogen loading, presented in paragraph 3 of this report. The agricultural actions are accurate fertilization, direct sowing, manure injection and catch crops in spring cereals. The second scenario (WWTP) accounts for the enhancement of the nitrogen reduction of all the Finnish wastewaters from 55% to 80% using the sediment filtration method. The model is applied over the period 2020-2029 with the weather input from the weather observed during 2005-2014 modified with A1B average climate change scenario with delta-change method.

The VEMALA v.3 simulation of nitrogen loading from the Kokemäenjoki catchment under present conditions over the period 2020-2029 estimates an average loading of 9425 tN yr^{-1}. Under the Agri scenario the average nitrogen loading to the Bothnian Sea decreases to 8430tN yr^{-1} (a reduction of about 1000tN yr^{-1} or 10%) ranging from -7 – -14% (-510 – -1470 tN yr^{-1}) compared to the present scenario (Figure 7). The nitrogen loading in the WWTP scenario decreases to on average 7930tN yr^{-1} (a reduction of about 1500tN yr^{-1} or 15%) ranging from -13 – -19% (-1330 – -1850 tN yr^{-1}) compared to the present scenario over the period 2020-2029.The reduction of the nitrogen loading is higher in the WWTP scenario than in the Agri scenario, except in 2021 when the two present similar reductions in loading. The annual variation of loading is due to different hydrological years.

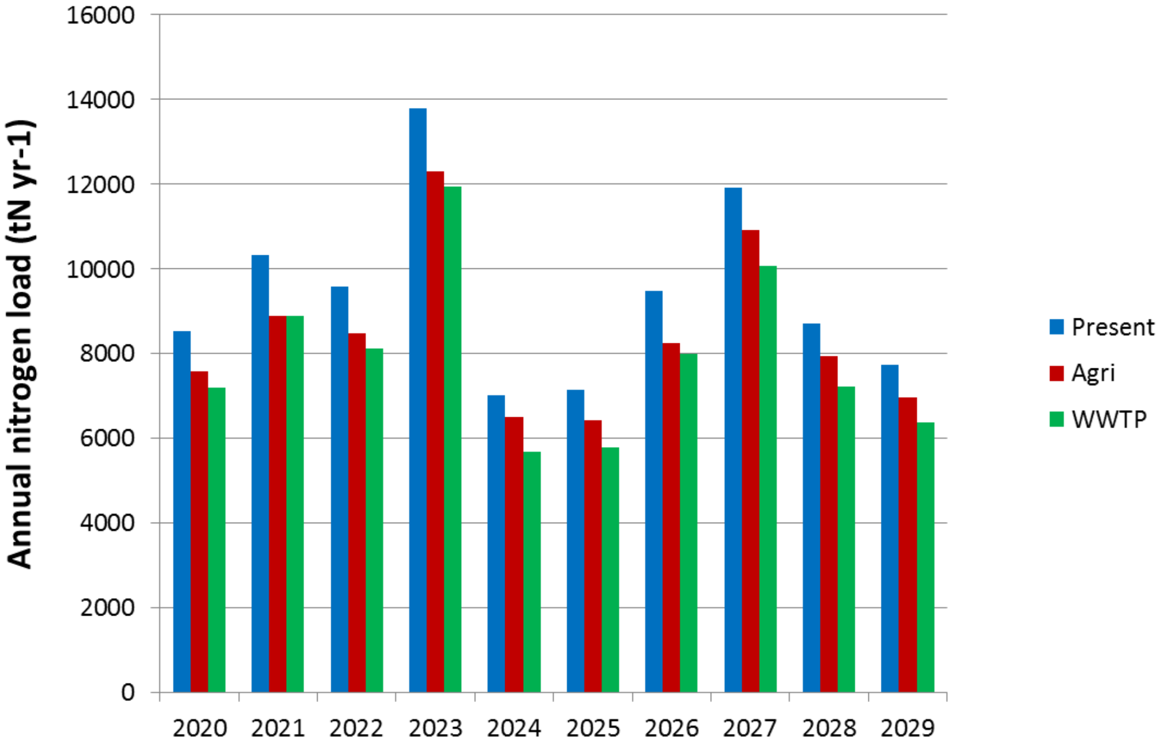

Figure 7: Annual total nitrogen loading to the Bothnian Sea from the Kokemäenjoki catchment over the period 2020-2029 under present agriculture and point source loading (Present), under scenario Agri and WWTP.

In the Vanajavesi catchment, we estimated that by implementing all the Agri scenario over the entire Vanajavesi catchment, the nitrogen loading could be reduced by a maximum of 137tN yr^{-1}, meaning the reduction in nitrogen loading would reach 182tN yr^{-1} at the outlet of the Vanajavesi catchment as the retention downstream of Vanajavesi is 25%. Therefore, the total nitrogen loading would be reduced from 2218tN yr^{-1} to 2036tN yr^{-1} (about 8%). If we consider the WWTP scenario, as the Vanajavesi catchment receives on average 277tN yr^{-1} from the WWTP. If the WWTP increased their nitrogen reduction from 55% to 80% before releasing their waters to the freshwater ecosystem, the average WWTP loading would be around 122tN yr^{-1}. Therefore, achieving a reduction in nitrogen loading of 155 tN yr^{-1}, thus the nitrogen loading from Vanajavesi would be reduced from 2218tN yr^{-1} to 2063tN yr^{-1} (about 7%). According to our simulations, the maximum nitrogen reduction achievable in the Vanajavesi catchment would be 337tN yr^{-1} (about 15% of the present nitrogen load). This reduction in loading is therefore close to the target of 300tN yr^{-1} if all nitrogen reduction measures were implemented from both the Agri and WWTP scenarios.

5. Impact of scenarios on the water quality

The simulation of the total nitrogen concentrations at the outlet of the Kokemäenjoki catchment shows that the two scenarios affect different loading periods during the year (Figure 8). Indeed, the Agri scenario reduces more the total nitrogen concentration during the flood peaks and the high loading periods, while the WWTP affects more the dry periods of the year (summer and winter during low flows), thus the low loading periods. The annual average TN concentration at the outlet of the Kokemäenjoki river basin was simulated over the period 2020-2029 as 1.11mg L^{-1} under present conditions and decreased to 1mg L^{-1} in the Agri scenario and 0.9mg L^{-1} in the WWTP scenario.

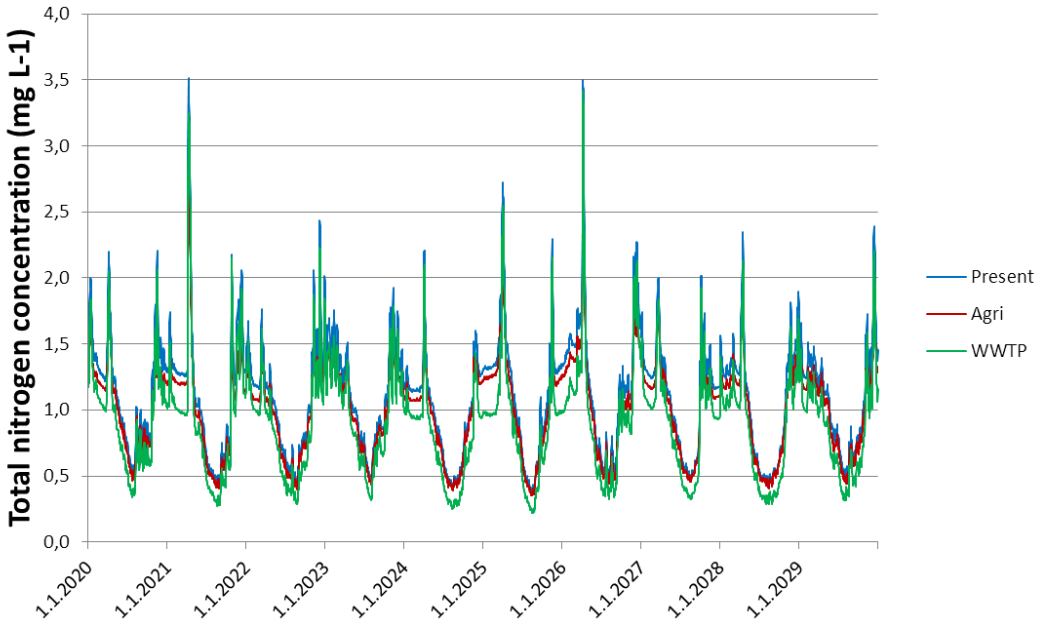

Figure 8: Total nitrogen concentrations (mg L^{-1}) at 35.111 Kojo 35 Pori-Tre as simulated under the present, Agri and WWTP scenarios over the period 2020-2029.

The simulation of the total nitrogen concentrations at the observation point Vanajav. Mierolansalmi 45 shows that the target concentration of 0.6 mg L^{-1} is not reached in either of the scenarios at the main inlet of the Lake (Figure 9). The annual average total nitrogen concentration at the inlet of Vanajavesi reaches 1.21 mg L^{-1} under the present scenario over the period 2020-2029. This annual average drops to 1.16 mg L^{-1} under the Agri scenario and 1.07mg L^{-1} under the WWTP scenario. In the Agri scenario the annual average concentration of total nitrogen in Vanajavesi Lake drops to about 1 mg L^{-1} and in WWTP scenario to about 0.8 mg L^{-1}. The application of both scenarios combined could decrease the average total nitrogen concentration further with a possibility to achieve the target concentration of 0.6mg L^{-1} required in the Vanajavesi Lake to reach a good ecological status. The Agri scenario reduces more the total nitrogen concentration during the flood peaks and the high loading periods, while the WWTP affects more the dry periods of the year (summer and winter during low flows), thus the low loading periods.

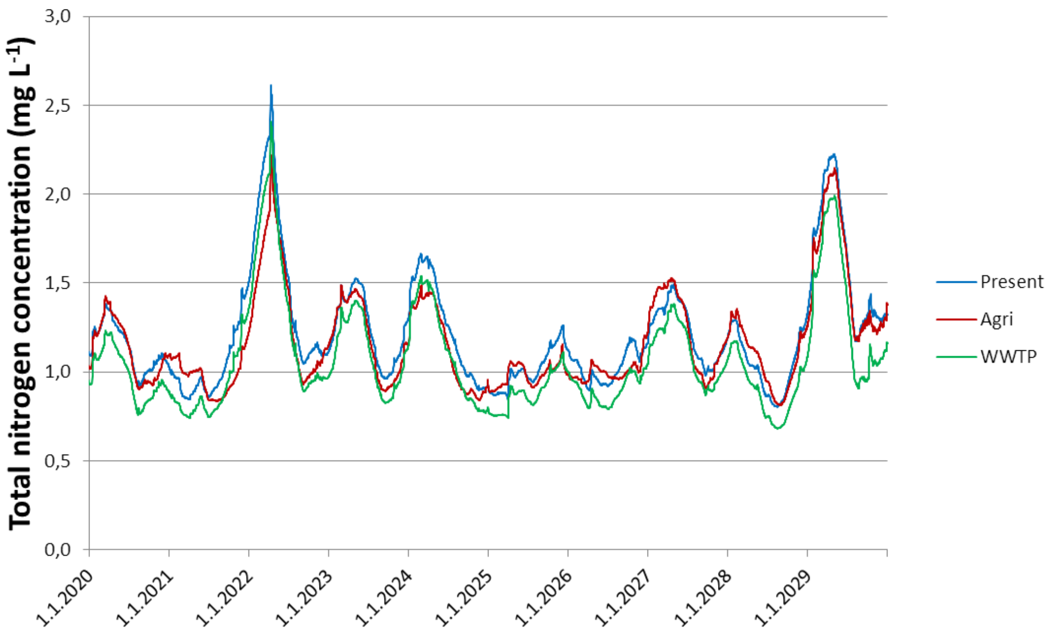

Figure 9: Total nitrogen concentrations (mg L-1) at 35.232 Vanajav.Mierolansalmi 45 as simulated under the present, Agri and WWTP scenarios over the period 2020-2029.

6. Conclusion

In Action C3 of the N-SINK project we simulated nitrogen loading and two separate scenarios to reduce nitrogen loading in Vanajavesi and Kokemäenjoki catchments using the water quality model VEMALA v.3. The application of the first scenario Agri (all agricultural management actions implemented), reduced the total nitrogen loading from 9425tN yr^{-1} to 8430tN yr^{-1}, a decrease by about 10% over the simulated period 2020-2029. The reduction in loading is concentrated in the high flow periods in the spring. The application of the WWTP scenario (implementation of the sediment filtration system to increase the reduction in loading from wastewaters from the current 55% to 80%) reduced the total nitrogen loading to the Sea to 7930tN yr^{-1}, a decrease by about 15% over 2020-2029. The impact of a reduction in nitrogen loading from wastewater treatment plants affects the total nitrogen concentrations particularly during low flow periods (summer and winter). These results show that although the total nitrogen loading in the Kokemäenjoki catchment is dominated by agricultural loading (41%) compared to only 14% originating from point sources, the WWTP scenario is valid and reduces the total nitrogen loading to the Bothnian Sea significantly up to 1850 tN yr^{-1}.

In the Vanajavesi catchment, the application of all the agricultural measures to reduce nitrogen loading could decrease the load from 2218tN yr^{-1} to 2036tN yr^{-1} by about 8%. On the other hand the implementation of the sediment filtration system could reduce the load from 2218tN yr^{-1} to 2063tN yr^{-1} by about 7%. If all the agricultural actions and all the wastewater treatment plants were increasing their efficiency in nitrogen removal to 80%, the Vanajavesi catchment could theoretically reach the reduction target of 300tN yr^{-1} and reach an annual average concentration of total nitrogen of 0.6 mg L^{-1}.

In the river basin management plan, the targets for reducing both nitrogen and phosphorus loading are considered together. The effectiveness of actions in agriculture to reduce nitrogen and phosphorus loading varies. Therefore, river basin management planning would benefit from studies, in the continuity of this project, assessing the cost effective set and location of actions impacting both nitrogen and phosphorus.

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