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Transport and retention of pollutants from different production systems

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Transport and retentions of agricultural pollutants both at farm level and catchment scale are key challenges faced by researchers, environmental managers, and regulatory agencies. Researchers have responded to this challenge by either monitoring or modelling strategies. Models, both empirical and theoretical, have been developed and used at different scales trying to evaluate the dynamics of the pollutants as they move from upland agricultural areas to water bodies. Monitoring studies at different scales (plot, field, catchment) have tried to represent the natural system and provide data-base for calibrating and testing mathematical models. Scientists have also used both modelling and monitoring strategies to evaluate the impact of different management practices such as contour cropping, vegetated buffer strips, riparian zones, and constructed wetlands on reduction of pollutant loads to water bodies. Manuscripts presented in this special issue provide results of both modelling and monitoring at different scales as they relate to transport and retention of nutrients in different landscapes. For example, it covers application of SWAT model in Finland to meet the environmental goals of European Water Framework Directive, and application of the same model in the US to meet the Total Maximum Daily Load mandated by US's 1972 Clean Water Act. Also covered are results on nutrient and sediment reduction due to different management practices including vegetated buffer strips, riparian zones, and constructed wetlands. Overall results of monitoring indicate effectiveness of such practices in attenuating sediment and nutrients, thus reducing their entry into the water bodies.

Introduction

Transport and retention of nutrients and pollutants at catchment scale are the key issues in environmental management directly influencing the quality of both productive fields in the upland and also freshwater bodies, wetlands and coastal ecosystems (Arheimer and Brandt 1998). To establish strategies for sustainable nutrient management, the priority of each identified element (upland, wetland, etc.) for different user groups (farmer, researcher, regulator, and consumer) at different scales need to be addressed (Shirmohammadi *et al*. 2005). In European Union (EU), the Water Framework Directive (WFD) as a framework for a European environmental legislation aims to harmonize existing European water policies and to improve water quality in all aquatic environments within the community area (Rekolainen 2006). This is a new integrated approach resulting in the protection and improvement of the sustainable use of all waters by introducing catchment management throughout Europe, thus having major impacts on the conservation and restoration of aquatic ecosystems (Pollard and Huxham 1998). United States Congress established the TMDL (Total Maximum Daily Load) program in the original Clean Water Act of 1972, Section 303(d) list (US Congress 1972), but it did not get much attention until 1991. Based on this Act, each state is required to identify the impaired water bodies based on its intended use and develop TMDL plans to resolve the impairment issues (Tetra-Tech 2005). Currently, two methods are available for tracking pollution in the environment and assessing the effectiveness of the FWD and TMDL process in improving water quality of impaired water bodies: field monitoring and modelling. Field monitoring may be the most appropriate and valuable method, but its use is limited due to high cost and extreme spatial and temporal ecosystem variability. Therefore, mathematical models provide an alternative to monitoring and can save time, reduce cost, and minimize the need for testing management alternatives.

Modelling of pollutant dynamics according to their source and sink areas, adequate measurement and modeling of retention processes are the key questions in successful implementation of water management policies including the TMDL and WFD (Rekolainen 2006, Shirmohammadi *et al*. 2006). Further investigations of nutrient dynamics are needed because some analyses show that the measures undertaken to reduce nutrient losses from agricultural catchments have not given satisfactory results. For instance, Granlund *et al*. (2005) showed that in the studied catchments in Finland little or no reduction of loads was achieved during the first period (years 1995–1999) of the Finnish Agri-Environmental Programme. The results suggest that water protection measures for agricultural production need to be further intensified if the eutrophication tendency of Finnish lakes, rivers and coastal waters is soon to be reversed. The delayed response of water quality must be taken into account in the implementation of the WFD (Granlund *et al*. 2005).

The aim of this paper is to highlight some significant aspects of the transportation and retention of pollutants from various production systems, especially regarding the issues considered in the 373rd seminar of the Nordic Association of Agricultural Scientists (NJF).

Modelling of nutrient transport at catchment scale

Numerous models are available to characterize pollutant transport and retention in landscapes. According to the DPSIR (Drivers, Pressures, State, Impact, Responses) approach (Parris 1998, Wascher 2000), models can be classified following Rekolainen (2006) as:

- Pressure quantification models are used to calculate pollution loading estimates from the present and anticipated future situations for drivers. These models range from simple regression and transfer coefficient models to comprehensive process-based models for point and non-point source pollution. These types of models and calculation methods are widely available, but models assessing hydro-morphological pressures and toxic substances might need further development.
- Chemical models are capable of using pressure information as input and accounting for relevant physical and chemical processes in surface and groundwater to produce the chemical state as the output. There are various examples for these types of models including river models, groundwater and lake models, and ranging from simple retention models to comprehensive commercial software packages.
- Ecological dose-response models can be used to simulate the causal relationships between the chemical status and ecological status. There are a number of models available that can account for some biological quality elements referred to in the WFD. Further work is required for models describing the complex relationships between water chemistry and other ecological quality elements. Some achievements could be made by improving the existing models, but also new

tools and methods are needed to assess the links between pressures, chemical status and ecological status, and also the direct links between hydromorphological pressures and ecosystem status.

In addition, socio-economic models and tools can be used to assess the effect of policy measures on different economic actors, i.e. how the actors respond to certain administrative, economic or information based policy instruments (linkage between Response and Driving forces). Again, optimization models, econometric models and partial equilibrium models may be used. Finally, other types of models may be needed to verify the expected ecosystem responses following the decided practices and implementations, thus evaluating their calculated effects on pressures and chemical state (Rekolainen 2006).

Most of the well-known models on nutrient (pollutant) transport and retention at catchment scale can be classified as Pressure models. The core of all these models is the hydrologic model, which acts as the driving force for transport and retention of various pollutants (Johnes 1996, Chu and Shirmohammadi 2004). One of the first widely used catchment-scale models is the AGNPS (AGricultural NonPoint Source) model (Young *et al*. 1989) which in combination with GRASS (Geographic Resources Analysis Support System) and GIS (Geographical Information System) has been successfully used for adequate prediction of runoff and sediment delivery from small watersheds (Mitchell *et al*. 1993). The process-based mass balance models like INCA are widely used in several catchments for assessing the effect of multiple sources and retention sites of nutrients on the water quality and aquatic ecology (Wade *et al*. 2002). Also, the INCA model has been successfully applied for assessing possible impacts of climate change on N deposition in boreal catchments (Kaste *et al*. 2004). Another well-known and well elaborated dynamic catchment model similar to INCA is the HBV model elaborated by the Swedish Meteorological and Hydrological institute (SMHI) and successfully applied for several catchments in Sweden (Arheimer and Brandt 1998, Arheimer and Wittgren 2002, Andersson *et al*. 2005). The HBV-N model helped to locate potential wetlands for nitrogen removal in Swedish agricultural catchments (Arheimer and Wittgren 2002). A similar model to INCA and HBV which calculates both nitrogen and phosphorus emissions from point and diffuse sources and the riverine nutrient loading is the MONERIS, which has mainly been applied for German catchments (Venohr *et al*. 2005, Berlekamp *et al*. 2007). Analogous to the models described is the Danish model TRANS that combines catchment information to soil type and land use with a physical hydrodynamic modeling system and several semi-dynamic empirical models on diffuse nutrient loading and retention in rivers, lakes and riparian areas (Kronvang *et al*. 1999). Several empirical landscape-analysis based models with large time step have also been successfully applied for the catchment management and landscape planning (Mander *et al*. 2000, Steinhardt and Volk 2003).

Critical source areas

One of the main issues facing watershed planners is how land use and management at the small scale is connected to the quality of watershed outflow. In most watersheds, relatively small and well-defined areas typically contribute much of the non-point source water, sediment, P and N exported in outflow. From a prediction, management and control perspective, it is important to recognize and develop the concepts, modelling tools and sampling protocols, in order to delineate and assess the impacts of these critical source areas (Heathwaite *et al*. 2000, Pionke *et al*. 2000). These are the highest priority areas for control, treatment, and remediation within the watershed. On the other hand, areas at lower elevation within the watershed, such as riparian buffer zones, receive all of the water and solid-material based fluxes from the upland locations. Thus, the riparian areas are important sinks of material (Correll 2005).

Management and control decisions for P export must be developed within a storm-based, source-area framework. This is because most P export originates from the relatively few larger storms and the relatively small critical source areas within the watershed. Soil P fertility, manure, and P fertilizer management should focus on these critical source areas, times and storm sizes (Gburek and Sharpley 1998). Conversely, management and control decisions for N export depend more on balancing N use over the watershed. Nitrogen sources are more diffuse rather than concentrated in space, time and by storm characteristics. The major exceptions are source areas where N use is excessive in terms of mass balance (Pionke *et al*. 2000). Optimal strategies and practices are needed to simultaneously control P and N export at the farm and watershed scales. One water quality problem may be aggravated as a result of solving another. On-farm practices applied to reduce surface runoff and P export by increasing infiltration may increase ground water and NO_3 recharge (Shirmohammadi *et al*. 1992).

Ecological engineering measures for the controlling of nutrient transport from watersheds

The most typical ecological engineering measures controlling nutrient transport from watersheds are erosion control on upland areas and slopes (e.g., contour-strip cropping (Gitau *et al*. 2006), no-tillage treatment (Francis and Knight 1993), terracing (Sharpley *et al*. 2001), hedgerows (Baudry *et al*. 2000) and shelterbelts (Ryszkowski and Kędziora 2007)), free water surface (FWS) constructed wetlands (CW) for the treatment of polluted water from agricultural catchments (Verhoeven *et al*. 2006), and riparian buffer zones and buffer strips that have multiple ecological functions (Mander *et al*. 1997). Although the water purification effect of riparian ecosystems has been thoroughly studied (Haycock and Pinay 1993, Vought *et al*. 1994, Mander *et al*. 1997), little is known about their internal cycling (Lowrance *et al*. 1983, Peterjohn and Correll 1984), especially concerning gaseous emissions (Groffman *et al*. 1991, Teiter and Mander 2005). Moreover, some studies have shown that water purification efficiency can be less favourable in riparian zones, which function as hotspots of greenhouse gas emissions with high global warming potential (GWP; Groffman *et al*. 2000). Therefore, further studies on the nutrient budgets within the riparian zones are of great importance.

Constructed wetlands for wastewater treatment can be classified according to the life-forms of the dominating vascular plants and water flow regime (Vymazal 2001). Constructed wetlands have mostly been used for the purification of wastewater, and to improve water quality in streams, rather than for non-point pollution purification (Kadlec and Knight 1996). However, certain prototypes of CWs (e.g. macrophyte ponds and shallow wetlands, artificially flooded meadows, root filters, and streamside wetlands) can be effectively used for the treatment of polluted waters from agricultural fields (Gustafson *et al*. 2000, Braskerud 2002). They can be located in gullies, next to places of intensive fertilization or manure storage, for the purification of rainwater from manufacturing areas, roads, parking lots, etc. However, the location of these wetlands in the catchment is a key question. Only those located downhill and next to critical source areas (Pionke *et al*. 2000) or in the riparian zone can provide a significantly efficient nutrient retention.

It is mostly FWS CWs that have been used in watershed management, because of their significantly lower construction costs and material requirements (Kadlec and Knight 1996). The FWS CWs also have structural and functional attributes that can even enhance the quality of the landscape. Restored and enhanced wetlands can provide compensation credits for the loss of wetland functions caused by human development activities (Mitsch and Gosselink 2000).

Probably the most important single factor with regard to CW effectiveness is the size of a CW, i.e. its area in relation to the area of its catchment (*W*/*C* ratio). The relationship between CW effectiveness and *W*/*C* ratio has been noted in several recent studies (Kovacic *et al*. 2000, Koskiaho *et al*. 2003). In spite of the uncertainty that is inevitably involved with such rankings, the message is clear: if substantial (> 20%) load reductions are desired, the *W*/*C* ratio should be more than 2% (Koskiaho and Puustinen 2005). In the case of runoff water treatment, dimensioning should be based on the input water volumes of the highest annual runoff events, because the high water periods account for a great deal of annual loading (Koskiaho *et al*. 2003).

Although the retention processes in FWS CWs treating agricultural runoff are basically well-known, there are still many aspects to study. One of them is the effect of aggregation on sedimentation of clay particles in CWS (Braskerud *et al.* 2000).

The special issue

The special issue consists of eight selected papers presented at the 373rd NJF seminar on "Transport and Retention of Pollutants from Different Production Systems" held in 11–14 June 2006 in Tartu, Estonia. During the symposium, 23 oral and 12 poster presentations from Denmark, Estonia, Finland, Germany, Latvia, Norway, Sweden, and USA, were presented. The papers covered the following general topics: (1) transport of nutrients, particles, and pesticides from agricultural catchment areas, (2) nitrogen and phosphorus dynamics in riparian buffer zones, (3) modelling of nutrient losses at catchment scale, (4) modelling of water balance and nutrient cycling in riparian buffer zones, (5) the EU Water Framework Directive: a need for research and tools.

Different production systems in agriculture affect water quality in surface, baseflow, and ground water. However, reduced soil tillage and optimum use of nutrients and plant protection or establishing buffer zones between cultivated land and the watercourse may decrease the transport of pollutants from agriculture. EU Water Framework Directive will increase a need for new research and tools on this area. The special issue focuses on measurement, monitoring and modeling the transport and retention of nutrients and particles (erosion). Studies conducted on plot scale, farming system scale, and larger catchment scale are discussed.

In the first two papers Shirmohammadi *et al.* (2008) and Bärlund and Kirkkala (2008) describe application of a catchment scale model, SWAT (Soil Water Assessment Tool), to small scale agricultural watersheds in northern Maryland and in the Eurajoki basin, Finland. The results of both studies indicate that SWAT can be calibrated against measured data, especially for discharge, using a "short list" of key parameters, but further calibration is needed, especially for water quality variables. Also, outcomes show that using average input parameter values without considering their variability due to media heterogeneity produces simulation outputs that are not 100% certain. However, for the multiple dynamic modeling, especially in combination with other models such as a decision support system (DSS), the SWAT model serves as the best available tool (Chu and Shirmohammadi 2004, Shirmohammadi *et al.* 2005). However, further development of model systems is required to be applicable, for instance within the WFD of EU.

The paper by Deelstra and Iital (2008) provides characterisation of the hydrological behaviour of four small agricultural catchments in Estonia and Norway using a flashiness index (FI) which reflects the frequency and rapidity of short term changes in runoff values. Large differences were obtained between the Norwegian and Estonian catchments, irrespective of whether average daily discharge or hourly discharge values were used. A comparison between the FI and the base flow index (BFI) showed that high values for the FI corresponded to low BFI-values. Norwegian catchments with a high FI or low BFI values show high nutrient losses while the contrary was observed for the Estonian catchments. Although the FI does not provide *a priori* information about the flow processes it is believed that the FI, as well as the BFI, might be helpful in explaining differences in nutrient and soil losses between catchments.

The following three papers concentrate on retention processes within riparian buffer strips for agricultural runoff treatment. Both Søvik and Syversen (2008) and Mander *et al.* (2008) found the riparian grey alder stands as a very effective buffer. They are effectively retaining particles and nutrients from agricultural runoff producing minimal leaching into the groundwater (*see* also Mander *et al.* 1997). Due to effective denitrification process, alder forests transform nitrates to the N_2 emission whereas fluxes of harmful greenhouse gas N_2O are minor (Mander *et al.* 2008). Kull *et al.* (2008) provide a thorough discussion on the effects of fluctuating climate conditions and weather events on nutrient dynamics in mosaic riparian peatlands. This work demonstrates that the high patchiness of riparian peatland supports different biogeochemical processes and guarantees buffering efficiency over the long term. This statement is coherent with outcomes from earlier analogous studies showing that complex riparian buffers are more effective than those with single structure (Lowrance *et al*. 2000).

The two last papers concentrate on mechanisms of nutrient and particle retention within constructed wetlands (CW) controlling agricultural runoff. Närvänen *et al*. (2008) studied a specific critical source area in agricultural catchments — equine paddocks — and found that extractable phosphorous washed out from the paddock soil can be effectively reduced in a sedimentation pond using ferric sulphate treatment. In their paper Sveistrup *et al*. (2008) demonstrate that aggregates explain the high clay retention of small CWs. To prevent breakdown of aggregates, wetlands should therefore be constructed as close to the source of erosion as possible. A correct prediction of particle retention in CWs has to take into account the presence of aggregates, thus, textural analysis methods, which require clay dispersion pre-treatment, are not suitable for the calculation of the retention of fine silt and clay in the CWs.

Following needs for further studies were pointed out during the 373rd NJF seminar: (1) impact assessment of the implementation of WFD and Agri-Environmental Programmes on catchment processes using various models such as SWAT combined with the DSS approach, (2) role of global warming (e.g., increasing number of thawing-freezing cycles) on nutrient runoff and greenhouse gas fluxes in agricultural catchments, and (3) long-term nutrient buffering capacity of riparian buffer zones and constructed wetlands for treating agricultural runoff.

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References

Andersson L., Rosberg J., Pers B.C., Olsson J. & Arheimer B. 2005. Estimating catchment nutrient flow with the HBV-NP model: sensitivity to input data. *Ambio* 34: 521–532.

Arheimer B. & Brandt M. 1998. Modelling nitrogen transport and retention in the catchments of southern Sweden. *Ambio* 27: 471–480.

Arheimer B. & Wittgren H.B. 2002. Modelling nitrogen removal in potential wetlands at the catchment scale. *Ecol. Eng*. 19: 63–80.

Bärlund I. & Kirkkala T. 2008. Examining a model and assessing its performance in describing nutrient and sediment transport dynamics in a catchment in southwestern Finland. *Boreal Env. Res*. 13: 195–207.

Baudry J., Bunce R.G.H. & Burel F. 2000. Hedgerows: an international perspective on their origin, function and management. *J. Environ. Manage*. 60: 7–22.

Berlekamp J., Lautenbach S., Graf N., Reimer S. & Matthies M. 2007. Integration of MONERIS and GREAT-ER in the decision support system for the German Elbe river basin. *Environ. Modell. Softw*. 22: 239–247.

Braskerud B.C., Lundekvam H. & Krogstad T. 2000. The impact of hydraulic load and aggregation on sedimentation of soil particles in small constructed wetlands. *J. Environ. Qual*. 29: 2013–2020.

Braskerud B.C. 2002. Factors affecting nitrogen retention in small constructed wetlands treating agricultural nonpoint source pollution. *Ecol. Eng*. 18: 351–370.

Chu T.W. & Shirmohammadi A. 2004. Evaluation of SWAT model's hydrology component in Piedmont Physiographic Region of Maryland. *Trans. ASAE* 47: 1057–1073.

Correll D.L. 2005. Principles of planning and establishment of buffer zones. *Ecol. Eng*. 24: 433–439.

Deelstra J. & Iital A. 2008. The use of the flashiness index as a possible indicator for nutrient loss prediction in agricultural catchments. *Boreal Env. Res*. 13: 209–221.

Francis G.S. & Knight T.L. 1993. Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New-Zealand. *Soil Till. Res*. 26: 193–210.

Gburek W.J. & Sharpley A.N. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. *J. Environ. Qual*. 27: 267–277.

Gitau M.W., Veith T.L., Gburek W.J. & Jarrett A.R. 2006. Watershed level best management practice selection and placement in the Town Brook watershed, New York. *J. Am. Water Resour. As*. 42: 1565–1581.

Granlund K., Räike A., Ekholm P., Rankinen K. & Rekolainen S. 2005. Assessment of water protection targets for agricultural nutrient loading in Finland. *J. Hydrol*. 304: 251–260.

Groffman P.M., Axelrod E.A., Lemunyon J.L. & Sullivan W.M. 1991. Denitrification in grass and forest vegetated filter strips. *J. Environ. Qual*. 20: 671–674.

Groffman P.M., Gold A. & Addy K. 2000. Nitrous oxide production in riparian zones and its importance to national emission inventories. *Chemosphere — Global Change Science* 2: 291–299.

Gustafson A., Fleischer S. & Joelsson A. 2000. A catchment-oriented and cost-effective policy for water protection. *Ecol. Eng*. 14: 419–427.

Haycock N.E. & Pinay G. 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffers trips during the winter. *J. Environ. Qual.* 22: 273–278.

Heathwaite L., Sharpley A.N. & Gburek W.J. 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *J. Environ. Qual.* 29: 158–166.

Johnes P.J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: The export coefficient modelling approach. *J. Hydrol.* 183: 323–349.

Kadlec R.H. & Knight R.L. 1996. *Treatment wetlands*. CRC Press LLC, Boca Raton, New York.

Kaste O., Rankinen K. & Lepistö A. 2004. Modelling impacts of climate and deposition changes on nitrogen fluxes in northern catchments of Norway and Finland. *Hydrol. Earth Syst. Sci.* 8: 778–792.

Kovacic D.A., David M.B., Gentry L.E., Starks K.M. & Cooke R.A. 2000. Effectiveness of constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile drainage. *J. Environ. Qual.* 29: 1262–1274.

Koskiaho J., Ekholm P., Räty M., Riihimäki J. & Puustinen M. 2003. Retaining agricultural nutrients in constructed wetlands — experiences under boreal conditions. *Ecol. Eng.* 20: 89–103.

Koskiaho J. & Puustinen M. 2005. Function and potential of constructed wetlands for the control of N and P transport from agriculture and peat production in boreal climate. *J. Environ. Sci. Heal. A* 40: 1265–1279.

Kronvang B., Svendsen L.M., Jensen J.P. & Dorge J. 1999. Scenario analysis of nutrient management at the river basin scale. *Hydrobiologia* 410: 207–212.

Kull A., Kull A., Jaagus J., Kuusemets V. & Mander Ü. 2008. The effects of fluctuating climatic conditions and weather events on nutrient dynamics in a narrow mosaic riparian peatland. *Boreal Env. Res.* 13: 243–263.

Lowrance R., Altier L.S, Williams R.G., Inamdar S.P., Sheridan J.M., Bosch D.D., Hubbard R.K. & Thomas D.L. 2000. REMM: The riparian ecosystem management model. *J. Soil Water Conserv.* 55: 27–34.

Lowrance R.R., Todd R.L. & Asmussen L.E. 1983. Waterborne nutrient budgets for the riparian zone of an agricultural watershed. *Agric. Ecosyst. Environ.* 10: 371–384.

Mander Ü., Kull A. & Kuusemets V. 2000. Nutrient flows and land use change in a rural catchment: a modelling approach. *Landscape Ecol.* 15: 187–199.

Mander Ü., Kuusemets V., Lõhmus K. & Mauring T. 1997. Efficiency and dimensioning of riparian buffer zones in agricultural catchments. *Ecol. Eng.* 8: 299–324.

Mander Ü., Lõhmus K., Teiter S., Uri V. & Augustin J. 2008. Gaseous nitrogen and carbon fluxes in riparian alder stands. *Boreal Env. Res.* 13: 231–241.

Mitchell J.K., Engel B.A., Srinivasan R. & Wang S.S.Y. 1993. Validation of AGNPS for small watersheds using an integrated AGNPS/GIS system. *Water Resour. Bull.* 29: 833–842.

Mitsch W.J. & Gosselink J.G. 2000. *Wetlands*, 3rd ed. John Wiley & Sons, New York.

Närvänen A., Jansson H., Uusi-Kämppä J., Jansson H. & Perälä P. 2008. Phosphorus load from equine critical source areas and its reduction using ferric sulphate. *Boreal Env. Res.* 13: 265–274.

Parris K. 1998. Agricultural nutrient balances as agri-environmental indicators: an OECD perspective. *Environ. Pollut.* 102 (Suppl. 1): 219–225.

Peterjohn W.T. & Correll D.L. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. *Ecology* 65: 1466–1475.

Pionke H.B., Gburek W.J. & Sharpley A.N. 2000. Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. *Ecol. Eng.* 14: 325–335.

Pollard P. & Huxham M. 1998. The European Water Framework Directive: a new era in the management of aquatic ecosystem health? *Aquat. Conserv.* 8: 773–792.

Rekolainen S. 2006. EU Water Framework Directive: a need for research and tools. *NJF Report* 2: 9–13.

Ryszkowski L. & Kędziora A. 2007. Modification of water flows and nitrogen fluxes by shelterbelts. *Ecol. Eng.* 29: 388–400.

Sharpley A.N., Kleinman P. & McDowell R. 2001. Innovative management of agricultural phosphorus to protect soil and water resources. *Commun. Soil Sci. Plan.* 32: 1071–1100.

Shirmohammadi A., Chu T.W. & Montas H.J. 2008. Modeling at catchment scale and associated uncertainties. *Boreal Env. Res.* 13: 185–193.

Shirmohammadi A., Chaubey I., Harmel R.D., Bosch D.D., Muñoz-Carpena R., Dharmasri C., Sexton A., Arabi M., Wolfe M.L., Frankenberger J., Graff C. & Sohrabi T.M. 2006. Uncertainty in TMDL Models. *Trans. ASAE* 49: 1033–1049.

Shirmohammadi A., Djodjic F. & Bergstrom L. 2005. Scaling issues in sustainable management of nutrient losses. *Soil Use Manage.* 21 (Suppl. 1): 160–166.

Shirmohammadi A., Shoemaker L.L. & Magette W.L. 1992. Model simulation and regional pollution reduction strategies. *J. Environ. Sci. Health A* 27: 2319–2336.

Søvik A.K. & Syversen N. 2008. Retention of particles and nutrients in the root zone of a vegetative buffer zone — effect of vegetation and season. *Boreal Env. Res.* 13: 223–230.

Steinhardt U. & Volk M. 2003. Meso-scale landscape analysis based on landscape balance investigations: problems and hierarchical approaches for their resolution. *Ecol. Model.* 168: 251–265.

Sveistrup T.E., Marcelino V. & Braskerud B.C. 2008. Aggregates explain the high clay retention of small constructed wetlands: a micromorphological study. *Boreal Env. Res.* 13: 275–284.

Teiter S. & Mander Ü. 2005. Emission of N_2O, N_2, CH_4 and CO_2 from constructed wetlands for wastewater treatment and from riparian buffer zones. *Ecol. Eng.* 25: 528–541.

Tetra-Tech 2005. *National management measures to control nonpoint sources pollution from forestry*. Report No. EPA 841-B-05-001. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

U.S. Congress 1972. Federal Water Pollution Control Act Amendments, vol. P.L. 92-500, pp. 103–104.

Venohr M., Behrendt H. & Kluge W. 2005. The effects of different input data and their spatial resolution on the results obtained from a conceptual nutrient emissions model: the River Stör case study. *Hydrol. Process.* 19: 3501–3515.

Verhoeven J.T.A., Arheimer B., Yin C.Q. & Hefting M.M. 2006. Regional and global concerns over wetlands and water quality. *Trends Ecol. Evol.* 21: 96–103.

Vought L.B.M., Dahl J., Pedersen C.L. & Lacoursiere J.O. 1994. Nutrient retention in riparian ecotones. *Ambio* 23: 342–348.

Vymazal J. 2001. Types of constructed wetlands for wastewater treatment: Their potential for nutrient removal. In: Vymazal J. (ed.), *Transformations of nutrients in natural and constructed wetlands*, Backhuys Publishers, Leiden, The Netherlands, pp. 1–94.

Wade A.J., Whitehead P.G. & Butterfield D. 2002. The Integrated Catchments model of Phosphorus dynamics (INCA-P), a new approach for multiple source assessment in heterogeneous river systems: model structure and equations. *Hydrol. Earth Syst. Sci.* 6: 583–606.

Wascher D.M. (ed.) 2000. *Agri-environmental indicators for sustainable agriculture in Europe*. ECNC Technical Report Series, European Centre for Nature Conservation, Tilburg.

Young R.A., Onstad C.A., Bosch D.D. & Anderson W.P. 1989. AGNPS: a nonpoint source pollution model for evaluating agricultural watersheds. *J. Soil Water Conserv.* 44: 168–173.