SOILS2SEA DELIVERABLE NO. 4.1

BONUS
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

Impacts of river damming on nutrient export and optimized reservoir operation with multi-objectives

SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

This page has intentionally been left blank

SOILS2SEA DELIVERABLE NO. 4.1

Impacts of river damming on nutrient export and optimized reservoir operation with multi-objectives

December 2015

Authors: Nicholas Zmijewski and Anders Wörman, KTH

SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

This report is a publicly accessible deliverable of the Soils2Sea project. The present work has been carried out within the project 'Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams (BONUS Soils2Sea)', which has received funding from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly from the European Union's Seventh Programme for research, technological development and demonstration and from Innovation Fund Denmark, The Swedish Environmental Protection Agency (Naturvådsverket), The Polish National Centre for Research and Development, The German Ministry for Education and Research (Bundesministerium für Bildung und Forschung), and The Russian Foundation for Basic Researches (RFBR).

N Zmijewski and A Wörman, Impacts on damming on nutrient export and optimized reservoir operation with multi-objectives. BONUS Soils2Sea Deliverable 4.1. Royal Institute of Technology (KTH), Stockholm, December 2015, www.Soils2Sea.eu

Contents

Contents 5
Abstract 6
1. Introduction 7
2. Methodology 10
2.1 General mathematical statement of reservoir regulation 10
2.2 Phosphorous transport model 11
2.3 Optimization model 13
3 Dalälven River (Case study) 15
4 Results 17
5 Discussion and conclusions 21
References 24

Abstract

Reservoir management alters the hydrological flow regime and can have significant impact on the transport of phosphorous. Reducing the phosphorous load to downstream areas is of great importance to aquatic habitats as well as the overall health of coastal areas. In this study a network of reservoirs is regulated considering the transport of nutrients within the watershed using a multi-objective approach. In this study the management of a network of reservoirs in River Dalälven, Sweden, is operated using a multi-objective approach, incorporating the mass balance of phosphorous. The model integrates hydropower production and flood control objectives with the objective of minimizing total phosphorous effluent mass export. The optimization model is used to derive trade-off curves between the two objectives, thereby demonstrating the method for use in valuation between possible usages for water management. The effect of management of River Dalälven on phosphorous transport is examined as a possible remediation method for mitigating phosphorous transport from the controlled river network. Further, the efficacy of valuation of ecological constraints using multi-objective reservoir optimization is demonstrated illustrating a possible real-world application quantifying the cost in the form of loss of total hydroelectric power. It is shown that a 2% reduction of the nutrient discharge can be achieved to a limited loss of future power production (<5 %), but that additional reduction is associated with a significant loss in power production.

1. Introduction

Over the past decades it has become clear that nutrient export to the coastal and estuary zones has become a significant problem, leading to eutrophication and regional hypoxia [*Backer et al.*, 2010; *Diaz and Rosenberg*, 2008; *Osterman et al.*, 2009; *Rabalais et al.*, 2010]. An established common goal of the European Union for future environmental management is to mitigate the causes of eutrophication of the larger water bodies as well as the estuaries of larger rivers[*EC*, 2000; 2008]. Sources of nutrient load to the oceans and regional seas are diverse, varying from direct input, atmospheric deposition to riverine inputs which in many cases passes a controlled reservoir. Nutrient load controls, to a certain extent, the severity and size of undesirable hypoxic zones, implying that the controlling temporal fluctuations of the loading is essential for mitigating ecological harm [*Kemp et al.*, 2009]. It has previously been seen that, though the expected mean values may not change, reservoir operation lowers the variance in water quality indicators over the year [*Cunha et al.*, 2014]. Increased water residence time within a reservoir alters the inherent dominating processes, providing conditions for deposition, biological assimilation and other bio-chemical processes. Large scale reservoir management alters the hydrological flow regime and can have significant impact on nutrient transport as well as other ecological factors, both within the watershed and at the estuary downstream [*Basu et al.*, 2010]. Reducing the nutrient load, or in many cases specifically phosphorous, to downstream areas is of great importance to aquatic habitats as well as the overall health of coastal areas. In this study a network of reservoirs is regulated considering the transport of phosphorous within the watershed, using a multi-objective approach. The model integrates hydropower production and flood control objectives with estuary water quality objectives. The effect of regulation of a large network of reservoirs on the transport of phosphorous through the watershed is examined, investigating the possible use of a controlled network of reservoirs as a measure for mitigating phosphorous discharge and the effect on current operation objectives, i.e. hydropower production.

Ecological considerations in reservoir operation have been made for a long time [*Jager and Smith*, 2008; *Straskraba*, 1994], however, in most cases implemented in the form of a minimum flow [*Gandolfi et al.*, 1997; *Goulter and Castensson*, 1988], the environmental impact of which has often been criticized for its questionable positive effect [*Bednarek and Hart*, 2005]. Variation in flow has been seen to play a significant role in ecological flow regimes, indicating that minimum flow requirements are not sufficient in remediation purposes. *Bizzi et al.* [2012] included flow variance in the optimization scheme providing a framework for including flow alteration in management decisions, while *Chen et al.* [2015] included a time-varying minimum ecological flow hydrograph. The valuation between power and ecological benefits is generally skewed since the latter is traditionally difficult to measure in any reliable quantity but instead reliant on various ecological indicators. [*Kotchen et al.*, 2006] compared operating scenarios using measured discharge series, evaluating the overall benefits of dam operation and determining that the benefit to environmental concerns (air and recreational fishing) from requiring a close to natural flow were greater than the expected producer costs for the considered area.

In general reservoirs are constructed for considering multiple objectives, however, the operational schedule is often determined considering only a single objective, specifying the alternative objectives of use of operation as hard constraints on the system. Several forms of specifying the multi-objective optimization problem have previously been used. *Yeh and Becker* [1982] described an objective as a constraint, iteratively determining trade-off curves between the five objectives considered. *Can and Houck* [1984] applied goal programming to the operation of a multi-reservoir system. By including two objectives in the operation objective function, weighting the considered objectives, and re-optimizing the relative trade-off between objectives can be examined [*Mendes et al.*, 2015]. *Hayes et al.* [1998] expanded the study of regulation for improving water quality considering temperature and dissolved oxygen as ecological variables [*Fontane et al.*, 1981], showing that water quality could be improved for a case study watershed with minor losses in production. Large non-linear optimization problems have in later years become more prevalent in management, increasing the interest in multi-objective optimization techniques and the examination of trade-offs between management objectives. The popular dynamic programming (DP) has been applied to systems considering multi objectives [*Bizzi et al.*, 2012] as well as alternate formulations of it [*Castelletti et al.*, 2014], the implementation of said scheme is however limited by the curse of dimensionality. Multi-objective evolutionary algorithms (MOEA) have increased in popularity as a result of the property that a single optimization run will produce a collection (population) of optimal solutions corresponding to the trade-off between objectives, i.e. the pareto curve. Extensive review on the subject of evolutionary algorithms in water resources was provided by *Maier et al.* [2014]; *Nicklow et al.* [2010]; *Reed et al.* [2013]. Since its development, the non-dominated sorting genetic algorithm II (NSGA-II) [*Deb et al.*, 2002] has been increasingly applied to problems involving multiple objectives. *Dhar and Datta* [2008] used a genetic algorithm to determine the operating schedule considering an extensive water quality model, tracking nitrate among others, for a single reservoir and upstream stretch. *Suen and Eheart* [2006] proposed an approach considering the ecological flow regime needs, estimating the relative benefit of chosen ecological objectives relative to production using the NSGA-II for the operation of a single reservoir. *H. Mala-Jetmarova et al.* [2015]; [2015] incorporated a nutrient/water quality model (EPANet) in the optimization routine (NSGA-II) for the optimization of operating schedule of a water distribution system (WDS), illustrating the competitiveness between various water uses as well as the efficacy of the approach. Mass sedimentation has long been considered a problem in reservoir management since it may result in a decrease of the manageable volume of the reservoir, as examined by Khan (2009). *Wang et* *al.* [2015] showed that despite several advancements within the field of evolutionary algorithms, the common and established NSGA-II remains a good choice in many cases.

Processes affecting the fate of phosphorous (such as transport and retention) can be described in several forms with varying complexity. A simplified form of considering transport is the compartmental model approach, meaning a discretization of the system into boxes, assuming instantaneous mixing of the solute within each box. Here, a multi-objective optimization model is used, incorporating the compartmental description of the transport and retention of nutrients in a regulated reservoir network. The use of alternative regulation objectives in reducing phosphorous loading to the coast is investigated in a case-study of the river Dalälven (Sweden) reservoir network. The focus of the study lies in the use of natural retention mechanisms of phosphorous and the cumulative consequences of considering a large network of reservoirs for reducing the discharge of total phosphorous mass downstream the watershed. The aim being to define a modelling framework and explore the implication of nutrient transport constraints on the hydropower production planning optimization, as well as determine optimal operating policies that can be used in combination with other mitigating measures to reduce phosphorous loading into the sea. The novelty of the present study is the valuation of the use of controlled reservoirs for the purpose of minimizing phosphorous effluent discharge. Optimization of a large-scale river network is done at great computational expense and the addition of additional states will increase the computational load significantly, for this reason several simplifications of the system dynamics are made. The general form of the model dynamics (as described in section 2) enables a clear assessment of the impact of the reservoir dynamics on production management and total resulting benefit on phosphorous deposition.

2. Methodology

2.1 General mathematical statement of reservoir regulation

The dynamics of each reservoir are described by the time-rate of change of the water storage, referred to as the water balance and expressed as:

$$\frac{dS_j}{dt} = q_n - q_j + q_{j,loc} \tag{1}$$

where S_j (m^3) is the volume of water in reservoir *j*, q_j (m^3/s) is the discharge from reservoir *j*, q_n (m^3/s) discharge at upstream located reservoir *n* considering instantaneous transfer between reservoirs. The same water balance is applied to all reservoirs, which leads to a simultaneous equation system that is coupled through the discharges q_n and q_j. The discharge from a reservoir can be expressed as the sum of production and spill discharge, i.e. $q_j = q_{j,prod} + q_{j,spill}$, where $q_{j,prod}$ (m^3/s) is the production discharge and $q_{j,spill}$ (m^3/s) is the spillage discharge. The total water inflow $q_{j,in}$ to reservoir *j* is then expressed by the sum of $q_n + q_{j,loc}$.

The potential for power production *P* (W) from a hydropower plant connected to a reservoir is expressed as:

$$P_j^k = \rho g \eta_j h_j^k q_{j,prod}^k \tag{2}$$

where h_j^k (m) is the fall height (difference between the reservoir and downstream water level), ρ (kg/m^3) is the density of water, *g* (m/s^2) is the acceleration due to gravity, *k* (-) is the current time-step and η_j (-) is the station overall efficiency which is assumed to be constant over time. The total energy produced, *E* (J) over a future time period, T_h (s) is then expressed by the integral of equation (2) as:

$$E_{,j} = \sum_{k=0}^{T_h/\Delta t} \Delta t \cdot P_j^k = \frac{\rho g \eta_j}{A_j} \sum_{k=0}^{T_h/\Delta t} \Delta t \cdot S_j^k q_{prod,j}^k \tag{3}$$

where $A_j = S_j/h_j$ *(m^2)* is the area of the reservoir and Δt is the numerical discretization time step. The operation of a reservoir system is complicated by the constraints set on discharge operation and levels of the reservoirs. These constraints can be expressed as:

$$S_{j,min} < S_j < S_{j,max} \tag{4}$$

$$0 < q_{j,prod} < q_{j,prod,max} \tag{5}$$

$$q_{j,min} < q_j < q_{j,max} \tag{6}$$

where $S_{j,min}$ (m^3) is the minimum storage, $S_{j,max}$ (m^3) is the maximum, $q_{j,min}$ (m^3/s) is the minimum discharge generally required by court decisions, $q_{j,prod.max}$ (m^3/s) is the maximum production limit in terms of turbine power capacity (m^3/s). The maximum discharge $q_{j,max}$ (m^3/s) is limited by the capacity of reservoir spillways or environmental concerns.

2.2 Phosphorous transport model

The transport of phosphorus in a regulated watershed is in large part controlled by the management of discharge [*Basu et al.*, 2010; *Bolin et al.*, 1987].The mass conservation of phosphorus can be described using two phases: a particulate phase and a dissolved phase, each phase discretized into a mobile and im-mobile zone (transient storage), as seen in Figure 1. The distinction between phases has previously been used considering reactive solutes in streams [Jakeman et al., 1999; Jonsson et al. 2004; Riml et al. 2011] and leads to a useful and general model description of the dynamics of phosphorous. A significant process is assumed to be the adsorption-desorption of the particulate phosphorous, however, the general nature of the model formulation lends itself to open interpretation and possible expansion in the case that additional processes, such as biological uptake, become more prevalent. The interaction between the mobile and immobile zones is assumed to be dominated by deposition processes and re-suspension dynamics. The mass-balance of the solute is expressed in analogy with (1) as:

$$\frac{d(S_j c_j)}{dt} = -q_j c_j + q_n c_n + q_{j,loc} c_{j,loc} + F\left(c_{p,j}\right) + G\left(g_{p,j}, q_j\right) \quad (7a)$$

$$\frac{d(V_j^{sed} g_j)}{dt} = -F\left(c_{p,j}, q_j\right) - G\left(g_{p,j}, q_j\right) \quad (7b)$$

where V_j^{sed} (m^3) is the assumed volume of the sediment, c_j (kg/m^3) is the total concentration of phosphorus in the mobile zone in the reservoir j, c_n (kg/m^3) is the total concentration of phosphorus in the mobile zone in the upstream reservoir n, $c_{j,local}$ (kg/m^3) is the concentration of phosphorus in the local runoff to reservoir j, g_j (kg/m^3) is the total concentration in the immobile zone, $c_{p,j}$ and $c_{d,j}$ are the particulate and dissolved form of phosphorous in the mobile zone while $g_{p,j}$ and $g_{d,j}$ are the particulate and dissolved form of phosphorous in the im-mobile zone. By assuming that an instantaneous equilibrium exists between the dissolved ($c_{d,j}$, $g_{d,j}$) and particulate ($c_{p,j}$,$g_{p,j}$) concentration the relationship between the phases in the two zones can be described using the partitioning constants $k_d = c_{p,j} / c_{d,j}$ (mobile zone) and $k_b = g_{p,j} / g_{d,j}$ (immobile zone). F and G are functions describing the relations between the concentration in the mobile and immobile zone. F describes the deposition process as a function of the fall-velocity of particle-bounded nutrient:

$$F(c_j, q_j) = -v_t(q_j)A_j c_{p,j} \quad (8)$$

where $v_t(q_j)$ (m/s) is the fall-velocity of the particle bound phosphorous which has been reported to vary wildly, ranging between -90 to 269 (m/year) depending on size, form and flow [*Panuska and Robertson*, 1999; *Reckhow*, 1979]. A negative value is here interpreted as as a net resuspension of the sediment particles. Several empirical formulations have been tested of the fall-velocity, and its dependence on flow description, which for reservoirs has been reported to be significantly higher than for lakes [*Bolin et al.*, 1987]. *Bolin et al.* [1987] suggested expressing the phosphorous fall-velocity as non-linear function of the water areal loading, i.e. the total water inflow divided by reservoir area $q_{j,in} / A_j$:

$$v_t = \alpha_1 \left(\frac{q_{j,in}}{A_j}\right)^{\beta_1} \quad (9)$$

where α_1 (-) and β_1 (-) are coefficients describing the non-linear relationship of deposition of phosphorous to inflow areal loading $q_{j,in} / A_j$. These coefficients are functions of different control variables, such as e.g. particle diameter and particle density according to Stokes law.

G describes the re-suspension of phosphorous as a non-linear function of flow discharge:

$$G(q_j, g_j) = \alpha_2 g_{p,j} {q_j}^{\beta_2} \quad (10)$$

where α_2 (-) and β_2 (-) are constants describing the non-linear relationship of re-suspension of phosphorous to reservoir discharge q_j.

The total mass of phosphorous discharged from a reservoir is expressed as:

$$TN_j = \sum_{k=0}^{T_h/\Delta t} \Delta t q_j^k c_j^k \quad (11)$$

where TN_j is the total mass of phosphorous discharged from a reservoir (kg) over the time-period T_h.

The phosphorous transport parameters (α_1, β_1, α_2, β_2 and initial sediment) are determined using the least-square (LS) method, minimizing the square of the difference between measured m_m and simulated $m_s = q_j c_j$ discharged phosphorous mass downstream ($\sum_{k=0}^{N}(m_m^k - m_s^k)^2$).

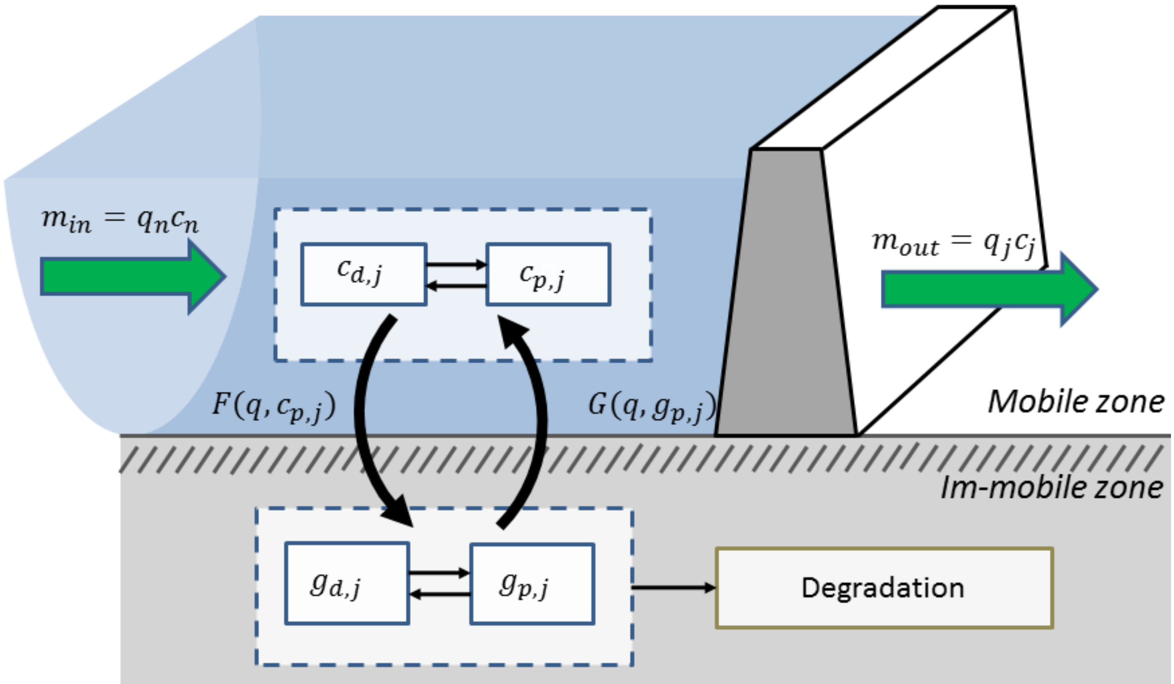

Fig. 1. *Description of the applied compartmental model describing the transport dynamics of phosphorous within a reservoir, describing the interaction between the mobile and immobile zones as well as the dissolved and solved phase of the solute considered within the optimization model.*

2.3 Optimization model

The objectives of minimizing nutrient effluent discharge and maximizing hydropower production from a watershed containing a network of reservoirs are conflicting, meaning there will not typically exist a feasible solution that achieves the best result for both objective functions simultaneously. A trade-off between the objectives therefore exists, where the solution cannot be improved for any of the objectives without decreasing the other objective, called a pareto optimal solution. The implication of including a phosphorous transport model in the optimization of a network of reservoirs is considered by examining the trade-off between the objectives of decreasing the total phosphorus discharged from the watershed in relation to the apparent constraint put on power production. This separation of the alternate objectives gives the possibility to value them against each other and determine the cost of reservoir regulation as a possible remediation measure for the area.

Maximized hydropower production objective

The objective of maximizing the total energy (*E*) produced from a network of reservoirs over the time-period considered is expressed using equation (3) as:

$$E = \sum_{j=1}^{NP} E_j = \sum_{j=1}^{NP} \sum_{k=0}^{T_h/\Delta t} \Delta t \cdot P_j^k = \frac{\rho g \eta_j}{A_j} \sum_{k=0}^{T_h/\Delta t} \Delta t \cdot S_j^k q_{prod,j}^k \tag{12}$$

where *NP* is the total number of reservoirs considered and T_h is the discrete time-horizon considered. In addition to the production over the examined time-period T_h the value of the water remaining in the reservoirs should be valued for its potential as future production value E_{pot}:

$$E_{pot} = \sum_{j=1}^{NP} \Delta t \cdot P_j^{T_h/\Delta t} = \frac{\Delta t \cdot \rho g \eta_j}{A_j} S_j^{T_h/\Delta t} q_{prod,j}^{T_h/\Delta t} \tag{13}$$

The total future production from the examined power production is then expressed by:

$$E_{tot} = E + E_{pot} \tag{14}$$

Minimized phosphorous discharge objective

The objective of minimizing the total phosphorous discharge is expressed using (11) as:

$$TM_\omega = \sum_{k=0}^{T_h/\Delta t} q_\omega^k c_\omega^k \tag{15}$$

where ω is the reservoir at the outlet of the watershed (i.e. $j = \omega$) and TM_ω (kg) is the total mass of the nutrient discharged from the watershed.

The final multi-objective optimization problem is then formulated as:

$$\mathrm{argmin}_x [-E_{tot} \quad TM_\omega] \tag{16}$$

where the control vector $\boldsymbol{x}$ is a collection of the time-dependent variables as:

$$\boldsymbol{x} = [\boldsymbol{q}_{prod} \quad \boldsymbol{q}_{spill} \quad \boldsymbol{s}] \tag{17}$$

The popular non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002), implemented in the MATLAB software package, was used as the multi-objective genetic algorithm (MOGA). By mimicking evolutionary behavior, non-dominated solutions (pareto front) can be determined for a stated optimization problem.

3 Dalälven River (Case study)

The Dalälven River (Figure 2) located in the middle of Sweden, stretches from the Norwegian mountains in the west and discharges in the Baltic basin to the east. Flow regulation in the watershed commenced in the late 19th century, and greatly expanded later in the 20th century when active regulation of greater reservoirs, such as Lake Siljan in 1922 and other greater basin reservoirs began. The watershed now encompasses in excess of 36 power stations and 13 larger reservoirs, with the primary purpose of hydropower production while respecting environmental constraints set on the reservoirs. Most of the power stations within the basin are operated as run-of-river production, while the larger reservoirs (mainly at the upper part of the basin) are used in flow regulation. The basin area is approximately 29,000 km^2, consisting to 7% of surface water, 4% agricultural land, 8% wetlands, 75% forest and 6% other usage. The Dalälven River has an average effluent discharge of 374 m^3/s and is estimated to experience an average total load of phosphorous of 270 tons/year while discharging an average of 151 tons of phosphorous per year (Figure 2). The total phosphorous load contributed to the Baltic basin via riverine inputs contributes significantly to the problem of eutrophication of the basin, for which the Dalälven watershed is responsible for approximately 0.5 – 1 % (*HELCOM*, http://www.helcom.fi/). Water-quality measurements close to the effluent of the watershed (*Älvkarleby*) are collected on behalf of state environmental monitoring program and the data published online (http://www.slu.se/sv/webbtjanster-miljoanalys/miljodata-mvm/), providing data of monthly-yearly resolution. In order to extend measured data, computed runoff and nutrient inflow to the basin from the compartmental catchment model HYPE (Hydrological Predictions for the Environment) set-up for Sweden (S-HYPE), developed and modelled by SMHI (Swedish Meteorological and Hydrological organization) [*Lindstrom et al.*, 2010] are used. The river discharge and precipitation to the basin are collected and processed, and the runoff and nutrient inflow is then simulated and published on the open data web portal Vattenwebb (http:// vattenweb.smhi.se/). The resolution (monthly) considered in this study is less than the maximum flow time-lag between reservoirs in the system, allowing the simplification of considered instantaneous flow time-lag between reservoirs. Reservoir and power station characteristics were supplied by relevant regulating agencies. The data used in this study were acquired for the time-period 1999-2011.

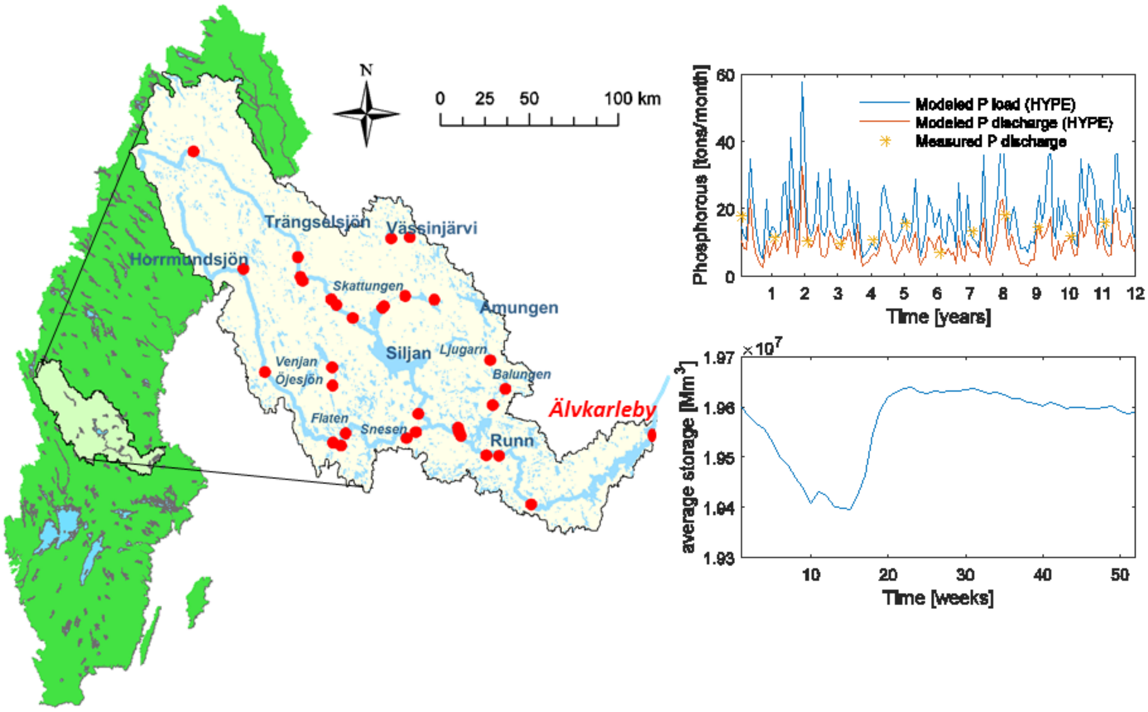

Fig. 2. *Schematic view of the Dalälven River catchment and its location within Sweden, including named main reservoirs and larger power stations (red). Included are diagrams of the distribution over time of water storage within the reservoirs in the river Dalälven as well as the effluent phosphorous discharge. a) total phosphorous inflow and effluent from the network over time b) total storage of water over time in the reservoirs within the network*

4 Results

A model is constructed describing the dynamics of the system, incorporating the transport dynamics of phosphorus. The optimal discharge schedule of the operation of a network of reservoirs is determined using a genetic algorithm defined in section 2.3 considering multiple management objectives. The alternative objective of minimizing total phosphorus mass effluent discharge, in addition to maximizing power production is considered. It is clear that decreasing the mass of the effluent phosphorous discharge requires decreasing the concentration of the mobile phosphorous, leading to the preference of greater storage and keeping the reservoirs levels high, this conflicts in many cases with the objective of maximizing the total energy production from the controlled reservoirs. The trade-off between the objectives is examined, considering the case of a single reservoir as well as the case of a large watershed (River Dalälven).

4.1 Validation of phosphorous transport model

The use of the considered description of the transport of phosphorous is validated by calibrating the transport parameters of the Dalälven network (assuming a network representative average / spatially constant), i.e., the fall-velocity parameters (α and β), the re-suspension parameters (α and β) as well as the solved-dissolved ratios (k_d and k_b) and initial sediment storage. The calibration procedure is performed using the least-square (LS) method against measured monthly data of phosphorous concentration at the downstream reservoir of *Älvkarleby* within the River Dalälven network over the time-period Jan 2012 – July 2012. The estimated model parameters were validated against the time-period July 2011 – Dec 2011 seen in Figure 3.

The calibration resulted in the deposition parameters α_1 and β_1 as 9.4 and 1.4, re-suspension parameters α_2 and β_2 as 1.8 and 0.001 respectively, the zone partitioning constants k_d and k_b as 12.9 and 12.6 respectively and the initial sediment storage was determined to be 47 times the mass initially suspended in the mobile zone, resulting in a LS measure of 118.

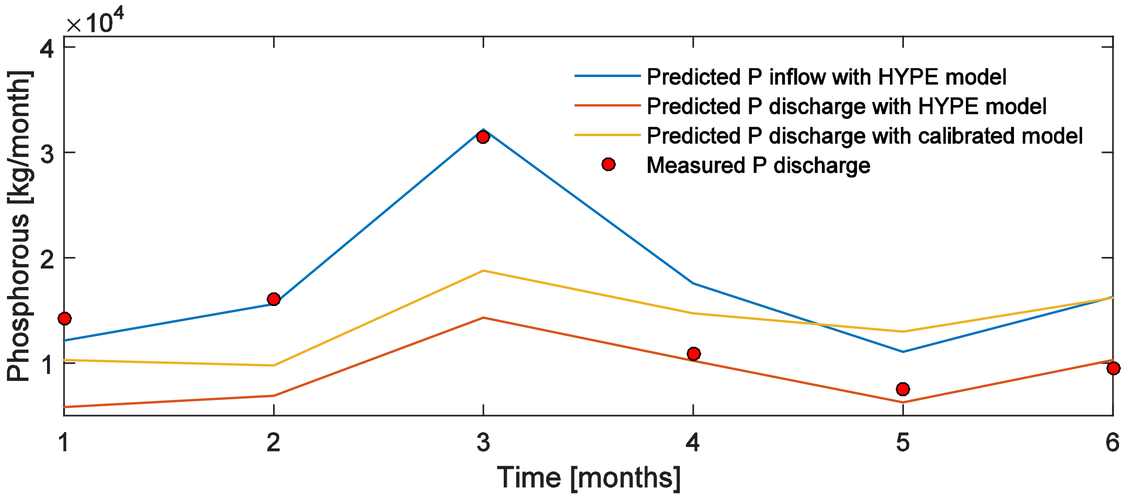

Fig. 3. *Nutrient transport model is calibrated against the measured phosphorous discharge from the Dalälven watershed at the discharge from reservoir Älvkarleby, considering spatially constant network transport parameters.*

4.2 Impact of considering phosphorous transport in reservoir operation

The described optimization scheme (section 2) is applied to the operation of the reservoirs within the Dalälven watershed considering the calibrated transport parameters. Figure 4b demonstrates a typical operation of a single reservoir, considering both the objectives, over a single year (1999). It is seen that for the examined year there is a maximum possible production of 0.85 TWh and that this results in a discharge of 9.8 tons of phosphorous. If considering the objective of minimizing the phosphorous discharge the total production over the year will decrease considerably as seen in Figure 4b. The implication on flow variables of a typical operation schedule of the single reservoir is demonstrated in Figure 4a-c, the resulting objective values are marked in the pareto-front (Figure 4b) as a red circle. It is noted that for both objectives it is beneficial to have increased storage, leading to both an increased hydraulic fall-height (h_j) as well as a decreased concentration of phosphorous in the mobile zone. However, the need for spillage is increased when the storage of the reservoir approaches the maximum level described by the hard constraints. The mean effluent discharge of phosphorous is shown to decrease as a result of regulation over the time-period examined, as indicated in previous research the impact on variance is also altered indicating the ability to significantly regulate phosphorous discharge over time.

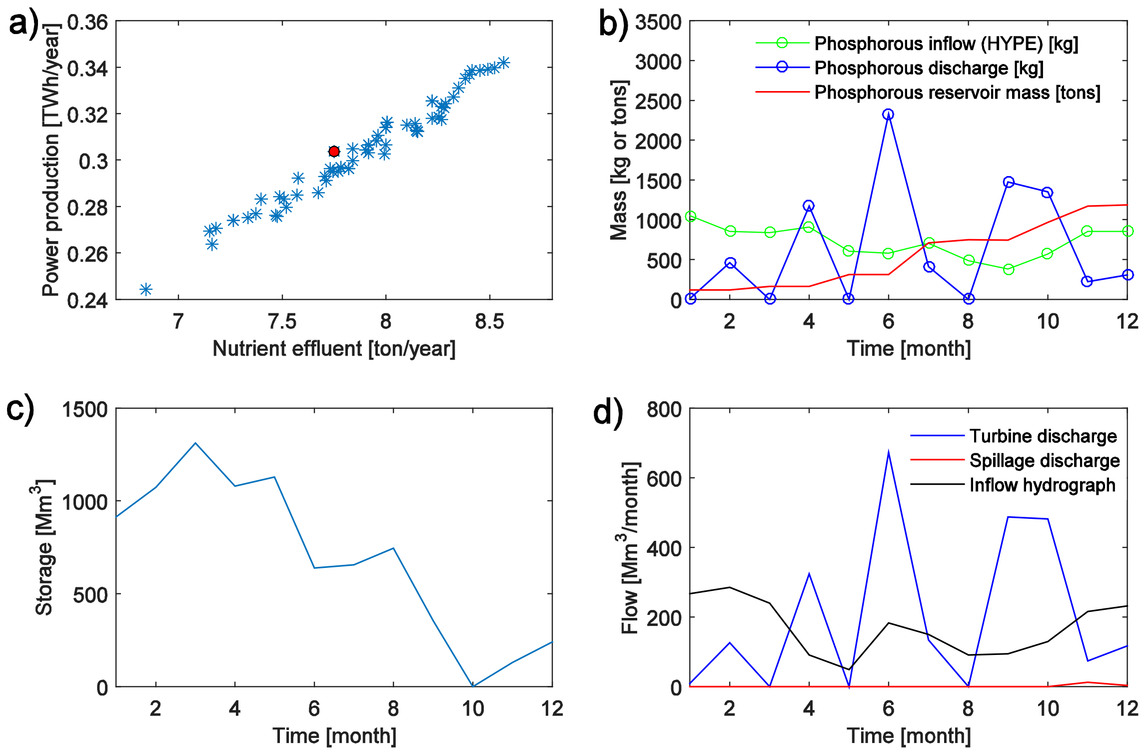

Fig. 4. *Optimized operation of a single reservoir (Trängslet) with connected power station for a year (1999), considering current operation constraints. Inflow runoff (q_{local}) and nutrient inflow (c_n) is taken from data supplied by SMHI.* ***a)*** *Pareto-diagram between the considered objectives of phosphorous discharge and total power production where the demonstrated scenario is marked with a circle (red)* ***b)*** *Mass of phosphorous* ***c)*** *Reservoir storage.* ***d)*** *Reservoir inflow q_{in} and optimized flow discharge from the reservoir q_j expressed as turbine and spillage discharge.*

By applying the optimization model (section 2.3) to the Dalälven reservoir network the impact of considering the additional objective of minimizing phosphorous discharge on total production can be examined. The trade-off between the total power production from the power stations within the reservoir network and the discharge of phosphorous from the effluent of the reservoir network is shown in Figure 5, illustrating a clear relationship between the two competing objectives. It is noteworthy that the relationship between the two objectives appears to be of a concave nature, implying a low initial cost of considering phosphorous as an additional objective (Figure 5).

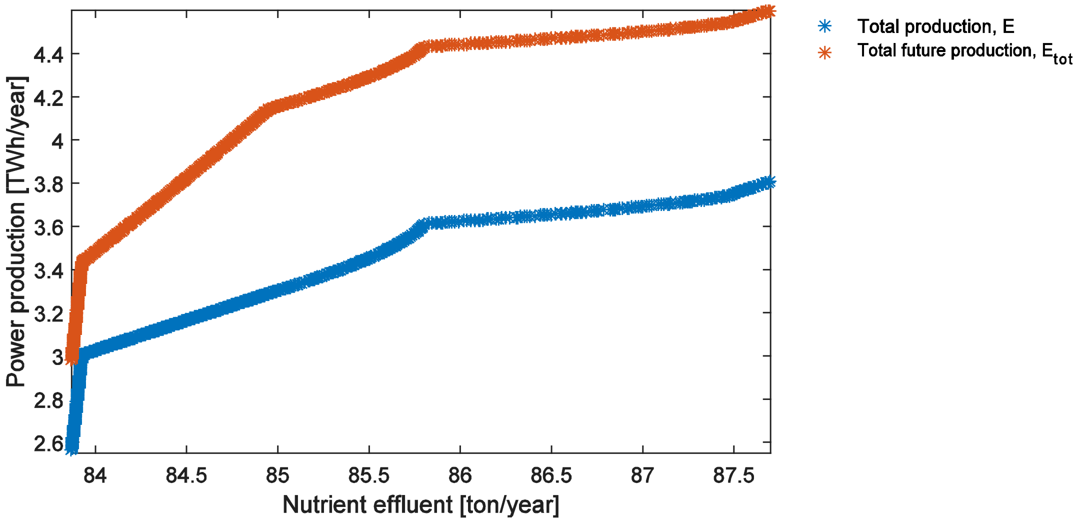

Fig. 5. *Pareto front describing the trade-off between estimated total power production (E) and the total future production (E_{tot}) with the phosphorous mass effluent discharge in the optimized operation of the reservoir network of the river Dalälven averaged over a year (1999), considering current operation constraints the optimization was completed for a half year (Jan – June 1999).*

5 Discussion and conclusions

Phosphorous transport is dependent on its input load, spatial distribution and connecting river hydrograph. For regulated watersheds contributing to the phosphorous load to downstream recipients at the coastal areas, the strategy for regulation may have a significant impact on water quality of the estuary. Here, a simplified transport model for phosphorous is implemented into a non-linear operation planning model and applied to the Dalälven reservoir network, whose contribution to the phosphorous load and subsequent eutrophication of the Baltic basin is not insignificant as described in section 3. Using the property that reservoir operation can increase the residence time of water and thereby increase the retention of phosphorous in the reservoirs, the trade-off between regular operation (defined by optimizing the total power production) and utilizing the reservoirs in mitigating the phosphorous effluent discharge is examined. It was shown that the model applied to the Dalälven watershed relates a significant decrease in phosphorous discharge at the expense of power production, illustrating that the two objectives are competitive which may incur significant costs during certain seasonal time-periods. Future research should address the effect of limiting hard constraints on the “form” of the trade-off curve as well as the effect of a demand curve, i.e. maximizing revenue as an alternative to the maximizing total production. By decreasing the predicted total future production by ~4.3% the phosphorous discharge of the Dalälven network could be decreased by ~2.25% or approximately 2 tons per year. The decrease in phosphorous as a result of regulation planning is primarily a result of increasing reservoir storage levels over time, facilitating the deposition of phosphorous in the sediment. Though the non-linear nature of the production function does benefit from the increased storage as a result of phosphorous retention objective it does not compensate for the overall decrease in discharge. The limits set on the reservoir storage forces a discharge, resulting in a forced discharge of phosphorous as can be seen in Figure 5. As a result of poor distribution of phosphorous concentration measurements (both temporally and spatially), several simplifications of the system description were made, including spatially constant phosphorous transport parameters. By complicating the description of the phosphorous transport incorporating vertical stratification (as a function of temperature), reservoir turbidity and additional degradation of the phosphorous, the accuracy of the phosphorous transport could be improved, influencing the shape of the resulting trade-off curve. Increasing the frequency of the reservoir regulation, i.e. decreasing the time-step, may not alter the results for systems with larger reservoirs (where the largest effect of reservoir regulation on phosphorous mass removal can be seen), since they are often seasonally regulated and may not be greatly affected by daily, or even weekly, reservoir regulation.

The proposed formulation of the optimization model can be applied to any reservoir network, however, the size of the search space does limit its applicability in terms of decision making as the computational load becomes excessive. The transport model of phosphorous could with minimal difficulty be expanded to included alternate formulations and mechanisms, such as fixation, degradation, biological activity and dissolved oxygen which may improve the description for certain watersheds.

The introduction of considering the mitigation of the discharge of phosphorous from the effluent reservoir as a second objective in the operation of the reservoir network enables the analysis of the “cost” of utilizing regulated reservoir for alternative environmental goals. Most previously published work focuses on the maximization of power production or revenue while treating the alternate goals as hard constraints. The concept of incorporating nutrient transport and soft environmental constraints as a second objective for the operation of a regulated network was demonstrated, illustrating the additional use of controlled reservoirs. Compromise solutions between the two objectives are illustrated by the pareto front (Figure 4a and 5), describing the trade-off afforded by the system. The developed trade-off curves can be incorporated into the decision making process, enabling a clearer valuation between potential benefits of alternative uses for managed reservoirs. Future research will focus on the alternative expression of cost versus gain in reservoir regulation.

6 Acknowledgements

Funding for this investigation was provided by the joint Baltic Sea research and development program, BONUS and the Swedish Environmental Protection Agency. The authors are also grateful to the Swedish Hydropower Centre (SVC), a center for education and research within hydropower and mining dams, for their continuing support for the research of reservoir operation.

References

Backer, H., et al. (2010), HELCOM Baltic Sea Action Plan - A regional programme of measures for the marine environment based on the Ecosystem Approach, *Mar Pollut Bull*, *60*(5), 642-649, doi: 10.1016/j.marpolbul.2009.11.016.

Basu, N. B., et al. (2010), Nutrient loads exported from managed catchments reveal emergent biogeochemical stationarity, *Geophysical Research Letters*, *37*, doi: Artn L23404 10.1029/2010gl045168.

Bednarek, A. T., and D. D. Hart (2005), Modifying dam operations to restore rivers: Ecological responses to Tennessee river dam mitigation, *Ecol Appl*, *15*(3), 997-1008, doi: Doi 10.1890/04-0586.

Bizzi, S., F. Pianosi, and R. Soncini-Sessa (2012), Valuing hydrological alteration in multi-objective water resources management, *Journal of Hydrology*, *472-473*, 277-286, doi: 10.1016/j.jhydrol.2012.09.033.

Bolin, S. B., T. J. Ward, and R. A. Cole (1987), Phosphorus Models Applied to New-Mexico Reservoirs, *J Water Res Pl-Asce*, *113*(3), 323-335, doi: 10.1061/(ASCE)0733-9496(1987)113:3(323).

Can, E. K., and M. H. Houck (1984), Real-Time Reservoir Operations by Goal Programming, *J Water Res Pl-Asce*, *110*(3), 297-309, doi: 10.1061/(ASCE)0733-9496(1984)110:3(297).

Castelletti, A., H. Yajima, M. Giuliani, R. Soncini-Sessa, and E. Weber (2014), Planning the Optimal Operation of a Multioutlet Water Reservoir with Water Quality and Quantity Targets, *Journal of Water Resources Planning and Management*, *140*(4), 496-510, doi: 10.1061/(Asce)Wr.1943-5452.0000348.

Chen, D., R. N. Li, Q. W. Chen, and D. S. Cai (2015), Deriving Optimal Daily Reservoir Operation Scheme with Consideration of Downstream Ecological Hydrograph Through A Time-Nested Approach, *Water Resources Management*, *29*(9), 3371-3386, doi: 10.1007/s11269-015-1005-z.

Cunha, D. G. F., M. D. Calijuri, and W. K. Dodds (2014), Trends in nutrient and sediment retention in Great Plains reservoirs (USA), *Environ Monit Assess*, *186*(2), 1143-1155, doi: 10.1007/s10661-013-3445-3.

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan (2002), A fast and elitist multiobjective genetic algorithm: NSGA-II, *Ieee T Evolut Comput*, *6*(2), 182-197, doi: 10.1109/4235.996017.

Dhar, A., and B. Datta (2008), Optimal operation of reservoirs for downstream water quality control using linked simulation optimization, *Hydrological Processes*, *22*(6), 842-853, doi: 10.1002/Hyp.6651.

Diaz, R. J., and R. Rosenberg (2008), Spreading dead zones and consequences for marine ecosystems, *Science*, *321*(5891), 926-929, doi: 10.1126/science.1156401.

EC (2000), Directive 200/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a framework for Community action in the field of water policy, *Official Journal of the European Communities*, *L327*, doi.

EC (2008), Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), *Official Journal of the European Union L164*, *19*, doi.

Fontane, D. G., J. W. Labadie, and B. Loftis (1981), Optimal-Control of Reservoir Discharge Quality through Selective Withdrawal, *Water Resources Research*, *17*(6), 1594-1604, doi: 10.1029/Wr017i006p01594.

Gandolfi, C., G. Guariso, and D. Togni (1997), Optimal Flow Allocation in the Zambezi River System, *Water Resources Management*, *11*(5), 377-393, doi: 10.1023/A:1007964732399.

Goulter, I. C., and R. G. Castensson (1988), Screening model for assessing 'cost' of minimum flow requirements in the Svartå River, Sweden, *Water Resources Management*, *2*(1), 35-55, doi: 10.1007/BF00421929.

Hayes, D. F., J. W. Labadie, T. G. Sanders, and J. K. Brown (1998), Enhancing water quality in hydropower system operations, *Water Resources Research*, *34*(3), 471-483, doi: 10.1029/97wr03038.

Jager, H. I., and B. T. Smith (2008), Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values?, *River Research and Applications*, *24*(3), 340-352, doi: 10.1002/rra.1069.

Kemp, W. M., J. M. Testa, D. J. Conley, D. Gilbert, and J. D. Hagy (2009), Temporal responses of coastal hypoxia to nutrient loading and physical controls, *Biogeosciences*, *6*(12), 2985-3008, doi.

Kotchen, M. J., M. R. Moore, F. Lupi, and E. S. Rutherford (2006), Environmental constraints on hydropower: An ex post benefit-cost analysis of dam relicensing in Michigan, *Land Econ*, *82*(3), 384-403, doi.

Lindstrom, G., C. Pers, J. Rosberg, J. Stromqvist, and B. Arheimer (2010), Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales, *Hydrology Research*, *41*(3-4), 295-319, doi: 10.2166/nh.2010.007.
Maier, H. R., et al. (2014), Evolutionary algorithms and other metaheuristics in water resources: Current status, research challenges and future directions, *Environmental Modelling & Software*, *62*, 271-299, doi: 10.1016/j.envsoft.2014.09.013.
Mala-Jetmarova, H., A. Barton, and A. Bagirov (2015), Exploration of the Trade-Offs between Water Quality and Pumping Costs in Optimal Operation of Regional Multiquality Water Distribution Systems, *Journal of Water Resources Planning and Management*, *141*(6), doi: 10.1061/(Asce)Wr.1943-5452.0000472.
Mala-Jetmarova, H., A. Barton, and A. Bagirov (2015), Impact of Water-Quality Conditions in Source Reservoirs on the Optimal Operation of a Regional Multiquality Water-Distribution System, *Journal of Water Resources Planning and Management*, *0*(0), 04015013, doi: 10.1061/(asce)wr.1943-5452.0000523.
Mendes, L. A., M. T. L. de Barros, R. C. Zambon, and W. W. G. Yeh (2015), Trade-Off Analysis among Multiple Water Uses in a Hydropower System: Case of São Francisco River Basin, Brazil, *Journal of Water Resources Planning and Management*, *0*(0), 04015014, doi: 10.1061/(asce)wr.1943-5452.0000527.
Nicklow, J., et al. (2010), State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management, *J Water Res Pl-Asce*, *136*(4), 412-432, doi: 10.1061/(Asce)Wr.1943-5452.0000053.
Osterman, L. E., R. Z. Poore, P. W. Swarzenski, D. B. Senn, and S. F. DiMarco (2009), The 20th-century development and expansion of Louisiana shelf hypoxia, Gulf of Mexico, *Geo-Mar Lett*, *29*(6), 405-414, doi: 10.1007/s00367-009-0158-2.
Panuska, J. C., and D. M. Robertson (1999), Estimating Phosphorus Concentrations Following Alum Treatment Using Apparent Settling Velocity, *Lake and Reservoir Management*, *15*(1), 28-38, doi: 10.1080/07438149909353949.
Rabalais, N. N., R. J. Diaz, L. A. Levin, R. E. Turner, D. Gilbert, and J. Zhang (2010), Dynamics and distribution of natural and human-caused hypoxia, *Biogeosciences*, *7*(2), 585-619, doi: 10.5194/bg-7-585-2010.
Reckhow, K. H. (1979), Uncertainty Analysis Applied to Vollenweider Phosphorus Loading Criterion, *J Water Pollut Con F*, *51*(8), 2123-2128, doi.
Reed, P. M., D. Hadka, J. D. Herman, J. R. Kasprzyk, and J. B. Kollat (2013), Evolutionary multiobjective optimization in water resources: The past, present, and future, *Advances in Water Resources*, *51*, 438-456, doi: 10.1016/j.advwatres.2012.01.005.
Straskraba, M. (1994), Ecotechnological Models for Reservoir Water-Quality Management, *Ecological Modelling*, *74*(1-2), 1-38, doi: 10.1016/0304-3800(94)90108-2.
Suen, J. P., and J. W. Eheart (2006), Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime, *Water Resources Research*, *42*(3), doi: 10.1029/2005wr004314.
Wang, Q., M. Guidolin, D. Savic, and Z. Kapelan (2015), Two-Objective Design of Benchmark Problems of a Water Distribution System via MOEAs: Towards the Best-Known Approximation of the True Pareto Front, *Journal of Water Resources Planning and Management*, *141*(3), 04014060, doi: 10.1061/(Asce)Wr.1943-5452.0000460.
Yeh, W. W. G., and L. Becker (1982), Multiobjective Analysis of Multi-Reservoir Operations, *Water Resources Research*, *18*(5), 1326-1336, doi: 10.1029/Wr018i005p01326.

The present work has been carried out within the project 'Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams (BONUS SOILS2SEA)', which has received funding from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly by the EU and national funding agencies: Innovation Fund Denmark, The Swedish Environmental Protection Agency (Naturvådsverket), The Polish National Centre for Research and Development, The German Ministry for Education and Research (Bundesministerium für Bildung und Forschung), and The Russian Foundation for Basic Research (RFBR).