A decision support procedure for integrative management of dammed raw water reservoirs

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ABSTRACT

Dammed drinking water reservoirs with their catchment areas and the downstream rivers are dynamic systems that change permanently under the influence of many factors. Their multifunctional use for drinking water supply, flood control, energy production, nature conservation and recreation as well as ecological constraints for the rivers downstream requires an integrative management considering and balancing between different requirements. Thus, an optimal reservoir management has to take into account scenarios of external influences and must be based on predictions of prospective raw water qualities. Furthermore, the impacts of short- and long-term changes of the raw water quality on drinking water treatment have to be considered. The problem is very complex and cannot be solved intuitively but requires the application of hydrological, ecological and process models. This approach was followed in the work presented here, as a tool to predict and evaluate the impacts of different reservoir management strategies in an integrative way is currently not available. The developed decision support procedure (DSP) allows for the estimation of the effects of different hydrological and water quantity management scenarios on raw water quality, water processing costs and ecology in the downstream river. Extreme hydrological events or changing boundary conditions (e.g. climate change) are taken into account.

Key words | decision support procedure (DSP), drinking water, integrative modelling, management of reservoirs, water quality

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NOMENCLATURE

A_e, km^2	Catchment area	Q_{in}, L s^{-1}; m^3 s^{-1}	Inflow
DOC, mg L^{-1}	Dissolved organic carbon	Q_m, L s^{-1}; m^3 s^{-1}	Average flow rate
DSP	Decision support procedure	Q_{max}, L s^{-1}; m^3 s^{-1}	Maximum flow rate
DW	Drinking water	Q_{out}, L s^{-1}; m^3 s^{-1}	Outflow
DWT	Drinking water treatment	TOC, mg L^{-1}	Total organic carbon
P	Phosphorus	WFD	Water Framework Directive

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INTRODUCTION

The management of dammed drinking water reservoirs is complex and many aspects partially counteracting have to be considered. For instance, there is a conflict between reliable supply of raw water in adequate quantity and quality and sufficient flood control (Sieber 2003). For optimum flood protection an almost empty dam is required which brings lower water quality along. To maintain high reservoir water quality due to the natural self-cleansing ability of the water body, the water level should be maintained as high and constant as possible. If drinking water supply has priority in reservoir management, a sufficient volume for drinking water production has to be primarily guaranteed. The flood retention is also limited with respect to water quality aspects. Consequently, a compromise and an integrative strategy are needed to cover these aspects in reservoir management. Another conflict concerns the amount and quality of compensation water released, which should be minimal in order to save high quality raw water, but there are also requirements and objectives of the EU Water Framework Directive (WFD) (European Commission 2000) which have to be fulfilled. In this context also the impact of changes in compensation water quality on the value and type of river ecosystem services should be considered (Costanza *et al*. 1997; Strayer & Dudgeon 2010). According to the WFD, most of the rhithral and potamal rivers beneath dams will not achieve a 'good ecological status' or a 'good ecological potential', respectively, until 2015 (Richter & Völker 2010). In spite of good water quality in the water column with high ecological potential, interacting processes between surface water, riverbed (morphology) and hyporheic interstitial can be interfered by fluctuating reservoir discharges. Hydraulic conditions and flow regime can be seen as a key variable which shapes the many fundamental ecological characteristics in rivers and streams (Richter *et al*. 1996). A possible consequence of unnatural hydraulic conditions is a functional loss of the hyporheic interstitial as a fundamental habitat for aquatic communities (e.g. Saenger & Zanke 2006; Borchardt & Pusch 2008).

Furthermore, raw water quality changes inevitably have an effect on drinking water treatment efficiency and costs. Increasing inputs of organic and particulate matter into the raw waters require a higher degree of treatment plant efficiency, mostly requiring changes to the whole treatment technology and supply system operation. Increasing concentrations of, e.g. humic substances deteriorate the coagulation of water contaminants. The disinfection by-product formation potential and the microbial contamination within the supply system will increase with decreasing treatment effectiveness. As a consequence of increasing concentrations of particles, algae and organic matter and temporary changes in iron and aluminium concentration within the raw water, more chemicals and volumes of backwash water are needed, higher amounts of sludge are produced and filter breakthrough will take place earlier. This will result in rising costs of operation and waste disposal.

Reservoir specific water management plans have to take into account the following aspects:

- Long (e.g. climate change) and short-term extreme hydrological events (floods, droughts).
- Structure and management of the drainage basin.
- Water demand and treatment technology installed at the water works.
- Ecological functionality of the lower reaches.

In contrast to these complex processes and partly counteracting interests, reservoir management is still mainly based on experience only. However, an increasing interest of water authorities can be recognised to support their decision by scientifically proven algorithms and models for future management. Therefore, tools integrally considering the different aspects are urgently needed. However, the evolution of reservoir management strategies that harmonise all demands is very difficult.

Consequently, the main and innovative objective of the multi-disciplinary study presented here was to develop a decision support procedure (DSP) for an integrative management of multipurpose drinking water reservoirs considering all the aspects mentioned above. For the DSP, a modular structure and the development and linking of models describing processes and interrelations in the subsystems were intended:

- water quantity and quality
- drinking water treatment
- downstream river water quality.

The linking of models should include all aspects of the physical, chemical or biological structure of the reservoir and consider the effects of meteorological or hydrological extreme events on:

- the raw water quality,
- the drinking water treatment, and
- the ecological state of the downstream river.

to establish a consistent framework.

Considering targets and limits defined by the reservoir operator and based on observed or simulated long-term run-off series, water quantity management rules should be derived and optimised. The aim was to predict their influences on the reservoir's physical structure and water quality depending on varying release depths of raw water and compensation water. Finally, the impacts of the resulting water quality on costs of drinking water treatment and on the ecology of the downstream river should be simulated. Moreover, it was intended to evaluate the results on the basis of the targets and limits defined. If the results do not fulfil the targets, the procedure can be repeated with a modified scenario. Thus, users of the DSP will be enabled to simulate and evaluate the complex consequences of different management strategies and flood protection demands on:

- reservoir water quantity and quality
- drinking water treatment
- river water quality.

MATERIALS AND METHODS

The reservoir system investigated comprised the reservoirs Klingenberg and Lehnmühle including their tributaries and pipelines (Figure 1). Both are situated in the South-eastern low mountain range of Saxony (Germany).

To optimise the operation rules for quantity related reservoir management, objective functions describing optimal management were set up. In this case, the guarantee of drinking water supply, dam stability and the protection of downstream sites have been the main objectives. Both flood protection and low-flow requirements downstream are achieved by keeping maximum and minimum tolerable discharges, respectively. By setting up the reservoir system

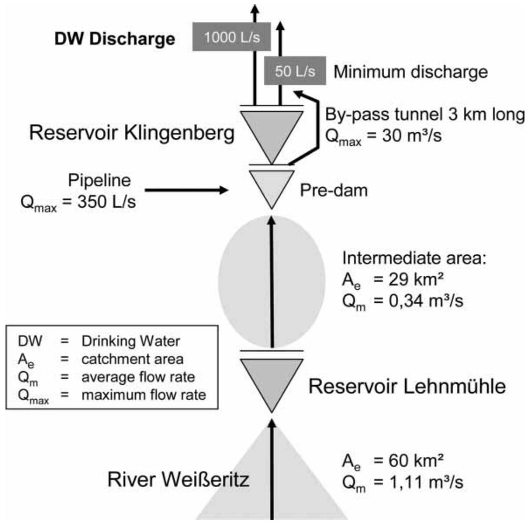

Figure 1 | Reservoir system investigated.

(Figure 1), the objective functions describing outflows from the reservoir are functions of inflows, season and the volume of all reservoirs in the system. In order to generate inflow as a function of time during the year, data from past precipitation-drainage-events and measured inflows to the reservoir were subjected to pattern recognition. Here, 100 scenarios were generated stochastically covering a period of 100 years, each describing typical inflow events. Thereby, all components were available to apply quantity optimisation using evolutionary strategy. As a parameter for the evolutionary strategy, the operating rules as relationships between discharges and selected state variables are considered, for example, in the simplest case, a relationship between discharge and reservoir volume. The rules themselves are described as 'if-then-functions'.

The integration of water quantity and quality management was performed using the software TALSIM developed by SYDRO Consult GmbH (Lohr 2001) but extended now to include several water quality criteria and allow the adoption of quantity based operation strategies according to the quality-related criteria (Rolinski *et al.* 2007).

To estimate the effects of different management strategies on water quality (at optimum quantity-management), the coupled physical–ecological model SALMO-HR was used for deterministic predictions. The model SALMO-HR is a vertically resolved one-dimensional hydrophysical–ecological model for lakes and reservoirs (Petzoldt *et al.* 2005; Rolinski *et al.* 2005; Rolinski *et al.* 2008). Its equations and parameters are defined in a generalised manner, so that site-specific calibration is restricted to waterbody specific properties such as planktivorous fish density, light extinction and sediment-P-release. The model consists of the ecological sub-model SALMO-1D developed at Technische Universität Dresden (Benndorf & Recknagel 1982; Petzoldt *et al.* 2005) and the hydrophysical k-ε-model LAKE of the Institute IAMARIS eV. (Baumert *et al.* 2005). The current final version of SALMO-HR simulates the seasonal development of temperature, stratification and turbulence (physical components) as well as the concentrations of phosphorus, nitrogen, phytoplankton (three groups), zooplankton, oxygen, DOC (including humic substances) and suspended matter (four particle classes) (Scheifhacken & Paul, unpublished data).

Extreme hydrological events, e.g. extreme floods or severe low water levels can substantially deteriorate the water quality and may even result in a malfunction of drinking water treatment (Paul & Scheifhacken 2009). Therefore, inflow concentrations and in-lake distributions of pollutants were investigated in order to develop dam-specific as well as general standards to complete the optimisation rules for the management of drinking water reservoirs in both water quantity and quality aspects. Special attention was paid to turbidity caused by floods and the characteristics of suspended particulate matter (Scheifhacken *et al.* 2010). Besides general water quality data, flux, concentration, size distribution and settling velocity of particles as well as fractions of dissolved natural organic matter were determined. The dataset was completed with historical data provided by the reservoir administration. Empiric models were used to describe the development of turbidity in the reservoirs depending on particle inflow and sedimentation. Following guidelines given in ATT (2009), a procedure was developed and implemented that allows for the determination of the minimum storage capacity and minimum hypolimnion volume of stratified reservoirs at the beginning of the summer stratification, which are needed to ensure basic raw water quality and quantity requirements with a user-defined statistical probability (Scheifhacken & Paul, unpublished data).

To model the impact of management strategies on river water quality downstream of the reservoir, the oxygen and nutrients concentrations in the water and the hyporheic interstitial were measured with probes and a data logger and were recorded automatically to investigate the influence of reservoir discharge on benthic invertebrates. Furthermore, oxygen, temperature, pH, conductivity, nitrogen, phosphorus, DOC and pressure variability were studied at three reference sampling sites in the catchment area downstream of the reservoirs. The interactions between surface and pore water in the sediment were modelled based on the temperature variability, the functionality was shown due to decelerated temperature exchange between both: vertical infiltration rates, reaction potential, detrital drive and mass transfer between the flowing water and the hyporheic interstitial dependent on discharge. Results of the water quality characteristics were compared with thresholds of chemical and physico-chemical variables given by LAWA (2007) to estimate the ecological state of water bodies according to WFD. Oxygen concentrations in the surface water were modelled according to different scenarios to predict water quality for specific management strategies. Benthic invertebrates were sampled in spring 2007 and 2008 according to standardised methods (Haase *et al.* 2004; Hering *et al.* 2004, Sundermann *et al.* 2008). Biological attributes of benthic invertebrates (e.g. taxonomic or functional composition) were selected to identify possible effects of unnatural inflow to the aquatic community.

To assess the impact of water quality on drinking water treatment, coagulation filtration experiments were planned according to factorial design and carried out at pilot scale. Treatment performance and costs were described as a function of organic load and turbidity using an empirical model. Required information had to be determined with maximum accuracy from as few as possible experiments. Using the method of factorial design, simultaneous variation and investigation of all variables within a single experimental plan was possible (Montgomery 2005). Thus, distinction of significant from insignificant variables as well as identification of relationships and optimum values could be achieved. Treatment performance was measured as filter run time until breakthrough, head loss, coagulant demand, acid/base demand for pH-adjustment, backwash water demand and sludge produced. The method of factorial design was applied to quantitatively describe the relationship between the investigated process parameters (raw water quality parameters, treatment parameters) and the dependent variable (treatment capacity). This approach was chosen because of the high complexity of mechanistic models describing treatment processes and the advantage of not being plant specific or requiring considerable model calibration and validation as mechanistic models do. The use of the method of factorial design was meant to develop regression models in the form of regression equations. This and the application of an optimisation algorithm finally resulted in the determination of optimum treatment parameters (pH, coagulant dosage and filter velocity) for each combination of organic load and turbidity. Then, with these optimised treatment parameters, specific treatment costs can be determined. As a result, the expected treatment costs for optimised treatment of each expected raw water quality can be calculated and plotted in three-dimensional diagrams (Slavik *et al.* 2010).

RESULTS

The DSP developed consists of a number of modules. The modules include model based mathematical descriptions and stochastic analysis of the processes and interrelations of the subsystems of a reservoir system (Figure 2). The data interchange among these modules offers the possibility to predict the consequences of different management strategies (different intake levels and amounts of raw water withdrawal and discharge to the lower reaches) in interaction with external factors (catchment area management, hydrological and climatic factors) on the particular subsystems (Figure 2). Finally, the optimal reservoir management strategy for current or prospective variable constellations can be derived and validated with respect to defined target values and limits.

The optimised flow of information and data between the particular modules are mandatory to apply the DSP (Figure 3). The starting point is the choice of a management strategy and the definition of ranges of acceptance for quality and treatment cost indicators (Figure 3). Different scenarios of raw water abstraction and discharge to the downstream reaches can be applied. Each management scenario is characterised by certain preferences of release levels for raw water and water to the downstream reaches, respectively. For example, raw water is taken from either the deepest (scenario 1) or the highest (scenario 2) possible hypolimnetic outlet structure. Alternatively, epilimnetic water will be abstracted to the downstream reaches and raw water is taken from a medium hypolimnetic outlet (scenario 3). For these three scenarios, the development of water quality parameters and their effects on drinking water treatment costs and the ecological state of the river downstream of the reservoir can be described (Figures 3 and 4).

Then, a mere quantity optimisation for the chosen management strategy follows within the module 'Simulation water quantity'. To optimise quantity, objective functions were set up as described before to guarantee drinking water supply, dam stability and the protection of downstream sites. Using these objective functions and the stochastically generated inflow loads, operation rules can be defined to optimise quantity management for the reservoir system investigated. On the basis of these operation rules, relationships between the inflow to the reservoir, the discharges

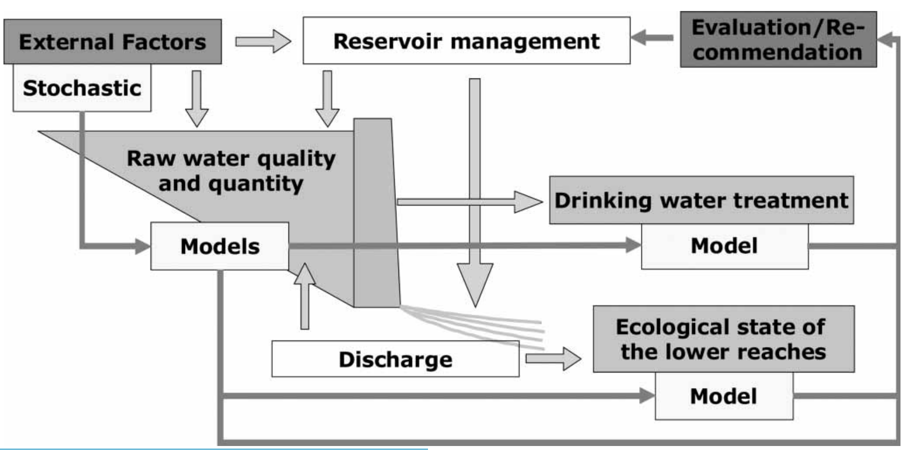

Figure 2 | Subsystem interactions and data flows considered in the decision support procedure.

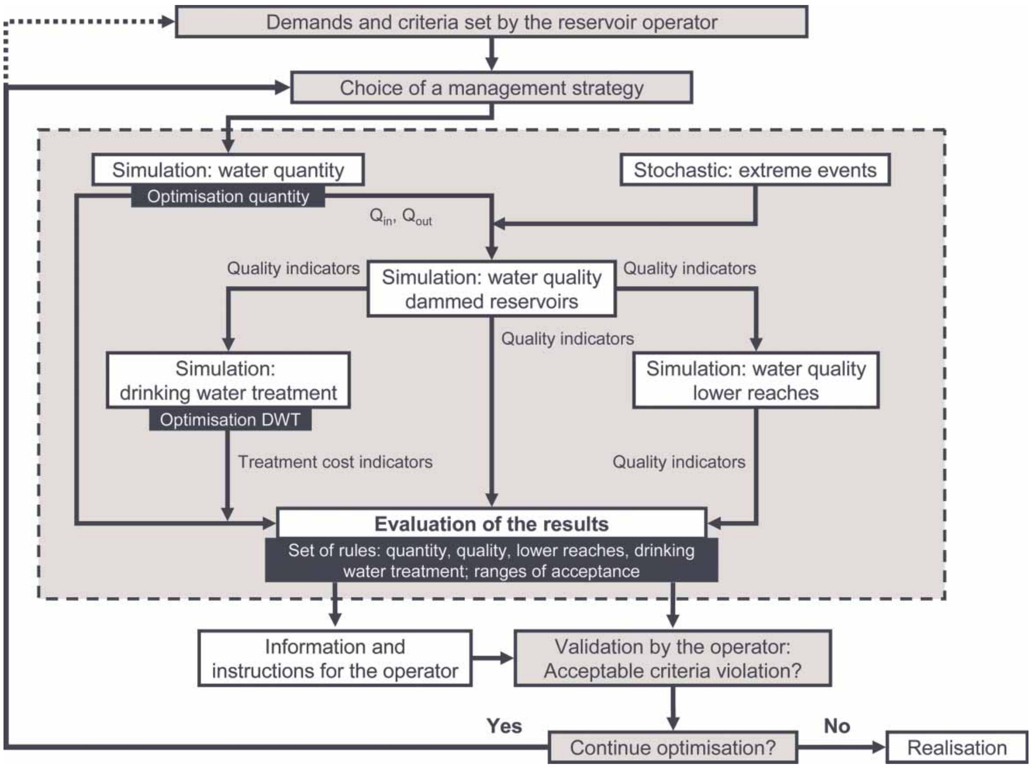

Figure 3 | Flow of information and data between the modules of the decision support procedure, DWT = drinking water treatment, Q_{in} = inflow, Q_{out} = outflow.

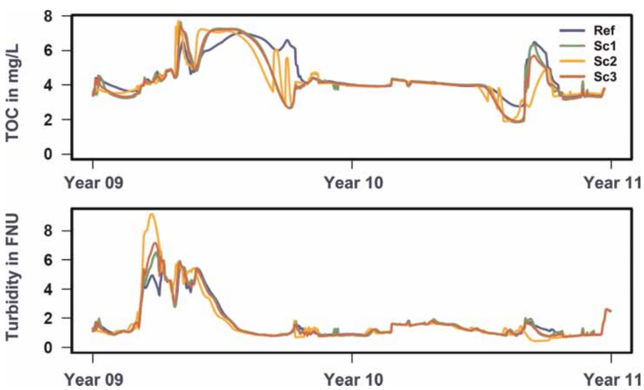

Figure 4 | Development of the TOC-concentration and the turbidity in the raw water reservoir during two generated years for the scenarios 1 to 3 (Sc1, Sc2, Sc3, raw water abstraction at the deepest, highest or medium hypolimnetic outlet, respectively) compared with a mere quantity optimised reservoir management strategy (Ref).

(drinking water treatment, rivers downstream) and the resulting storage level can be described. The results of the quantity related calculations (Q_{in}, Q_{out}, storage level) serve as input data for the simulations of dammed reservoir water quality and directly enter the all-up evaluation.

Within the quality-related optimisation, investigation results of inflow and in-lake distribution of pollutants during extreme hydrological events (e.g. extreme floods or severe draw-downs of the storage level) are also taken into account. Using stochastic simulations, the minimum storage and the minimum hypolimnion volume are calculated under consideration of the water quantity management rules determined before, which are necessary to ensure raw water withdrawal from hypolimnetic layers during summer stagnation with a user defined probability. Additional rules for the quantity management at extreme situations are derived.

The subsequent reservoir water quality simulation in the module 'Simulation: water quality dammed reservoirs' is using these boundary conditions and gives information under which constellations of the inflow, the reservoir storage and the discharge etc. quality-related problems can occur. Moreover, scenario based modelling shows how quality problems can be prevented by changing the height of raw water intake for drinking water production and/or discharge to the river, respectively. The stochastically generated time series from the water quantity management model were used as hydrological input data and complemented with meteorological records and empirically derived import concentrations (nutrients, humic substances, particles). Subsequently, indicators for the quality of raw water and ecological impacts on the downstream reaches of the discharge were determined using these simulation results. The comparison of different variants of operational reservoir management on the basis of simulated scenarios allows objectifying management decisions, which guarantee a best possible raw water quality for drinking water production and good ecological conditions downstream. The results of these simulations do not only contribute to the all-up evaluation but are also used as input data for the calculations within the modules 'Simulation: drinking water treatment' and 'Simulation: water quality lower reaches'.

The quality simulation of the lower reaches within the module 'Simulation: water quality lower reaches' shows under which constellation of the discharge quality-related problems occur downstream and whether, and if necessary how, these can be reduced by changes in discharge. By using a model describing transport and transformation processes, especially the oxygen conditions (River Water Quality Model No. 1; Reichert *et al.* 2001) in the flowing water and the hyporheic interstitial dependent on different reservoir management strategies, river water quality can be predicted. As a result, these simulations provide indicators for the quality of raw water being discharged to the lower reaches. According to the different defined scenarios of discharge, model based results of water quality variables (e.g. oxygen, phosphorus, nitrogen) do not exceed thresholds in surface water by LAWA (2007), but long-lasting minimum discharges to the lower reaches have an impact on the oxygen content of the deeper sediment layers. The benthic invertebrate community is not influenced by reservoir discharge with regard to assessment methods used to classify ecological status by WFD. However, significant changes in biocoenotic composition of invertebrates were identified in consideration of selected biological attributes adapted to functionality of hyporheic interstitial (Oligochaeta, Diptera) and discharge (Rheoindex, active filter feeders).

To investigate impacts of different raw water qualities on drinking water treatment within the module 'Simulation: drinking water treatment', a model was developed to optimise drinking water treatment which takes into account short-, mid- and long-term factors impacting raw water quality (Slavik & Uhl 2007; Slavik & Uhl 2009; Slavik *et al.* 2010). To assess the impact of water quality resulting from reservoir management on drinking water treatment, at first analyses of historical quality data and treatment performance during extreme events were carried out. Furthermore, an extensive series of experiments using pilot-scale filter plants was run, planned and evaluated by factorial design. Input parameters for simulation of drinking water treatment are TOC and turbidity, obtained from the water quality module. Based on the results of data analysis and pilot investigations and the model developed herewith, optimum treatment parameters (filter velocity, coagulant dosage, pH-value) were determined for minimum costs per m^3 drinking water produced. To evaluate drinking water treatment within the framework of the DSP, treatment cost indicators can be set by the user.

Finally, an overall evaluation of the simulation results can be done. After running the combined models, the user of the DSP will have to decide whether a possible violation of the chosen criteria is acceptable or not. Furthermore, the decision on continuing the optimisation has to be made. An optimisation and iteration cycle will be finished on the decision of the user if a management strategy can be found which ideally fulfils the quality and quantity-related objectives as well as the demands on drinking water treatment efficiency or rather will show least possible deviation. Moreover, the user will get information and instructions for the operation and management of a raw water reservoir. Otherwise, a new management strategy has to be chosen to start the optimisation and iteration cycle again.

For the three abstraction scenarios described above, the simulation results with respect to raw water quality and drinking water treatment costs are exemplarily shown (Figure 4). Within the water quality model, the seasonal dynamics of the reservoir water can be reproduced reasonably well, especially in terms of particulate substances, physical variables (e.g. temperature) and phytoplankton (abundances, biomass). As this seasonal dynamic is decisive for raw water quality with regard to drinking water treatment, results for e.g. the TOC-concentration are derived on a daily time step. As result, the development of raw water quality parameters in the reservoir can be simulated, exemplarily shown in Figure 4 for the TOC-concentration and the turbidity for two generated years. Following this, specific costs (in Euro per m^3) of drinking water treatment by coagulation–filtration can be calculated on the basis of the simulated TOC-concentration and turbidity when the model for drinking water treatment simulations is applied. The effects of the abstraction level and the resulting development of the water quality parameters on drinking water treatment costs are shown in Figure 5.

SUMMARY

The entire system of a raw water reservoir for drinking water production with its catchment area, the river downstream and the drinking water treatment plants is very complex and dynamic. With increasing demands and external pressures such as climate change, future management of drinking water reservoirs should not only be based on water management plans and the operator's experience any more. Here, we introduce a newly developed integrative approach to manage raw water reservoirs by applying a DSP. All aspects of water quality and quantity, flood protection, cost efficient drinking water treatment as well as guarantee of an acceptable ecological state of downstream river sections are implemented. Furthermore, the impact of extreme hydrological events and long-term changes (e.g. due to climate change) are included. This was done on the basis of linking and partly coupling of models describing the processes and interrelations within a drinking water reservoir system. Within the modules water quantity and raw water quality, already existing software tools were developed further with respect to the intended purposes of this project and interlinked. The results of the water quantity and quality simulations serve as data for the calculations to optimise treatment efficiency for drinking water production as well as to describe transport and transformation processes in the lower reaches. By combining all simulation results and by setting up demands and criteria for raw water reservoir operation, users of this DSP will be able to simulate and to evaluate the complex consequences of different management strategies and flood protection demands on reservoir water quantity and quality, drinking water treatment and river water quality.

According to ecological health and environmental objectives by WFD of lower reaches, there is a need to improve a more dynamic discharge and flow regime out of dams. Hydraulic conditions close to natural ones ensure ecological functionality with regard to aquatic communities, morphological alterations and hyporheic interstitial.

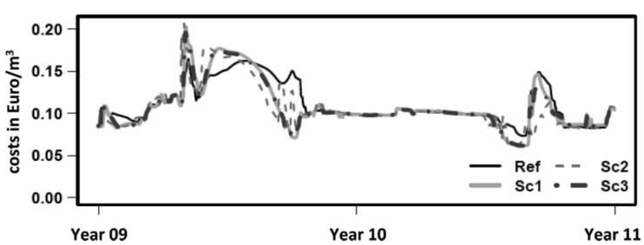

Figure 5 | Development of specific costs (in Euro per m^3) of drinking water treatment by coagulation–filtration during two generated years for the scenarios 1 to 3 (Sc1, Sc2, Sc3 see Figure 4) compared with a mere quantity optimised management strategy (Ref).

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REFERENCES

ATT 2009 *Integrale Bewirtschaftung von Trinkwassertalsperren gemäß DIN 19700. Arbeitsgemeinschaft Trinkwassertalsperren e.V., ATT-Schriftenreihe Band 7*. Oldenbourg Industrieverlag, München 2009.

Baumert, H. Z., Benndorf, J., Bigalke, K., Goldmann, D., Nöhren, I., Petzoldt, Y., Post, J. & Rolinski, S. 2005 Das hydrophysikalisch ökologische Talsperren- und Seenmodel SALMO-HR – Modelldokumentation und Leitfaden für den Anwender. Dresden.

Benndorf, J. & Recknagel, F. 1982 Problems of application of the ecological model SALMO to lakes and reservoirs having various trophic states. *Ecological Modelling* **17**, 129–145.

Borchardt, D. & Pusch, M. (eds) 2008 An integrative, interdisciplinary research approach for the identification of patterns, processes and bottleneck functions of the hyporheic zone of running waters. *Fundamental and*

Applied Limnology. Special Issue Advances in Limnology **61**, 1–7.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P. & van den Belt, M. 1997 The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260.

European Commission 2000 Official Journal L 327, 22.12.2000, p. 1; Directive 2000/60/EC (EU Water Framework Directive).

Haase, P., Lohse, S., Pauls, S., Schindehütte, K., Sundermann, A., Rolauffs, P. & Hering, D. 2004 Assessing streams in Germany with benthic invertebrates: development of a practical standardised protocol for macroinvertebrate sampling and sorting. *Limnologica* **34** (4), 349–365.

Hering, D., Meier, C., Rawer-Jost, C., Feld, C. K., Biss, R., Zenker, A., Sundermann, A., Lohse, S. & Böhmer, J. 2004 Assessing streams in Germany with benthic invertebrates: selection of candidate metrics. *Limnologica* **34** (4), 398–415.

LAWA – Länderarbeitsgemeinschaft Wasser AO 2007 Rahmenkonzeption Monitoring. Teil B – Bewertungsgrundlagen und Monitoring. Arbeitspapier II Hintergrund- und Orientierungswerte für physikalisch-chemische Komponenten. Stand 07.03.2007.

Lohr, H. 2001 *Simulation, Bewertung und Optimierung von Betriebsregeln für wasserwirtschaftliche Speichersysteme*. Mitteilungen des Instituts für Wasserbau und Wasserwirtschaft Heft 118, Technische Universität Darmstadt, Darmstadt.

Montgomery, D. C. 2005 *Design and Analysis of Experiments*, 6th Edition 2005. John Wiley, New York.

Paul, L. & Scheifhacken, N. 2009 *Einfluss von Wassermengenbewirtschaftung auf die vertikale Verteilung allochthoner Trübstoffe in Trinkwassertalsperren nach Hochwässern*. DGL Tagungsband 2009, Oldenburg. Eigenverlag der DGL, S. pp. 144–148, Hardegsen 2010.

Petzoldt, T., Rolinski, S., Rinke, K., König, M., Baumert, H. Z. & Benndorf, J. 2005 SALMO: Die ökologische Komponente des gekoppelten Modells. *Wasserwirtschaft* **95** (5), 28–33.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyody, L. & Vanrolleghem, P. A. 2001 *River Water Quality Model No.1, Scientific & Technical Report No. 12.* International Water Association, London. ISBN: 9781900222822, 144 pp.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. 1996 *A method for Assessing Hydrologic Alteration within Ecosystems. Conservation Biology* 10 (4), pp. 1163–1174.

Richter, S. & Völker, J. 2010 *Water Framework Directive – The Way Towards Healthy Waters. Results of the German River Basin Management Plans 2009*. Published in July 2010 from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, 75 pp.

Rolinski, S., Petzoldt, T., Baumert, H. Z., Bigalke, K., Horn, H. & Benndorf, J. 2005 Das physikalisch-ökologisch gekoppelte Talsperrenmodell. *Wasserwirtschaft* **95** (5), 34–38.

Rolinski, S., Petzoldt, T. & Benndorf, J. 2008 Nutrients, Weather, Food Web: What do we need to model Trophic Change? In: *Proceedings of the Workshop 'Perspectives of lake modeling towards predicting reaction to trophic change'*, Kompetenzzentrum Wasser Berlin Publication Series, 9, pp. 30–37, ISBN 978-3-9811684-3-3.

Rolinski, S., Petzoldt, T., Hillert, K., Paul, L. & Benndorf, J. 2007 Linking water quality to water quantity: Integration of disturbance variables into the management strategies of drinking water reservoirs, In: *American Geophysical Union Fall Meeting*, abstract #B51B-0378, San Francisco, USA.

Saenger, N. & Zanke, U. C. E. 2006 A depth -oriented view of hydraulic exchange patterns between surface water and the hyporheic zone: analysis of field experiments. *Fundamental and Applied Limnology. Special Issue Advances in Limnology* **61**, 9–27.

Scheifhacken, N., Horn, H. & Paul, L. 2010 Comparing *in situ* particle monitoring to microscopic counts of plankton in a drinking water reservoir. *Water Research* **44**, 3496–3510.

Sieber, H.-U. 2003 Talsperren als multifunktionale Anlagen. *WWT* **12**, 17–21.

Slavik, I. & Uhl, W. 2007 Optimizing water treatment to respond to quality changes due to reservoir management and climate change, In: *Proc. Am. Water Works Ass. 'Water Quality Technology Conference'*, Charlotte, USA.

Slavik, I. & Uhl, W. 2009 Analysing water quality changes due to reservoir management and climate change for optimization of drinking water treatment. *Water Science and Technology - Water Supply* **9** (1), 99–105.

Slavik, I., Skibinski, B., Watzlawik, S. & Uhl, W. 2010 Beschreibung von Einflüssen der Wasserqualität auf den Aufwand für die Trinkwasseraufbereitung – ein statistisches Modell. In: *Proc. Wasser 2010 – Jahrestagung der Wasserchemischen Gesellschaft*, Bayreuth, 10–12. May, 2010.

Strayer, D. L. & Dudgeon, D. 2010 Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society* **29** (1), 344–358.

Sundermann, A., Pauls, S. U., Clarke, R. T. & Haase, P. 2008 Within-stream variability of benthic invertebrate samples and EU Water Framework Directive assessment results. *Fundamental and Applied Limnology (Archiv fuer Hydrobiologie)* **173**, 21–34.

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