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Research article

Optimizing withdrawal from drinking water reservoirs to reduce downstream temperature pollution and reservoir hypoxia

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ABSTRACT

Sustainable management of drinking water reservoirs requires balancing the demands of water supply whilst minimizing environmental impact. This study numerically simulates the effect of an improved withdrawal scheme designed to alleviate the temperature pollution downstream of a reservoir. The aim was to identify an optimal withdrawal strategy such that water of a desirable discharge temperature can be supplied downstream without leading to unacceptably low oxygen concentrations within the reservoir. First, we calibrated a one-dimensional numerical model for hydrodynamics and oxygen dynamics (GLM-AED2), verifying that the model reproduced water temperatures and hypolimnetic dissolved oxygen concentrations accurately over a 5 year period. Second, the model was extended to include an adaptive withdrawal functionality, allowing for a prescribed withdrawal temperature to be found, with the potential constraint of hypolimnetic oxygen concentration. Scenario simulations on epi-/metalimnetic withdrawal demonstrate that the model is able to autonomously determine the best withdrawal height depending on the thermal structure and the hypolimnetic oxygen concentration thereby optimizing the ability to supply a desirable discharge temperature to the downstream river during summer. This new withdrawal strategy also increased the hypolimnetic raw water volume to be used for drinking water supply, but reduced the dissolved oxygen concentrations in the deep and cold water layers (hypolimnion). Implications of the results for reservoir management are discussed and the numerical model is provided for operators as a simple and efficient tool for optimizing the withdrawal strategy within different reservoir contexts.

1. Introduction

Dams and reservoirs have mainly been built for the purposes of drinking and irrigation water supply, electric power generation and flood protection (Kennedy, 1999). These artificial water bodies interrupt the natural course of a river, and, as a consequence, both water flux and water quality in the downstream river are affected by the obstruction (Nilsson et al., 2005). Globally, this has threatened water security and biodiversity from local to global scales (Vörösmarty et al., 2010). Protecting rivers and reservoirs as freshwater resources in times of climate change and global population growth (Brookes et al., 2014) requires efficient reservoir management practices that can help to balance the economical aims against environmental conservation requirements. For reservoir operators, the adjustment of the withdrawal regime is one of the few management options to control water quality in the reservoir and in the downstream river.

For decades, the hypolimnetic withdrawal has been the standard withdrawal strategy in many European and North American reservoirs. The withdrawal of cold water from the deepest part of a reservoir is a relict from the times of intense eutrophication and has been implemented to maximize the export of phosphorus. It further reduces the release of nutrients and metals out of the sediment by avoiding hypolimnetic anoxia (Olszewski, 1961; Nürnberg, 1987; Nürnberg et al., 1987). Another advantage of bottom outlet withdrawal is the flushing of deposited sediments to preserve the storage capacity of hydro-power dams (Espa et al., 2016).

Recently, the negative effects of hypolimnetic withdrawal on the thermal regime of downstream rivers and in-reservoir dynamics have been studied in more detail. Dam operations have led to an alteration of the temperature regime, also called temperature

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pollution. There are a wide range of examples on the severe effect of large dams on the downstream river in the United States (Flaming Gorge Dam, Gathright Dam, see Olden and Naiman, 2010; Shasta Dam, see Bartholow et al., 2001) or in Australia (Burrendong Dam, Keepit Dam, see Preece, 2004; Hume Dam, see Sherman et al., 2007). In most river systems the temperature pollution is specified to cold water pollution of downstream rivers that modifies habitats and the respective biological communities (Olden and Naiman, 2010). For example, year-round cold waters may interfere with temperature triggered events in a species' life-history (e.g. emergence of insects), or in some cases cold adapted fish species have been found to establish, displacing native species (Sherman et al., 2007). In addition, Gaugush (1984) has shown that a withdrawal from the hypolimnion will weaken the stratification of the water body and lead to a warming of the hypolimnion. It is reasonable to expect that this will influence nutrient and phytoplankton dynamics (Barbiero et al., 1997). From an economic point of view, hypolimnetic withdrawal also results in a loss of highly valuable cold water for drinking water supply.

To control the thermal regime both in the downstream river and in the reservoir water body, the concept of a selective reservoir withdrawal, mostly from the epi- or metalimnion has been adapted. This idea is not new: the first dam with selective withdrawal was the Tibi irrigation dam in Spain, which was completed in 1594 (Cassidy, 1989). Brooks and Koh (1969) first described selective withdrawal in detail. Since the 1970's and 1980's many reservoirs in the United States have been operated using a selective withdrawal to maintain a required water temperature in the downstream river. In some cases, numerical models have been applied to assist optimal reservoir management. For example, Fontane et al. (1981) was using a one-dimensional reservoir thermal simulation model and optimization techniques to optimally control the discharge temperature using selective withdrawal. A more recent model study on a tropical reservoir also showed the ability to improve the quality of the discharged water by optimizing reservoir withdrawal (Kunz et al., 2013).

Besides improving the downstream river quality, several studies were carried out to determine the effect of a changing withdrawal regime on the thermal structure of the reservoir water body. Casamitjana et al. (2003) showed a significant effect of selective withdrawal on the thermal structure of the Boadella Reservoir (Spain) with scenario simulations. They emphasized an increase of the hypolimnetic water volume when withdrawing from the epi- or metalimnion and found that the withdrawal height controls the thermocline depth and the thermal stability during summer. Moreno-Ostos et al. (2008) and Kerimoglu and Rinke (2013) suggested a positive effect of an epilimnetic withdrawal to increase the thermal stability and to lower the flux of hypolimnetic nutrients into the upper warm and turbulent water layer (epilimnion). This could be a viable strategy for limiting harmful algal blooms (Brookes and Carey, 2011) in eutrophic reservoirs. Furthermore, Barbiero et al. (1997) investigated the stratification patterns for surface withdrawal in Eau Galle Reservoir, Wisconsin, and they found that a reduced growth of cyanobacteria could be the result of higher thermal stability.

However, recent studies (Çalişkan and Elçi, 2009; Zhang et al., 2013) provided evidence for potential negative impacts of an epilimnetic withdrawal strategy on reservoir water quality. Marcé et al. (2010) used numerical simulations to support the planning of a new dam project in Spain, suggesting optimal reservoir management to avoid anoxia by controlling the oxygen dynamics in the hypolimnion. Multi-objective modelling based on mathematical optimization techniques to improve reservoir operation was used by Kerachian and Karamouz (2006) and Castelletti et al. (2014). The combination of optimization methods and numerical reservoir models is a powerful tool but sometimes difficult to apply for reservoir operators because they are not designed for operational use. As a result, there is still a need for simulation tools in reservoir operations to include management rules in the model code so that they come into play during the runtime of the simulation.

This study investigates the effects of selective withdrawal regimes on reservoir water quality by a one-dimensional reservoir model. In addition, we include operational reservoir management as it will be implemented according to the development of water quality to achieve a realistic prediction. We are not aware of previous approaches that could provide such an inclusion of management aspects enabling a reservoir model to evaluate and optimize envisaged management strategies. Our model simultaneously takes into account the temperature requirements of the downstream river as well as the water quality in the reservoir and automatically determines the best withdrawal height during the runtime of the simulation. The numerical code is freely available for possible users (http://aed.see.uwa.edu.au/research/models/GLM/latest_release.html).

2. Methods

2.1. Study site and monitoring

The oligotrophic and monomictic Grosse Dhuenn Reservoir (51.066°N, 7.190°E, Fig. 1a) has a maximum volume of 81 million m^3 (main reservoir with 76 million m^3) and a maximum depth of 53 m. It is one of the largest drinking water reservoirs in Germany, providing up to 42 million m^3 of raw water per year for 1 million people. Besides raw water supply, the reservoir is used for flood protection and maintaining an ecological minimum discharge in the river Dhuenn. With a mean discharge for raw water supply (36.5 million m^3) and for the downstream river (22.4 million m^3) during 1996 and 2014, the mean residence time of the reservoir at maximum water level is 1.3 years.

On average, the Grosse Dhuenn Reservoir is supplied with 44 million m^3 of water per year from its own catchment and with an additional 12 million m^3 by water transfer from an adjacent catchment. The reservoir has 17 smaller dams above the main reservoir (pre-dams) to reduce nutrient and suspended solid inputs from the numerous tributaries.

Since the operation started in 1987, water for downstream river Dhuenn has been taken from the bottom outlet (Fig. 1b) and has therefore been cold year-round. River temperatures did not significantly increase (0.7 °C, mean over 2006–2012) over the first five river kilometres and never reached the mean upstream temperature within the 20 km river stretch below. As a result, cold adapted fish species like trout have been dominating (Wupperverband, 2008) and have prevented the establishment of diverse fish communities typical for the grayling zone. To fulfill the demands of the EU Water Framework Directive for river Dhuenn, the reconstruction of the natural temperature regime has been proposed as a solution to allow the reestablishment of a natural fish community. This requires the withdrawal of warmer water (12–16 °C instead of 4–6 °C) into the downstream river. Therefore a pivoted pipe was installed at the withdrawal tower with an operating range of ~16 m between 150.9 and 167.1 m above mean sea level (AMSL) to withdraw warmer water from the epi-/metalimnion of the reservoir. Water from that pivoted pipe can also be mixed with water from the bottom outlet. The withdrawal structure for drinking water at Grosse Dhuenn Reservoir offers six outflow depths (see Fig. 1b). While the bottom outlet always withdraws into the downstream river, the six depth-specific outlets can be used for raw water provision or downstream river discharge.

Vertical profile measurements of water temperature and