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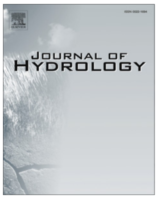

Sensitivity to climate change of the thermal structure and ice cover regime of three hydropower reservoirs

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SUMMARY

This study examines the effect of climate-induced changes on the thermal state and ice cover regime of three reservoirs in Norway: Tesse, Follsjoe and Alta. The model used for the task is *MyLake* which is a one-dimensional deterministic model for lake ice and thermal stratification, which we modified to handle the effects of reservoir outflows. The model was first validated using observational datasets and it reproduced the vertical temperature profiles of the reservoirs, the withdrawal temperatures, and the ice cover dynamics reasonably well. The mean absolute error for vertical temperature predictions ranged from 0.7 °C to 1.13 °C. The validated model was then applied to investigate the impacts of climate change on the ice cover regime, the seasonal temperature profiles in general and the withdrawal water temperatures in particular. The climate change model forcings come from the medium level emission scenario A1B and two global circulation models (GCMs), which are dynamically downscaled using a regional climate model (RCM). Some of the predicted effects of climate change include: a reduction in ice cover duration ranging between 15 to 44 days in 2050s and 27 to 81 days in 2080s, depending on the scenarios and hydro-climatic conditions of the reservoirs. As a consequence of this, the period of stratification is lengthened by 20–31 days in 2050s, and 22–36 days in 2080s. The results also revealed that the southern near coastal reservoir (Follsjoe) is much more sensitive to the climate change signals compared to the inland (Tesse) and arctic (Alta) reservoirs.

1. Introduction

Creating reservoirs on rivers or regulating natural lakes for various uses lead to physical, chemical, and biological alterations in the rivers downstream and the lakes/reservoirs themselves (Collier et al., 1996; Wetzel, 2001a). One of the physical alterations of reservoir operation is its influence on the in-reservoir thermal stratification as well as the temporal flow and thermal regimes downstream (Baxter, 1977; Bevelhimer et al., 1997; Collier et al., 1996; Jager and Smith, 2008). The largest temperature changes in Norwegian rivers, for example, are linked to the outflows from the deep mountain reservoirs. Temperatures in rivers downstream power plants fed by these reservoirs are 1–5 °C lower in mid-summer and 0.5–2 °C higher in winter than before the regulation (Saltveit, 2006).

Thermal and density stratification is a phenomenon that occurs in almost all lakes and reservoir impoundments in cold regions (Imberger, 1982). The thermodynamics and ice cover dynamics of a freshwater lake or reservoir are governed by meteorological forcings that determine the surface heat flux and the inflows and outflows of water (Henderson-Sellers, 1986), which are all in turn dependent on climatic conditions. A reservoir is essentially different from a natural lake due to the complexity associated with dynamic outflows (Fischer et al., 1979). That is, water level changes are more dynamic in the case of reservoirs than natural lakes. Hence, the vertical movement of the water mass and the advective heat transfer as a result can play an important role in the distribution of water temperature (Arai, 1973), and possibly on the ice cover dynamics. Generally, because of vertical mixing due to water withdrawal, the temperature in the summer season in the deep layer of the reservoir becomes higher than that of a natural lake at the same depth (Arai, 1973; Ford and Johnson, 1986). The reverse of this can happen in winter as the colder upper layers are mixed with the warmer bottom layers.

The complexities of the hydrodynamic and thermal processes in a reservoir require the use of numerical models to provide an accurate description of the thermal and density stratification (Arai, 1973; Bonnet et al., 2000; Çalışkan and Elçi, 2009; Parker et al., 1975), as well as ice cover evolution (Imberger, 1982; MacKay et al., 2009). Water quality models of lakes and reservoirs can be formulated in different complexities ranging from a fully mixed

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zero-dimensional model to a complex three-dimensional one in space (Stefan et al., 1989). A large number of mathematical models have been developed over the years to model the water quality including temperature of reservoirs, most of which are one-dimensional models that consider variations in the vertical direction only. Some examples include CE-QUAL-R1(Environmental Laboratory, 1995), DYRESIM (Imerito, 2007), WESTEX (Fontane et al., 1993), WQRRS (USACE, 1986) and SELECT (Schneider et al., 2004). We also have some applications making use of two-dimensional models (with longitudinal and vertical elements), e.g. CE-QUAL-W2 (Cole and Wells, 2008), BETTER (TVA, 1990); and three-dimensional computational fluid dynamics (CFD) models, e.g. EFDC (Çalışkan and Elçi, 2009), FLOW-3D (Bender et al., 2007), and others. Higher order dimensional models (2D and 3D) require, in increasing order of complexity, detailed information on reservoir bathymetry and hydrological regimes including inflows and outflows, and boundary conditions (Martynov et al., 2012). Given the complexity in input data and the higher computational cost involved, one dimensional models are better suited for climate change impact studies of lakes and reservoirs that require multi-year simulations (Peeters et al., 2002). An important aspect of interest in cold regions is the evolution of the thermal regime during winter and its impact on the ice regime in the reservoirs themselves and the river reaches downstream of the reservoirs (Marcotte, 1980). To model these aspects, a reservoir hydrothermal model should also include in its formulation the formation, development and ablation of ice covers, so that the annual thermal cycle as well as the ice cover dynamics can be simulated.

There is growing consensus on human induced climate change (IPCC, 2007), and there has been considerable focus on assessing the impacts on socio-economic and bio-physical systems. The most commonly used tools to predict future climate conditions are global circulation models (GCMs). The GCMs are driven by greenhouse gas forcings corresponding to various possible paths of future development that lead to different emissions scenarios (Nakićenović and Swart, 2000). GCMs of the climate system suggest above global-average rates of future warming in the higher latitudes (Christensen et al., 2007). The GCMs have coarse spatial scales ($\geqslant$100 km), though they have improved significantly over the years, and can fail to capture local variations in climate. For that reason, it has become a standard practice to use nested regional climate models (RCMs) driven by GCM forcing as boundary conditions. The RCMs have a higher spatial resolution (10–50 km) and are generally thought to be able to better capture local climatic variations. Warming of the climate system and other changes predicted by GCMs/RCMs will affect the water- and energy-balance of river systems in general and water reservoirs in particular. There have been a number of studies that have examined the potential impacts of future climate scenarios for lakes and reservoirs (Brown and Duguay, 2011; Dibike et al., 2011; Gebre et al., 2013; Sahoo and Schladow, 2008, 2010; Sahoo et al., 2011). In northern regions, where there is a wider use of reservoirs for energy generation, navigation and as winter roads, the study of changes in the ice cover regime in the future is not only of scientific significance but also of societal interest, as changes in the ice cover regimes can have significant consequences for reservoir management.

Operational aspects of dams for hydropower or other uses are strongly connected to environmental effects downstream and in the reservoir itself. Regulation of reservoirs leads to colder releases during warmer period and warmer releases during the cold periods compared to pre-regulation. These changes in the thermal regime of rivers play a crucial role in stream productivity (Caissie, 2006). During the ice season, higher discharges during winter for power generation can inhibit/delay freeze-up (Ashton, 1979), or can breakup an ice cover that has already formed creating ice jams and risks of flooding (Beltaos, 1995). Ice jams can also severely erode stream beds and banks and have adverse effects on fish (USACE, 2002). Reduced ice cover in rivers or reservoirs makes accessibility using winter roads dangerous or even impossible (Corell and Cleveland, 2010). Ice cover plays an important role in the thermal regime of reservoirs. Shorter ice cover season on reservoirs due to earlier break-up, for example, will advance summer stratification and lead to higher surface temperatures and a delay in autumn turnover. This will have ramifications to the operation of reservoirs as reservoir operators have to satisfy downstream temperature requirements set by regulators. Ice loads on dams are a direct function of the ice thickness (Kjeldgaard and Carstens, 1980), and changes in ice thickness will have an effect on the overall safety of the dam. Another effect of ice formation on reservoirs is the immobilization of a portion of the reservoir water that gets converted to ice. Hence, the fate of ice on reservoirs in a future climate could have considerable influence on reservoir operation.

The objective of this study is to examine the impact of climate change on the thermal characteristics and ice cover regimes of three regulated lakes (reservoirs) in Norway. We modify a one dimensional (1-D), process based lake thermal and ice cover model – *MyLake* (Saloranta and Andersen, 2007) to take into account the effect of reservoir outflows on the hydrodynamic and thermal regime of the reservoirs. The modified model is then used, after proper calibration and validation with observational data, for the climate change impact study. The three study sites: Follsjoe, Tesse and Alta, are selected based on data availability as well as to represent different hydro-climatic zones, namely, near coastal, inland and arctic, respectively. The main interest is to evaluate the changes in reservoir thermal structure, reservoir withdrawal temperatures and ice cover dynamics, i.e., duration and thickness. We make use of signals from two different GCMs that are dynamically downscaled with a RCM, and the changes are also investigated for two future time periods 2041–2070 and 2071–2100 compared to the baseline period that generally falls within 1981–2010. The results presented in this paper are not as such exact predictions due to the uncertainties inherent in the emissions scenarios, the climate models and the thermal and ice-cover model itself. However, they provide useful insight to the changes that might be expected under future climate scenarios.

2. Study area and data

2.1. Study sites

The study was conducted on three reservoirs that are located in different climatic setting in Norway. The reservoirs are Follsjoe, Tesse, and Alta which are all regulated for hydroelectricity generation. Follsjoe is a near coastal reservoir and Tesse represents an inland/highland reservoir. Both of these reservoirs are sub-arctic. The Alta reservoir represents a northern reservoir in the arctic. The location of the three study sites is shown in Fig. 1. Table 1 summarizes the physical characteristics of the three reservoirs that relate to the modeling work.

2.2. Data for model validation

The reservoir thermal balance and ice cover regime are determined by complex conditions of heat exchange with the atmosphere and the ground, as well as the hydraulic and morphometric peculiarities of the reservoir (Donchenko, 1966). Input data required for our modeling setup include: meteorological forcing to compute the energy balances on a daily time step, hydrological forcing data such as daily inflow and outflow discharges and inflow temperatures, and reservoir geometry. In addition, the model also requires observed vertical temperature profiles