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Internal waves and mixing in a stratified reservoir: Insights from three-dimensional modeling

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ABSTRACT

In this study, the three-dimensional (3D) Estuary and Lake COmputer Model (ELCOM) was used to model a mid-sized reservoir (Rappbode Reservoir, Germany) during the period of summer stratification to identify and illustrate the source of internal waves as well as to characterize water exchange between the hypolimnion and epilimnion under different wind speed conditions with a focal point on one episode of high and sustained winds. The modeling revealed that wind stress was the key driver of the observed internal waves while the role of water withdrawal was negligible. Our results also showed that within the range of wind speeds considered, wind-induced upwelling greatly enhanced mixing between the hypolimnion and epilimnion with a rate that varies approximately as the square of the wind speed. This numerical correlation affirmed that processes connected to wind stress, i.e. internal waves or direct upwelling, were responsible for the mixing of the hypolimnetic water into the surface water rather than direct input of turbulent kinetic energy.

Introduction

Reservoirs are aquatic systems and in this respect they are very similar to natural lakes with the exception that they are man-made impoundments where the outflow is usually regulated and is in most cases independent of the inflow regime. Similar to natural lakes in the temperate climate zone, deep reservoirs undergo seasonal changes in stratification and show a dimictic annual stratification pattern. Reservoirs, particularly those used for drinking water supply, have a low content of dissolved substances and density stratification is mostly controlled by change in temperature with depth (e.g. Boehrer and Schultze, 2008). The latter is called the thermal stratification and, in summer, is responsible for the formation of three distinct layers differing in temperature and known as the epilimnion – a layer of warm and relatively well mixed water at the surface; the metalimnion or thermocline – a layer of large temperature changes; and the hypolimnion – a layer of cold and relatively calm water at the bottom. The density gradient in the thermocline separates the epilimnion from the hypolimnion and provides a physical barrier between these two layers which limits mixing between them. As a consequence, the bottom water tends to become depleted of dissolved oxygen but rich in nutrients, while the surface water tends to be rich in dissolved oxygen but can become depleted of nutrients due the uptake of nutrients by phytoplankton that largely sink down to the bottom removing nutrients from the epilimnion. In most cases, the upward flux of nutrients from the hypolimnion, where phytoplankton are mineralized and nutrients are released, to the epilimnion is reduced by the density gradient and nutrients that were assimilated by phytoplankton and removed from the epilimnion during the stratification period can not be replaced. The lack of mixing between the epilimnion and hypolimnion in summer has a number of important ecological consequences including but not limited to reduced primary production in the epilimnion due to nutrient limitation. In larger lakes, wind-induced upwelling episodes may induce major upward fluxes of nutrients from deep waters into the surface layer and increase productivity of plankton communities afterwards (Corman et al., 2010; Bocaniov et al., 2012). Mixing in lakes may also be driven by turbulent kinetic energy introduced by wind stress at the surface or by the interaction of internal waves with the lake walls.

Internal waves are a universal feature of almost any stratified aquatic system and they can lead to mixing. In small to

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medium-sized water bodies, they are the most important driving force for horizontal and vertical transport of energy and matter below the surface mixed layer during the stratification period (Hodges et al., 2000) and they have been shown to have a number of ecological effects (Pannard et al., 2011). Vertical transport can be enhanced through shear instabilities (Boehrer et al., 2000; Boehrer, 2000) and side wall friction, and nutrients can thereby be transported from the hypolimnion into the surface mixed layer (MacIntyre and Jellison, 2001; Gaxiola-Castro et al., 2002) and, therefore, affect phytoplankton composition during periods of prolonged stratification (Evans et al., 2008; Pannard et al., 2008). They can affect the vertical distribution of both phytoplankton (Kushnir et al., 1997; Cuypers et al., 2011) and zooplankton (Rinke et al., 2007). Finally, internal waves can influence the exposure of phytoplankton to light and greatly enhance photosynthetic rates by moving phytoplankton through a vertical light gradient (Evans et al., 2008; Pannard et al., 2011).

Internal waves can be generated by wind (e.g. Stevens et al., 1996) and/or by inflows/outflows, for example, by large periodic water withdrawals from reservoirs. Nowadays, in many countries, the bulk of the power supply comes from the combustion of fossil fuels or nuclear power, but it has to be supplemented from other sources including hydropower during hours of high demand. Periodic withdrawals of large water masses are required, for example, to meet the peak demand in morning hours. Their recurrence with a periodicity of approximately 24 h may affect reservoir hydrodynamics and may be responsible for water motions including internal waves and water currents (Johnson and Merritt, 1979; Owens, 1998). During withdrawal there is a current toward the dam and when withdrawal is stopped the disturbance of isopycnals is relaxed. This can cause oscillations in the thermocline. If the period of these oscillations is close to 24 h they can resonate with the daily withdrawal cycle.

The proper understanding of the hydrodynamic processes of any reservoir requires the characterization of possible effects of water withdrawal on its hydrodynamics including water currents and internal waves. However, it can be difficult to separate these effects, if wind forcing coincides with the timing of water withdrawal. Field observations are obviously necessary to understand reservoir hydrodynamics but they have limitations as it is difficult to separate the overlapping concurrent effects of wind forcing and water withdrawal. Numerical modeling with adequate spatial representation of hydrodynamic processes can be used to separate both effects and reveal the influences of the recurring diel cycles of water withdrawal on reservoir hydrodynamics.

Despite considerable efforts to study the diverse ecological implications of internal waves with some significant recent advances being made, the relationship between wave-induced hypolimnetic–epilimnetic exchange and atmospheric forcing events, such as episodes of high and sustained winds, has received little attention and, therefore, is not yet well understood. This is especially relevant when our climate is changing and there is a growing concern over its impacts on aquatic ecosystems (Meyer et al., 1999; Schindler, 2001). Climate change will not only affect air temperatures, it will also change the intensity and frequency of atmospheric forcing events (Knippertz et al., 2000; Leckebusch and Ulbrich, 2004; Donat et al., 2011). A comprehensive assessment of climate change effects in lentic ecosystems will therefore require the characterization of how wind events of different intensities may affect the internal wave-induced exchange between the hypolimnion and the epilimnion. The use of hydrodynamic models that are capable of reproducing internal wave dynamics correctly can be extremely helpful and provide a necessary tool for quantitative estimation of the exchange rate under modified wind speed scenarios while retaining all other possible influences. As the transport processes are fundamentally three-dimensional (3D), the usefulness of 1D and 2D models is limited. They may also be insufficient to fully describe wind-driven mixing (Martin, 1985). Modeling in three-dimensions may provide better and more realistic results.

Table 1
Main morphometric characteristics of the Rappbode Reservoir. Values in brackets indicate minimum and maximum values.

Parameter	Value
Max. surface area (km^2)	3.95
Max. volume ($\times 10^6$ m^3)	113.1
Max. depth (m)	88.93
Mean depth (m)	28.6
Water elevation at max. depth (m)	423.6
Direction of major axis	North-east
Mean water residence time[a] (days)	380
Mean annual water level fluctuation[b] (m)	14.4 (8.2, 22.4)
Mean daily water level fluctuation[b] (cm)	8
Max. observed daily water level fluctuation[b] (cm)	110

[a] For the past 5 years (2008–2012).
[b] For the past 10 years (2003–2012).

In this study, we apply a 3D hydrodynamic model to a mid-sized European reservoir (Rappbode Reservoir, Germany) during the period of summer stratification in June 2011 in a study with two goals: (1) to identify the generation mechanisms of basin-scale internal waves and illustrate the effect of water withdrawal on reservoir hydrodynamics; and (2) to characterize the water exchange rate between the hypolimnion and the epilimnion under different wind speed scenarios with a focal point on one episode of high and sustained winds.

Methods

Study site

The Rappbode Reservoir is the largest drinking water reservoir in Germany providing high quality water for more than one million people (Rinke et al., 2013). It lies at an elevation of 423.6 m in the Harz Mountains in central Germany (Fig. 1a). The reservoir was constructed in 1959 and has the tallest dam in Germany (106 m). The Rappbode Reservoir is a major part of a network of several other reservoirs that form the flood protection system in the eastern Harz Mountains, and is linked to the downstream and upstream reservoirs via its outflow and inflows. It receives water from three upstream reservoirs (Königshütte reservoir, Hassel and Rappbode pre-dams) and discharges into the Wendefurth reservoir located downstream (Fig. 1b). The reservoir basin is located in a valley oriented south-west (upstream) to north-east (downstream) and is likely to be sensitive to southwesterly winds that can be considered as potentially upwelling favorable winds. The Rappbode Reservoir has a surface area of about 4 square kilometers (Table 1) and a complex shape reminiscent of the shape of a flying dragon. It is 8 km long and is deep with a maximum depth of 89 m and mean depth of 28.9 m (Table 1). It has a small island in the middle of the reservoir and two significant and relatively deep side arms facing north and south that are located in the lower reach of the reservoir, between the island and the dam wall (Figs. 1b and 2). The Rappbode Reservoir is a typical dimictic reservoir that experiences two periods of full mixing in autumn and spring and stratifies in summer and usually freezes in winter. The water level fluctuates significantly during the year (Table 1) with the maximum and minimum levels usually observed in the early spring and late autumn, respectively. The daily amount of water withdrawal is quite significant (Table 2) and results, on average, in a water level drop of about 8 cm per day (Table 1). The water residence time of the reservoir is slightly more than one year (Table 1) so that internal processes in the reservoir should be important.