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Consequences of thermal pollution from a nuclear plant on lake temperature and mixing regime

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SUMMARY

We investigated the combined effects of thermal pollution from a nuclear power plant (NPP) and regional climate warming on the thermal regime of a lake. For this purpose, we used the lake model FLake and analyzed 50 years of temperature data from Lake Stechlin, Germany, which served as the cooling water reservoir for the Rheinsberg NPP from 1966 until 1990. Both modeling and statistical data analysis revealed a strong influence of the NPP cooling water discharge on the lake water temperatures and the vertical stability of the water column. A remarkable effect of thermal pollution consisted of strong vertical mixing in winter produced by the discharge of warm water into the lake when ambient water temperatures were below 4 °C. This effect caused a significant increase in the deep hypolimnion temperatures and a corresponding decrease of the vertical stability in the summer. In turn, climate warming had the opposite effect on the summer stability by increasing lake surface temperatures. Both the thermal pollution and climate change increased the duration of the summer stratification period. Our results suggest that industrial thermal pollution in temperate lakes during winter is stored in the deep water column until the next winter, whereas heat added in the summer dissipates relatively rapidly into the atmosphere. Accordingly, the winter thermal pollution could have a long-lasting effect on the lake ecology by affecting benthic biogeochemical processes.

1. Introduction

Thermal pollution from industrial plants has been recognized as a problem for aquatic environments since the end of World War II (Davidson and Bradshaw, 1967). The cooling water discharge from nuclear power plants (NPPs) is among the greatest local sources of thermal pollution due to the high levels of energy produced per plant. In addition, nuclear power plants require 30–100% more cooling water than other types of plant with a comparable power output (Davidson and Bradshaw, 1967; Cairns, 1971; EPRI, 2008). In earlier periods, thermal pollution was not a primary concern when compared to other ecological threats from the production of nuclear power. Despite the recent tendency to reduce the energy production of nuclear plants in many developed countries, plans exist to build new nuclear power plants in rapidly developing countries due to their increased energy demands (Dittmar, 2012). The energy demand coincides with the demand for natural water resources, thus making thermal pollution an important issue. Another important environmental aspect is the anthropogenic climate change, which imposes additional thermal stress on water bodies affected by the cooling water discharge. The regional climate warming can potentially reinforce negative environmental effects from thermal pollution from point sources such as NPPs. The persistent warming signal due to climate change is now reported in many lakes (see, e.g., Adrian et al., 2009) with ecological effects considered to be similar to those resulting from point-source thermal pollution (Cole, 1969; Parker et al., 1970). In the present study, we consider the effects of thermal pollution and climate warming on a small natural lake and analyze the similarities and differences in the lake's response to both warming stressors. We use observational data from Lake Stechlin in Germany which received cooling water from May 1966 to June 1990 from an NPP located at the lake shore. Our analysis is based on a long-term lake temperature time series combined with data on heat discharge from the NPP and with meteorological observations. In addition, we apply one-dimensional modeling of temperature and mixing to reconstruct the lake temperature and mixing regime without disturbance by the thermal pollution from the NPP. Using this method, we separate the effects of the warm water discharge from the lake's response to the climate-scale atmospheric warming.

2. Study site and methods

2.1. Site description

Lake Stechlin is located in the eastern part of Germany's South-Baltic lake region (53°10′ N, 13°02′ E, 59.8 m a.s.l.) and is

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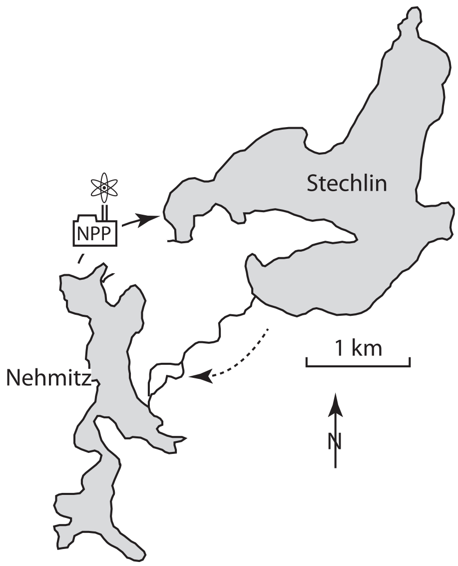

Fig. 1. Schematic map of Lake Stechlin and the NPP cooling circuit.

approximately 75 km north of Berlin. The Lake Stechlin area is one of Germany's oldest nature reserves (formed in 1938) and protects approximately 9000 ha. Lake Stechlin has a high recreational value as one of the few oligotrophic clear-water (mean 1970–2010 water transparency is 7.8 m) lakes in Germany's South-Baltic lake region. Both the lake and the surrounding landscape were formed during the continental glaciations some 12,000 years ago. The lake is divided into three basins by a peninsula stretching from west to east (Fig. 1). The mean depth of the lake is 23.2 m, the maximum depth is 69.5 m, and the volume is 98.7×10^6 m^3 (Koschel and Adams, 2003). Lake Stechlin is located at the transition between temperate maritime and temperate continental climate zones with moderately warm summers and relatively mild winters (Fraedrich et al., 2001). The mean monthly temperatures vary between −0.8 °C in January and 17.3 °C in July. Groundwater and precipitation are the major sources of water (Richter and Koschel, 1985). The theoretical water retention time is >40 years (Holzbecher et al., 1999).

Originally, Lake Stechlin was a seepage lake with no connection to any running waters. In the early 1960s, Lake Stechlin, together with its neighbor, the much smaller Lake Nehmitz, became the principal cooling water resource for the nearby nuclear power plant Rheinsberg. From May 1966 to June 1990, on average, 300,000 m^3 day^{-1} of cooling water was extracted from Lake Nehmitz, heated by approximately 10 °C (min/max 6–20 °C) by the NPP and subsequently released into Lake Stechlin. Both lakes were connected by a channel, thus completing the external cooling water circuit (Fig. 1). During periods without stratification (typically December through April), the water retention time of Lake Stechlin dropped to only 335 days as a result of pumping. During thermal stratification, only the mixed layer was integrated in the cooling water circuit, thus resulting in a retention time of 124 days (Koschel et al., 1985).

Remarkable changes in the thermal regime of Lake Stechlin due to thermal pollution were previously reported by Koschel et al. (1985) and Richter and Koschel (1985). The thermal pollution was almost completely confined to Lake Stechlin, as there appeared to be no detectable warming of Lake Nehmitz. As a result, an average increase in water temperatures by 1–2 °C was registered.

2.2. Data sources

Meteorological data and data on the heat discharge from NPPs were provided by the German Meteorological Service (DWD) from the lakeshore weather station. Vertical profiles of water temperatures were taken at the deepest point of the lake by the DWD from 1958 to 1996 and by the Leibniz-Institute for Freshwater Ecology and Inland Fisheries (IGB) from 1970 to 2009. The DWD series consisted of monthly measurements in 2 m intervals from 0 to 20 m and then in 10 m intervals to the deepest point. Profiles in the IGB series were generally taken monthly, but were taken less often in the 1980s and were then taken biweekly during the vegetation period after 1991. In the epilimnion, profiles were taken at 2.5 m intervals (1.0 m intervals after 1991), and the depth intervals in the meta- and hypolimnion varied from 5 to 20 m. When interpolated linearly on equidistant time intervals, the two datasets revealed discrepancies with an average value of 0.2 °C, which is comparable to the suggested accuracy of manual sampling (0.1 °C standard instrumental error). Therefore, the two series were combined for further analysis without any corrections.

2.3. Statistics

To separate the effects of climate warming and of water discharge from the nuclear power plant, the different periods within the time series were examined separately. Specifically, we examined the period before (1958–1965), during (1966–1990) and after the NPP operation (1991–2009). We also compared the periods when the NPP was not in operation (pooled data from 1958 to 1965 and 1991 to 2009) with the periods when the NPP was in operation (1966–1990). Long-term monotonic trends in temperature and stratification data were analyzed by means of the non-parametric Mann–Kendall trend test with Sen's estimator of slope. Seasonal effects on trend estimations were excluded by using annual means and treating seasons separately. Step trends (sudden changes of the lake characteristics) arising from the effects of the start/stop of the NPP operation were assessed using the non-parametric Wilcoxon rank sum test with the Hodges–Lehmann estimator for the size of the step. When the step trends due to the NPP were superimposed on monotonic trends due to climate warming (Fig. 2), we calculated the difference between the observed values during the NPP operation and the corresponding linearly interpolated values from the monotonic trend during this period. Then we tested whether these differences (vertical lines in Fig. 2) were significantly different from zero using the Wilcoxon signed rank test. The statistics were analyzed using R (Version 2.13.0, R Development Core Team, 2009, Vienna) with the Kendall and (McLeod, 2009) and Zyp (Bronaugh and Werner, 2009) packages.

2.4. Treatment of seasonal stratification

The dimictic Lake Stechlin is thermally stratified in winter and summer and is mixed down to the bottom by convection during

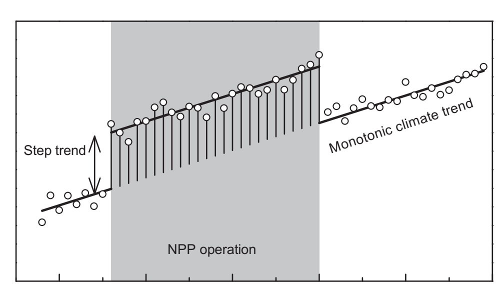

Fig. 2. Schematic showing methods of trend analysis. We tested for the presence of step trends during NPP operation (from 1966 to 1990) caused by the NPP superimposed on monotonic trends caused by climate warming (calculated with data from 1958 to 1965 and 1991 to 2009). Circles represent observed data.