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Multiple long-term trends and trend reversals dominate environmental conditions in a man-made freshwater reservoir

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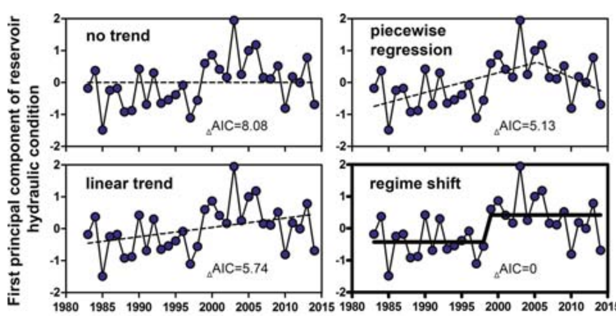
HIGHLIGHTS

- Several competeing models were used to identify trends in reservoir time series.
- Numerous contrasting trends and trend reversals were found.
- Trend reversals in hydrochemistry resulted from dramatic socioeconomic changes
- Decrease in the water level resulted in a regime shift in reservoir hydrodynamics
- Our analyses highlight the utility of the model selection to describe temporal trends.

GRAPHICAL ABSTRACT



The model selection approach was used for fitting the time series. The most parsimonious model for the hydraulic conditions of the reservoir was the regime shift model with the lowest AIC value.

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ABSTRACT

Man-made reservoirs are common across the world and provide a wide range of ecological services. Environmental conditions in riverine reservoirs are affected by the changing climate, catchment-wide processes and manipulations with the water level, and water abstraction from the reservoir. Long-term trends of environmental conditions in reservoirs thus reflect a wider range of drivers in comparison to lakes, which makes the understanding of reservoir dynamics more challenging. We analysed a 32-year time series of 36 environmental variables characterising weather, land use in the catchment, reservoir hydrochemistry, hydrology and light availability in the small, canyon-shaped Římov Reservoir in the Czech Republic to detect underlying trends, trend reversals and regime shifts. To do so, we fitted linear and piecewise linear regression and a regime shift model to the time series of mean annual values of each variable and to principal components produced by Principal Component Analysis. Models were weighted and ranked using Akaike information criterion and the model selection approach. Most environmental variables exhibited temporal changes that included time-varying trends and trend reversals. For instance, dissolved organic carbon showed a linear increasing trend while nitrate concentration or conductivity exemplified trend reversal. All trend reversals and cessations of temporal trends in reservoir hydrochemistry (except total phosphorus concentrations) occurred in the late 1980s and during 1990s as a consequence of dramatic socioeconomic changes. After a series of heavy rains in the late 1990s, an administrative decision to increase the flood-retention volume of the reservoir resulted in a significant regime shift in reservoir hydraulic conditions in 1999. Our analyses also highlight the utility of the model selection framework, based on

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relatively simple extensions of linear regression, to describe temporal trends in reservoir characteristics. This approach can provide a solid basis for a better understanding of processes in freshwater reservoirs.

1. Introduction

Long-term records of environmental and ecological data are indispensable for the understanding of factors driving the dynamics of ecosystems and for predictions of their future state (Franklin, 1988). Long time series are a prerequisite for the detection and quantification of slow ecological processes, time-lagged responses, rare events, and the cumulative effects of multiple stressors (Dodds et al., 2012), and therefore play an important role in formulating and testing ecological theory (Lindenmayer and Likens, 2009).

Long-term changes in freshwater habitats and ecosystems can involve gradual changes such as eutrophication (O'Neil et al., 2012) or acidification (Adrian et al., 2009) and the equivalent reverse phenomena. Some of these changes can be conveniently characterised by linear regression, which has been commonly used to identify temporal trends in freshwater ecology and hydrology. Nevertheless, linear regression cannot adequately capture more complex phenomena that often occur in longer time series (Tome and Miranda, 2004; Mueller et al., 2009; Magee et al., 2016). These phenomena may include cessation of trends, trend reversals and ecological or hydrological regime shifts, defined as rapid reorganisations of the system from one relatively stable state to another (Andersen et al., 2009; Nicholls, 2011). Shallow lakes are a classic example of a freshwater system that may undergo dramatic regime shifts between a clear-water, macrophyte-dominated state and a turbid state with high phytoplankton production (Scheffer et al., 1993). These shifts may arise from either rapid, persistent changes in external forcing or relatively small variations in environmental conditions reinforced by internal feedback mechanisms within alternate states such as vertical stratification, internal nutrient cycling, and shading (Scheffer et al., 2001; deYoung et al., 2008; Andersen et al., 2009).

Despite a large number of freshwater reservoirs recently being built on almost all large rivers (e.g. Nilsson et al., 2005), studies evaluating long-term (>20-year period) data series, based on reservoir monitoring programs, are scarce (e.g. Marce et al., 2010). Freshwater reservoirs are artificial water bodies of special interest, as they provide a wide range of ecosystem services including the supply of drinking water, irrigation, transportation, industrial and cooling water supplies, power generation, flood control and recreation (Wetzel, 2001). Reservoirs represent a transition between lotic and lentic systems characterised by complex hydrodynamic conditions and physical and chemical gradients that affect aquatic biota (Šimek et al., 2008; Jones et al., 2011). Moreover, reservoirs are frequently found in densely populated areas, and the environmental drivers affecting their ecosystems thus include both natural processes and anthropogenic activities, which can vary substantially over relatively short timescales due to, e.g. profound socio-economic changes in the catchment (Kopáček et al., 2017).

Reservoirs, in particular the common canyon-shaped ones constructed by damming a river valley, differ from natural lakes in several key aspects: elongated morphology, shorter water residence time, pronounced water level fluctuation and irregular water withdrawal, often from various strata (Thornton et al., 1990; Wetzel, 2001; Hayes et al., 2017). Responses of reservoirs to environmental change can thus differ from those of lakes (Hayes et al., 2017). For example, manipulation of the water level and changes in water abstraction leading to rapid alterations of reservoir hydrology can affect rates at which nutrients enter the reservoir ecosystem and amplify or dampen naturally occurring processes such as water brownification.

The dynamic nature of reservoir environments and their relatively young age (compared to natural lakes) suggests that at least some temporal trends in environmental conditions in reservoirs are nonlinear and may include cessation of trends, trend reversals and regime shifts. In particular, the regime shift concept has been widely used in studying various freshwater systems (Capon et al., 2015), but little is known about its relevance for man-made reservoirs. Detection of trend cessations, reversals and regime shifts requires statistical techniques beyond simple linear regression, such as piecewise linear regression (Toms and Lesperance, 2003; Tome and Miranda, 2004) and regime shift analysis (Rodionov, 2004). These techniques can detect breakpoints at which the time series changes behaviour, but have been surprisingly little used in the analyses of lake and reservoir environmental characteristics until very recently. For example, Flaim et al. (2016) used piecewise regression to determine the effects of re-oligotrofication and climate change on lake thermal structure.

Long-term intensive monitoring of the Římov Reservoir in the Czech Republic since its construction in 1979 covers the hydrology, chemical and biological development of the reservoir and its tributaries, land use changes and anthropogenic activities in its catchment, and climate (Znachor et al., 2016). It provides an ideal case study to detect trends and explain relationships between environmental conditions and observed changes in the reservoir ecosystem. In this paper, the Římov Reservoir data were used to identify long-term trends in reservoir hydrochemistry and limnology. Instead of the traditional approach of fitting the data to a single model with null hypothesis testing, we adopted the model selection approach in which several models were confronted with data. In addition to constant and linear models, we compared the suitability of piecewise linear regression and regime shift analysis for detecting breakpoints in time series of environmental variables characterising weather conditions, land use in the catchment, reservoir hydrochemistry, hydraulic conditions, and light availability. Competing models were compared by evaluating their support for the given data using the Akaike information criterion corrected for sample size (AICc). Models were ranked and weighted, thereby providing a quantitative measure of relative support for each competing hypothesis (Burnham and Anderson, 2002). Unlike various null hypothesis tests, AICc relies on maximum likelihood as the measure of fit and allows for comparison of both nested and non-nested models. The main goal of our study was to demonstrate the applicability of the model selection approach to identify patterns in long-term environmental conditions that can drive other changes in the reservoir.

2. Material and methods

2.1. Study site and its long-term monitoring

The Římov Reservoir (Fig. 1 and Table 1) is a dimictic, deep-valley and 13.5 km long reservoir that became fully operational in 1979. It was built in 1974–1979 to store drinking water by damming of the River Malše, the main reservoir tributary that accounts for about 95% of the water inflow (Hejzlar and Straškraba, 1989). The reservoir is filled by headwaters from a medium-sized hilly catchment (489 km^2; elevation range from 428 to 1112 m a.s.l.) covered by forests (53%; mostly Norway spruce), arable land (9%), pastures and meadows (34%), urban areas (2%) and water surfaces (1%). Land cover characteristics of the catchment were determined from the land cover database of the Czech Republic (ZABAGED, www.cuzk.cz) and the LANDSAT 7 ETM+ satellite images (on the territory of Austria) in 2009. The catchment has approx. 20,000 inhabitants. Municipal wastewaters have been treated since the beginning of the reservoir construction and released into the River Malše and its tributaries. The largest town (Kaplice; approx. 7000 inhabitants) is situated upstream on the river and has