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A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network

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A B S T R A C T

The modelling community has identified challenges for the integration and assessment of lake models due to the diversity of modelling approaches and lakes. In this study, we develop and assess a one-dimensional lake model and apply it to 32 lakes from a global observatory network. The data set included lakes over broad ranges in latitude, climatic zones, size, residence time, mixing regime and trophic level. Model performance was evaluated using several error assessment metrics, and a sensitivity analysis was conducted for nine parameters that governed the surface heat exchange and mixing efficiency. There was low correlation between input data uncertainty and model performance and predictions of temperature were less sensitive to model parameters than prediction of thermocline depth and Schmidt stability. The study provides guidance to where the general model approach and associated assumptions work, and cases where adjustments to model parameterisations and/or structure are required.

1. Introduction

Vörösmarty et al. (2000) urged the international "water sciences community" to work together in the collation and dissemination of hydrological data and modelling techniques to improve our understanding of freshwater ecosystems and "secure a more complete picture of future water vulnerabilities". Lakes, in particular, are highly valued ecosystems as they provide important water and food resources, and numerous other ecosystem services (Wilson and Carpenter, 1999). Human activities such as fresh water diversion and increased nutrient loading, in addition to indirect pressures from climate change, have led to an increased vulnerability of lakes on a global scale (Folke et al., 2004). These challenges have given rise to international networks of scientists such as the Global Lake Ecological Observatory Network (GLEON: gleon.org). Collaborative networks can take advantage of shared data, techniques, and expertise to enable scientists to address the ecological challenges facing lakes globally (Eigenbrode et al., 2007; Adams, 2012; Goring et al., 2014). GLEON was initiated in 2005 as a grassroots science community with a vision to observe, understand and predict freshwater systems at a global scale (Weathers et al., 2013).

Collaboration between scientists and synthesis of data collected through international networks has led to advances in our understanding of how lake ecosystems respond to external changes and contribute to effective lake management on a local (Gal et al. 2009), regional (Read et al., 2014; Trolle et al., 2015) and global scale (O'Reilly et al., 2015). Analyses based on data from a broad spectrum of lakes across the globe have provided insight into metabolism and carbon cycling in lakes (Hanson et al., 2011; Solomon et al., 2013), the role of wind and heat exchange in lake physics (Read et al., 2012), the impact of climate change (Adrian et al., 2009), response and recovery of lakes to extreme events (Jennings et al., 2012; Klug et al., 2012), incorporation of high frequency data for model validation (Hamilton et al., 2015) and assisted in development of models (Staehr et al., 2010; Read et al., 2011; Kara et al., 2012; Hipsey et al., 2017). Further interrogation of the emerging multi-lake datasets offers the potential to advance our understanding of how lakes respond to pressures such as climate or land use change from the individual to global scales.

The collaborative network also creates opportunities for developing and testing modelling tools. Aquatic ecosystem models are recognized as essential instruments to improve understanding of processes, analyse relationships, test hypotheses and predict the state of a system (Trolle et al., 2012). These models have evolved since the first attempts in the early 1920s, with a recent review of aquatic ecosystem models revealing the diversity of existing models from simple 0-D to complex 3-D coupled hydrodynamic-biogeochemical models (Janssen et al., 2015). This diversity creates challenges for integration and synthesis of model approaches (Mooij et al., 2010). The Aquatic Ecosystem Modelling Network (AEMON: https://sites.google.com/site/aquaticmodelling/home) originated to foster collaboration and improve model development, predictability, transparency and reliability. One of the major challenges facing modellers is how to develop generic models that can capture the diversity of ecosystems while allowing prediction with confidence of the processes of each system. In order to undertake analytical synthesis across multiple sites, there is a need to assess the transferability of the underlying model and standardise its structure, parameterisation, development and examination. While the need to develop a set of standards for model assessment and reporting is widely recognized (Bennett et al., 2013; Grimm et al., 2014), the ability to test these standards across multiple systems and highlight both strengths and limitations of a particular model remains a challenge.

For lakes and reservoirs in particular, one-dimensional (1-D) models that resolve vertical profiles of temperature and density have found widespread use due to their computational efficiency and minimal calibration requirements. The reduced complexity of 1-D models is advantageous whenever greater computational efficiency is needed, e.g., in ensemble modelling (Trolle et al., 2014), model inter-comparison projects such as LakeMIP (http://www.unige.ch/climate/lakemip) (Stepanenko et al., 2010; Thiery et al., 2014), probabilistic studies (Schlabing et al. 2014), long-term scenario analysis (Gilboa et al., 2014) or when linking lake models to global climate models (Balsamo et al., 2012) or catchment models (Hipsey et al.,