Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

POJEDNOSTAVLJENI MODEL ZA PROGNOZU VERTIKALNOG TEMPERATURNOG PROFILA U MALIM, MONOMIKTIČNIM JEZERIMA

Simplified model for prediction of the vertical temperature profile in small monomictic lakes

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Sažetak:

Temperatura vode, zajedno s njezinim vertikalnim profilom, bitan je čimbenik koji izravno ili indirektno utječe na fizikalne, kemijske i biološke procese te na transport plinova i nutrijenata u jezerima. Ovaj utjecaj dalje se odražava na biološku aktivnost i raznolikost unutar jezera i njihovoj okolini. Sveprisutne klimatske promjene značajno utječu na vodene sustave diljem svijeta. Jezera, kao zatvoreni ekosustavi, izuzetno su osjetljiva na te promjene, što rezultira nizom posljedica s kompleksnim povratnim vezama.

Termodinamičko ponašanje jezera pod utjecajem je različitih procesa, a ključni pokretač su meteorološki uvjeti koji determiniraju toplinski tok na površini jezera. S ciljem omogućavanja pouzdane prognoze vertikalnog temperaturnog profila uz minimalan broj ulaznih meteoroloških varijabli, razvijen je model za mala monomiktična jezera, nazvan SIMO, temeljen na rješavanju jednodimenzionalne jednadžbe energetske bilance. Model je primijenjen na dva jezera unutar sustava Plitvičkih jezera, Prošće i Kozjak. Rezultati kratkoročnih simulacija (duljine do 30 dana) pokazuju da model ima zadovoljavajuće performanse u prognozi vertikalnog temperaturnog profila na satnoj skali. Dugoročnom (jednogodišnjom) simulacijom demonstrirana je sposobnost modela da predvidi proljetni početak stratifikacije jezera i njezino jačanje tijekom ljeta te nastupanje jesenskog konvektivnog miješanja.

Nakon kalibracije i verifikacije, model je primijenjen na prognozu buduće temperature vode u jezeru Kozjak za tri različita scenarija buduće klime, RCP2.6, RCP4.5 i RCP8.5. Rezultati ukazuju na značajan porast temperature vode u pesimističnijim scenarijima, s umjerenim jačanjem stratifikacije procijenjenim na temelju Schmidtovog indeksa stabilnosti. Unatoč većem porastu temperature u epilimniju, difuzija i konvektivno miješanje doprinose zagrijavanju i dubljih slojeva, čime je ograničeno jačanje stratifikacije. No čak i u najoptimističnijem scenariju, primjećuje se signifikantno produljenje trajanja stratifikacije.

Time je po prvi puta analiziran utjecaj klimatskih promjena na temperaturu i stratifikaciju jezera Kozjak, što je prva takva analiza za neko jezero u Hrvatskoj općenito. Razumijevanje njegovog odgovora na klimatske promjene ključno je za učinkovito upravljanje i očuvanje jezera i s njime povezanih ekosustava. Predviđeno povećanje temperature vode i produljeno razdoblje stratifikacije nose ozbiljne ekološke implikacije. Dobiveni rezultati predstavljaju temelj za buduća istraživanja u različitim područjima, kao što su biologija jezera, geokemija, sedimentologija itd.

Extended abstract:
1. Introduction

Water temperature significantly influences various lake properties, including gas and mineral solubility, chemical reactions, and biological activity. Furthermore, the vertical temperature profile plays a crucial role in gas and nutrient transport within a lake. Stable stratification can lead to methane and nutrient accumulation, along with reduction of oxygen concentrations, potentially causing hypoxic conditions. While meteorological forcing is the main driver of lake thermodynamic behavior, the lake-atmosphere interaction is two-way, as lakes also significantly influence local and regional weather and climate.

Lakes are often called "sentinels of climate change" due to their ability to reflect both natural and anthropogenic activities in their catchment area, providing valuable insights into the patterns and mechanisms of terrestrial and aquatic systems' response to climate change. The complex and diverse responses of lakes to climate change, within the lakes and their surroundings, emphasize the need for detailed studies of individual lakes in order to capture spatial and temporal heterogeneity of these responses.

This thesis focuses on the Plitvice Lakes system, more precisely on lakes Prošće and Kozjak, the first and the twelfth lake in the system. The Plitvice Lakes system has formed through the continuous process of tufa deposition. This biodynamic process depends on the balance of a number of physical, chemical and biological factors where the water temperature has a significant role. Despite conservation efforts, Plitvice Lakes face vulnerability to climate and anthropological changes.

Considering the role of the water temperature in the entire ecosystem and its influence on weather and climate, in the last couple of decades there has been a growing interest in modelling the lake thermal regimes and understanding their sensitivity to climate change. There is a number of different numerical models for water temperature prediction, ranging from complex coupled 3-D models to simple 1-D models. The latter are widely used due to their simplicity and computational efficiency. These models fall into three categories: (1) mixed layer models based on the energy-budget approach, (2) differential models based on solving the 1-D heat transfer equation (thermal diffusivity models), and (3) second-order turbulence closure models. Lake models also differ in the processes they incorporate, such as wind sheltering, sediment heat flux, light attenuation, convective mixing, etc. The choice of processes depends on the model's purpose, which can range from improving weather prediction and climate models to evaluating the effects of climate change or conducting specific limnological studies focusing on gas emissions, oxygen and nutrient levels, heat and mass exchange with the atmosphere, evaporation and lake level fluctuations, etc.

The goal of this thesis is to develop a simplified model for predicting the vertical temperature profile in small, warm, monomictic lakes forced with a reduced number of meteorological input variables. Considering the sensitivity of the lake ecosystems to climate change, the second goal of this thesis is to apply the developed model to analyze the temperature and stratification dynamics of Lake Kozjak under various future climate scenarios.

2. Data

The Plitvice Lakes represent a mountainous lake system in Croatia, comprising 16 named and several unnamed lakes interconnected by cascades and waterfalls, covering a total water surface of 1.949 km^2. Designated as Croatia's first national park in 1949 and an UNESCO World Heritage site since 1979, the Plitvice Lakes are renowned for their natural beauty, biodiversity, and hydrogeological uniqueness. Situated in the Dinaric karst region, the area displays distinctive geological, geomorphological, and hydrological features. Scientific exploration of this area dates back to 1850, and a comprehensive multidisciplinary review was presented by Klaić et al. (2018).

The performance of the proposed numerical model forced by measured meteorological data was evaluated against lake temperatures measured continuously during an observational campaign under the Hydrodynamic Modeling of Plitvice Lakes project. Temperatures were recorded in two major lakes of the system: Lake Prošće (the southernmost lake) and Lake Kozjak (the largest lake). Temperatures were measured at 15 depths ranging from 0.2 to 27 m in Lake Prošće (with a maximum depth of 37.4 m) and at 16 depths ranging from 0.2 to 43 m in Lake Kozjak (with a maximum depth of 46 m). The meteorological forcing data measured at the Plitvice Lakes automatic meteorological station were provided by the Croatian Meteorological and Hydrological Service (DHMZ) which also provided quality control of the data. The data set consists of hourly values of air temperature, wind speed, atmospheric pressure, relative humidity, precipitation amount and ultraviolet B (UVB) radiation.

In the climate projection scenarios (RCP2.6, RCP4.5, and RCP8.5), data from the CORDEX initiative were used. Data were obtained from the general circulation models NorESM1-M (for scenarios RCP2.6 and RCP4.5) and IPSL CM5A-MR (for scenario RCP8.5), dynamically downscaled using REMO2015 regional climate model.

3. Methodology

The proposed SIMO model, which stands as an acronym for SImplified MOdel, is based on solving the 1-D energy balance equation, commonly employed in similar differential models. The goal was to develop a model that estimates the net heat flux and vertical thermal diffusion using only routinely measured hourly mean meteorological variables. Namely, the model incorporates carefully chosen parameterizations to calculate the surface heat flux components, including longwave and shortwave radiation, and sensitive and latent heat flux, using only the air temperature, relative humidity, atmospheric pressure, wind speed, precipitation amount, and UVB radiation. The only additionally needed input are the climatological air temperature data. Apart for the initial vertical temperature profile, the model does not use any lake-specific variables. The model accounts for convective mixing through an algorithm that checks for density inversion and assumes complete mixing of the involved layers if inversion is detected. For solving the 1-D energy balance equation, the assumption of constant horizontal cross-sectional area of the lake was found appropriate. However, it was observed that during the convective mixing phase, this assumption results in water temperature overprediction. Thus, the convective mixing algorithm takes into account the shrinking of the lake cross-section with depth.

The model is implemented in MATLAB using an implicit Euler integration scheme.

The uncalibrated model performance was evaluated against observational data using common bivariate measures: mean bias error, mean absolute error, root mean square error, and maximum absolute error, as well as index of agreement. Results from simulations of different lengths, ranging from 1 to 30 days, were used to evaluate the model performance sensitivity to the simulation length. Additionally, the model's capability to predict the springtime onset of lake stratification and autumn convective overturn was examined by running a year-long simulation initiated with an approximately uniform vertical profile of the lake temperature (≈ 4°C).

After evaluating the uncalibrated model performance, the model is calibrated and applied to predict future water temperature of Lake Kozjak under three different future climate scenarios (RCP2.6, RCP4.5, and

RCP8.5) from 2006 to 2100. In addition to analyzing the trends in water temperature at various depths in detail, the average temperatures of the epilimnion, hypolimnion, and the whole lake are also calculated and analyzed. Furthermore, the surface and bottom layer temperatures and their relation to specific forcing parameters are studied. The changes in stratification dynamics were mainly explored trough the thermocline depth and the Schmidt stability index (SSI). The thermocline depth is determined as the depth of the highest vertical temperature gradient. The SSI was employed as a quantitative indicator of lake stability. The stratification criterion used for Lake Kozjak is SSI ≥ 460 Jm^{-2}. This criterion was used to identify the start, end, and duration of the stratification period, expressed in days of the year.

4. Results and discussion

Historically, Lakes Prošće and Kozjak have been considered warm dimictic lakes. However, the measured data analyzed in this study, as well as recent subjective observations, have revealed a change in the stratification regime which had shifted from dimictic to monomictic, with stratification happening only during the warm summer period and convective mixing in autumn and winter. The surface heat flux is the main driver of the lake thermodynamic behavior, with the shortwave radiation identified as its key component being an order of magnitude larger than all the other components.

The SIMO 1.1 model performed reasonably well. Specifically, the onset of the stratification period and both the vertical temperature profile and the deepening of the thermocline over time were well captured. In general, the model tended to overestimate temperatures in the epilimnion, especially for Lake Prošće during the summer stratification period. Furthermore, while the upper metalimnion boundary was well reproduced for both lakes, its thickness was overestimated, leading to an underestimation of the maximum temperature gradient. Despite these discrepancies, the model satisfactorily predicted stratification dynamics and convective mixing. Several possible causes for the differences between modeled and measured temperatures were identified, including the underestimation of turbulent heat transfer in the epilimnion during windy periods. Furthermore, the model can not simulate internal seiches and the related water and heat exchange between the warmer epilimnion and cooler hypolimnion. Despite these limitations, considering the simplifications in the model, it demonstrated relatively good behavior and satisfactory performance. Sensitivity analysis regarding simulation length demonstrated that, with appropriate meteorological data (as in the case of Lake Kozjak), the model could provide reasonable water temperature forecasts for periods of at least 30 days. The lower performance for Lake Prošće is mainly attributed to the influence of inflows. Namely, the inflow influence is much more pronounced in Lake Prošće compared to Lake Kozjak, as Lake Prošće is the first lake in the system. However, the model assumes closed water system and does not consider the inflow effect. Another influencing factor is the greater distance of Lake Prošće from the meteorological station providing the input data. This emphasizes the importance of precise meteorological data for the specific lake location, given that meteorological forcing is a key driver of lake thermodynamics.

A year-long simulation indicated that the model could predict the onset and intensification of stratification and the occurrence of convective mixing with relatively good accuracy. Calibration of the model parameters further improved the model's representation of the metalimnetic layers and reduced the temperature overestimation. Despite its simplicity, SIMO 1.1 shows comparable performance to more complex models in reproducing water temperature profiles.

The simulation of the Lake Kozjak's water temperature under different future climate scenarios revealed that the climate change would have significant effects on the lake's future water temperature as well as on its stratification strength and duration. Mean temperature increases of 0.51, 1.41, and 4.51°C$(100\ y)^{-1}$ were projected for scenarios RCP2.6, RCP4.5, and RCP8.5, respectively. The temperature increase is slightly more pronounced in the epilimnion than in the hypolimnion. Most rapid temperature increase occurs in the surface layer during summer under scenario RCP8.5, with a peak of 6.63°C(100 y)$^{-1}$ in August, driven by changes in shortwave radiation heat flux.

The lake consistently exhibits monomictic behavior across all scenarios. While no significant trend was observed in the annual average thermocline depth, its maximum depth increased by 7.3 m(100 y)$^{-1}$ under RCP8.5 and 3 m(100 y)$^{-1}$ under RCP4.5. The stratification strength increased substantially only under the baseline RCP8.5 scenario. The increase in stratification strength is limited by the annual convective mixing through the whole water column due to Lake Kozjak's relatively small depth. However, earlier onset and delayed cessation of stratification by the end of the century was observed regardless of the scenario. The projected stratification period was extended by approximately 47, 28, and 16 d(100 y)$^{-1}$ under RCP8.5, RCP4.5, and RCP2.6 scenarios, respectively.

Predicted surface temperature increases for Lake Kozjak are within the range of values reported in global lake studies. Intriguingly, predicted deeper layer temperature increases surpass global average, hinting at Lake Kozjak's distinctive behavior.

The projected increase in lake water temperature, coupled with changes in stratification dynamics, could have significant and wide-ranging consequences. The complex interconnected processes in the dynamic system may trigger cascading effects and positive feedback loops, impacting the Plitvice Lakes ecosystem. While a comprehensive analysis of these changes requires a multidisciplinary approach, notable issues include a potential impact on phytoplankton diversity, cyanobacteria growth, and an increased risk of lake eutrophication due to higher temperatures and nutrient input. Additionally, the anticipated rise in water temperature may lead to faster tufa deposition and barrier growth processes, resulting in changes in the morphology of the lake system in a warmer climate.

5. Conclusion

This doctoral dissertation successfully accomplishes its two main goals: the development and evaluation of a simplified 1-D model for predicting the vertical temperature profile in small, warm, monomictic lakes using a reduced set of input meteorological variables, and the application of this model to analyze the influence of climate change on temperature and stratification of Lake Kozjak. This study marks the first attempt to model and forecast the water temperature and stratification of some of the Plitvice Lakes, as well as of lakes in Croatia in general, encompassing both short-term and long-term simulations. It is also the first effort aimed at analyzing the water temperature and stratification trends under future climate scenarios of a lake in this region, contributing valuable insights to the understanding of the Plitvice Lakes' dynamics in the face of changing environmental conditions.

Unlike other, more complex models, SIMO relies solely on meteorological variables routinely measured at meteorological stations, along with the climatological mean air temperature and basic lake characteristics, such as geographic coordinates, altitude, depth, and trophic status. The reduced number of necessary input data makes it practical for use in regions where specialized measurements, such as shortwave or longwave radiation, are not available. While the model was employed without specific prior calibration of input parameters, the availability of more detailed lake information could enhance its performance through parameter calibration. The short-term simulations proved that the model provides reasonable hourly water temperature forecast for periods of at least 30 days. The long-term simulation performance of SIMO makes it appropriate for climatological studies and for year-long simulations. Even in cases where no water temperature profile data is available, simulations can simply be initiated with uniform temperature profile, characteristic for the period when the lakes are completely mixed. The results of such simulations are useful for assessing the formation and strengthening of lake stratification, which is crucial for various research areas such as lake biology, geochemistry, sedimentology, etc.

The presented evaluation of SIMO is limited to a single geographical area. To more reliably confirm the general applicability of the model, it should be applied to a larger number of different temperate, monomictic lakes. However, given that the performance measures were calculated without prior parameter calibration, similar performance values can be expected for other lakes.

The analysis of the climate change effects predicts significant temperature rise and prolonged stratification in Lake Kozjak that would have serious consequences with numerous feedback mechanisms, including morphological changes of the lake system.

Considering Lake Kozjak's geography and climate, the study provides insights into potential responses of similar temperate lakes in mountainous regions. The findings lay a foundation for future studies in lake biology, geochemistry, sedimentology, and related fields.