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Projecting climate change impacts on water balance and nitrate dynamics in European lakes

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Climate change poses significant threats to freshwater ecosystems, necessitating comprehensive research on its impacts. This study investigates the impacts of climate change on water balance and nitrate dynamics in European lakes using stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) and machine learning techniques (e.g., random forest, RF). The research aimed to identify vulnerability patterns in temperate lake systems and to assess how factors such as lake size, lake type, altitude, nutrients, and potential groundwater-lake connectivity influence water dynamics. Data from over 350 lakes across Europe, collected between 2022 and 2024, were analyzed using stable water isotopes alongside ratios of evaporation-to-inflow (E/I), transpiration-to-evaporation (T/ET), and groundwater level to maximum lake depth (GW/L). The RF modeling was used to determine key drivers of lake water balance, including mean annual temperature, agricultural land use intensity, catchment forest cover, lake size, lake type, altitude, E/I, potential groundwater-lake connectivity, and T/ET ratios. The findings revealed that lakes in lowland regions in Central Europe, exhibited significantly higher E/I ratios compared to those in Alpine forelands, closely correlating with regional temperature gradients. Results indicated that smaller lakes, characterized by higher surface-area-to-volume ratios, experience greater evaporation rates and lower T/ET ratios. This pattern can exacerbate water scarcity during dry periods. Artificial lakes in agricultural catchments are particularly vulnerable to nitrogen contamination. In contrast, lakes at higher altitudes demonstrated lower evaporation and T/ET rates, resulting in distinct nitrate dynamics due to cooler temperatures and reduced agricultural activity. Furthermore, lakes with high potential groundwater inflow maintain more stable water levels, thereby buffering the impacts of climate change. The predictive models for 2050 suggest that lowland lakes—especially smaller ones in agricultural regions with low or disconnected groundwater connectivity—face heightened risks of exceeding critical E/I thresholds, leading to water scarcity and nutrient contamination. The study emphasizes the importance of incorporating lake size, land use, altitude, groundwater-lake connectivity, and T/ET into predictive models to develop effective management strategies against the threats of climate change, water scarcity, and nutrient contamination in freshwater ecosystems.