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Anthropogenic impact of lake surface water temperature of lakes: A case study of eleven lakes on the yunnan-guizhou plateau

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ABSTRACT

In the past 40 years, the surface water temperature of lakes worldwide has generally shown an upward trend, with a significant spatial heterogeneity. Previous studies generally attributed the change in lake surface water temperature to direct impact of climate change. However, few studies have explored the potential impact of additional anthropogenic factors, resulting in an incomplete understanding of the anthropogenic influence on lake surface water temperatures. We thus propose a new method to quantify the anthropogenic impact on the surface water temperature of lakes. We selected 11 lakes characterized by significant variations in the intensity of watershed urbanization development on the Yunnan-Guizhou Plateau in China for an empirical study, and discussed the trend of LSWT (lake surface water temperature) changes under the anthropogenic impact, as well as the potential link between these changes and human social policies. The research results show that (1) The mean annual rate of change in LSWT due to anthropogenic impact fluctuates of 0.06℃ per year. (2) LSWT is sensitive to changes in anthropogenic activities; a 1℃ increase in LSWT due to anthropogenic factors typically results in a mean temperature variation of 0.24℃. (3) During the three years of the COVID-19 pandemic, LSWT on the Yunnan-Guizhou Plateau was significantly affected by anthropogenic activities.

1. Introduction

Lakes are important ecological resources that affect the ecological environment, sustainable development of cities, and quality of life for people within the watershed (Hong and Nguyen, 2023; Zhang et al., 2015). Lake Surface Water Temperature (LSWT) is a critical indicator within lake ecosystems (Weber et al., 2018). In the past fourty years, the global average LSWT has rapidly increased at a rate of 0.30℃/decade (O'Reilly et al., 2015; Witze, 2015), potentially disrupting the thermal environment of lakes (Wilk-Woźniak et al., 2024), frequently triggering cyanobacteria blooms (Paerl and Huisman, 2008), and fatally affecting the physical, biological, and chemical processes of lakes (Dokulil, 2014; O'Reilly et al., 2003). For instance, significant proliferation of cyanobacteria has been observed in coastal waters of Korea (Lim et al., 2021) and in Qiandao Lake (Huang et al., 2021).

The changes in LSWT are driven by both natural and anthropogenic factors (Vörösmarty et al., 2000). Yang attributes the variations in LSWT to natural factors such as near-surface air temperature (NSAT), surface pressure (SP), solar radiation (SSR), total cloud cover (TCC), wind speed (WS), and depth (SD), quantifying their contributions to LSWT changes (Yang et al., 2020a). From an anthropogenic perspective, as urbanization, GDP, and population increase, there is a general expansion in the impervious surface area of lake basins (Liu et al., 2023; Luo et al., 2018; Pekel et al., 2016). The increase in impervious surfaces leads to urban heat island effects and urban thermal runoff, which further warm the LSWT (Luo et al., 2023, 2018; Yi et al., 2019; He, 2023). Studies indicate that the scale of population and economic development in lake basins will significantly influence the future supply and demand of water resources (Vörösmarty et al., 2000), exceeding the impacts of climate change (Hondzo and Stefan, 1993). Research into anthropogenic factors affecting LSWT is crucial for mitigating economic regulation and population pressures on lake water environments (Pekel et al., 2016; Yang et al., 2019, 2018).

From a heat transfer perspective, anthropogenic factors do not

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directly heat the LSWT but indirectly alter it by changing factors directly related to LSWT, such as air temperature and radiation (Luo et al., 2023). Previous studies on anthropogenic impacts have quantified these effects using linear regression and neural network approaches. However, these studies inadequately address anthropogenic impacts by only considering watershed population and GDP (Yang et al., 2020b), neglecting urban thermal runoff's effect on LSWT and failing to distinguish between natural and human-driven changes (Trumpickas et al., 2009; Winslow et al., 2017). This oversight results in an incomplete understanding of LSWT variability (Grant et al., 2021). The current challenge in quantifying human impact involves comprehensively addressing all anthropogenic factors, which necessitates a model capable of precisely isolating non-human influences. The design of the Air2water model is solely based on air temperature to estimate water temperature (Piccolroaz et al., 2017; Piccolroaz et al., 2015), without accounting for the influence of urban runoff during the modeling process. The MODIS water temperature product data, widely utilized in the field of LSWT research, is obtained through continuous monitoring of water body temperature. It provides a comprehensive description of LSWT (Woolway et al., 2020; Woolway and Merchant, 2017). By combining the MODIS product data with the Air2water model, we can effectively quantify the anthropogenic impacts that contribute to the changes in LSWT.

To sum up, anthropogenic impacts are closely related to the ecological stability of lake basins. Quantifying anthropogenic impact on LSWT is crucial for maintaining the ecological stability of these basins. It is essential to further investigate the potential correlations between anthropogenic impacts and changes in LSWT. Therefore, based on previous research (Luo et al., 2023, 2018; Peng et al., 2022; Yang et al., 2021, 2020c2019; Yu et al., 2021b, 2021a, 2020a, 2020b), the 11 naturally formed lakes in the Yunnan Guizhou Plateau were selected for study, the main objectives of this study are: (1) to quantify the

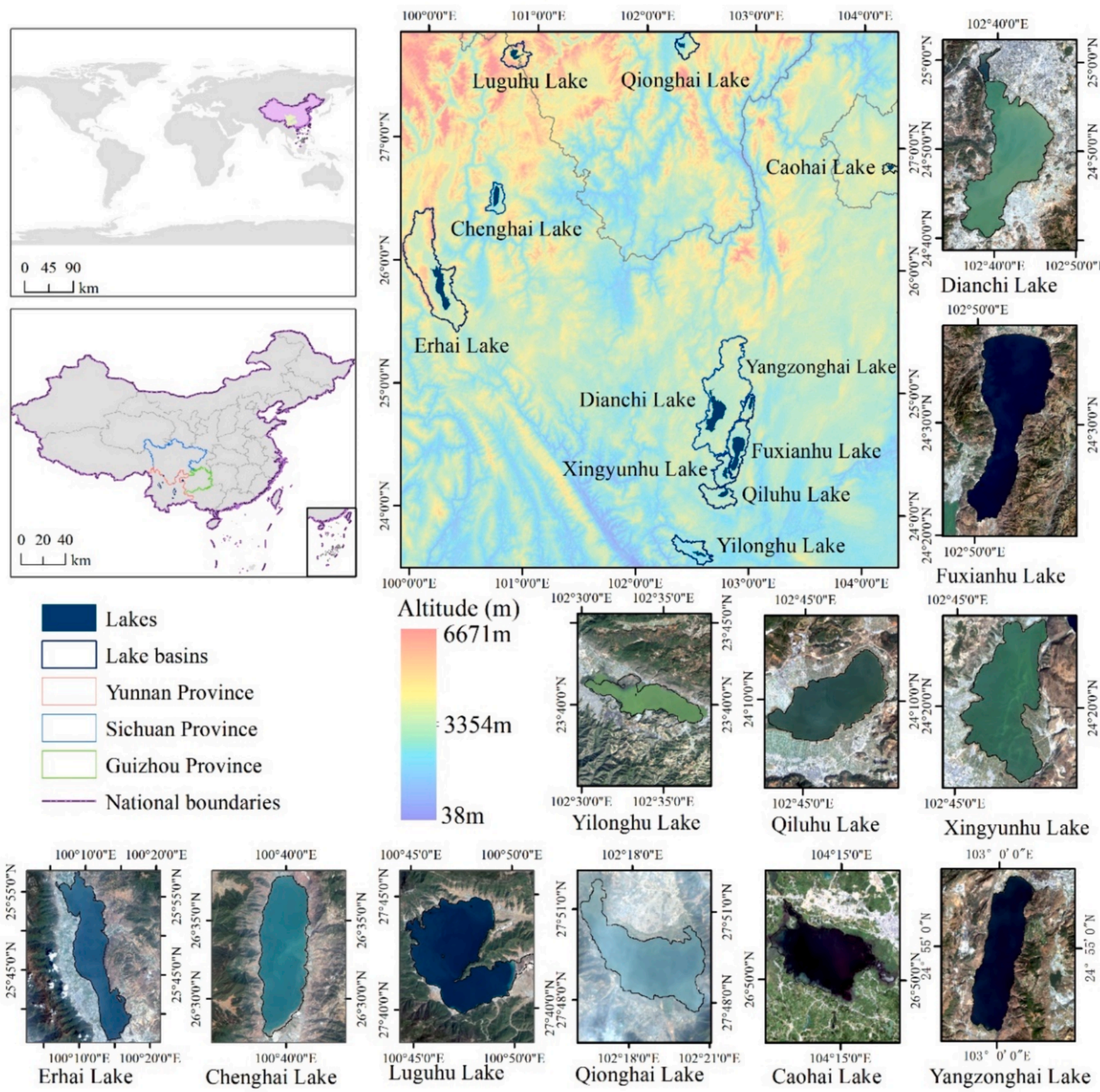

Fig. 1. Overview of the study area.

anthropogenic impacts on LSWT, (2) to calculate the contributions and sensitivities of these anthropogenic impacts to LSWT changes based on their impact on LSWT, (3) to show the association between abnormal LSWT changes and social policies by using key climate variables, in combination with lake types and social policies. These findings will contribute to a better understanding of LSWT variability in the Yunnan-Guizhou Plateau and the water environment management under social policy influences. Additionally, they will reinforce our perspective on the relationship between LSWT and human activities.

2. Study area and data

2.1. Study area

The intense movement of crustal structure in Yunnan-Guizhou Plateau forms 11 inland plateau lakes (Fig. 1), including 9 lakes in Yunnan Province (Dianchi Lake, Fuxian Lake that is the second deepest lake in China, Xingyun Lake, Yangzong Lake, Qilu Lake, Yilong Lake, Erhai Lake, Chenghai Lake, and Lugu Lake), Caohai Lake in Guizhou Province, and Qionghai Lake in Sichuan Province. These lakes are representative among China's fault-type lakes (Hutter et al., 1998) and there are another information of lakes in the Supplementary material (Table 1). Their water supply mainly comes from precipitation. Lake water usually is inactive, lacking of self-purification capabilities, and as a result, easily affected by human activities and climate change. There are generally three types of lakes in the Yunnan-Guizhou Plateau: urban lakes, semi-urban lakes, and natural lakes (Yang et al., 2019). These lakes provide good experimental examples. The non-permeable coverage and morphological parameters of the lake basins are shown in Table 1 in the appendix.

2.2. Data

MODIS surface temperature data is a key parameter for hydrological, meteorological, climatic, and environmental research (Li et al., 2014). The MOIDS data processing involves a series of steps, including format conversion, reprojection, splicing, resampling, cropping based on lake boundaries, mean extraction, and accuracy validation. The accuracy validation is performed using the measured water temperature data from the HaiGeng station of Dianchi lake between 2005 and 2012, as shown in Fig. 3(I). The MODIS11A2 data considers all surface-atmosphere interactions which is used to study lake heatwaves and seasonal changes in lake water temperature (Woolway, 2023; Woolway et al., 2021), and to analyze the driving factors of lake surface water temperature (Yang et al., 2020). Therefore, in this study, MODIS11A2 data (https://urs.earthdata.nasa.gov/) was used to characterize lake surface water temperature. The air temperature data used in this study comes from the European Centre for Medium-Range Weather Forecasts (ECMWF, https://cds.climate.copernicus.eu/), with a spatial resolution of 0.1°×0.1°. The full names and abbreviations of the terms used in this study are shown in Table 1, and specific descriptions of the data sources are shown in Table 2.

Landsat 8 OLI data and digital elevation model (DEM, https://gdex.

Table 2
Potential links between human social policy and LSWT.

Lake	Mutation Year(LSWT)	Mutation Year(AF)	Social Policy	Reference
DCL	2018	2016/ 2018	The Niu Lang River Water Diversion Project	(Liu et al., 2014)
QLL	2018	2018	Qilu Lake Basin Water Pollution Comprehensive Prevention and Control Plan	https://www.docin.com/p-944135644.html
XYL	2011	2013	The outflow of Fuxian Lake is diverted into Xinyun Lake	
CAHL	2005/2006/ 20https:// doi.org/10/ 2013/2017	2010	Caohai Comprehensive Management Master Plan	https://www.gz-travel.net/lysx/bj/200811/6007.html
EHL	2011	2003/ 2019	Erhai management "seven actions" planning in 2017	https://news.youth.cn/jsxw/201705/t20170512_9741443.htm
QHL	2014	2007/ 2011/ 2017	Three Gorges Dam affects water vapor exchange in lakes	(Yang et al., 2021)
YZHL	2014/2018	2018	Arsenic contamination	(Zhang et al., 2022)
YLL	2019	2020	Three-Year Action Plan (2016–2018) and Thirteenth Five-Year Plan for Environmental Protection and Management of Isolong Lake Basin in Honghe Prefecture	(Wu et al., 2021)
CHHL	2005	2015	Spirulina production enterprises anthropogenic heavy metal emissions	(Zhang et al., 2015)
FXL	2010	2019	The outflow of Fuxian Lake is diverted into Xinyun Lake	(Dai et al., 2017)

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Table 1
Nomenclature table of the Attachment.

Type	Abbreviation	Full name	Unit	Type	Abbreviation	Full name	Unit
Factors	LAWT	Lake surface water temperature	℃	Lakes	CAHL	Caohai Lake	–
	NSAT	Near surface air temperature	℃		CHHL	Chenghai Lake	–
Parameters	TS_c	Comprehensive change rate	℃ /decade		DCL	Dianchi Lake	–
	TS_{month}	Change rate of month	℃ /decade		CAHL	Caohai Lake	–
	TS_{season}	Change rate of season	℃ /decade		CHHL	Chenghai Lake	–
	TS_{year}	Change rate of year	℃ /decade		DCL	Dianchi Lake	–
	CF	Comprehensive Forcing	℃ /decade		EHL	Erhai Lake	–
	DI	Direct Impact	℃ /decade		FXL	Fuxian Lake	–
	AI	Anthropogenic Impact	℃ /decade		LGL	Lugu Lake	–
	AS	Anthropogenic Impact Sensitivity	–		QLL	Qilu Lake	–
Lake Type	UL	Urban Lake	–		QHL	Qionghai Lake	–
	SUL	Semi-urban lake	–		XYL	Xingyun Lake	–
	NL	Nature Lake	–		YZHL	Yangzonghai Lake	–

cr.usgs.gov/gdex/) data were obtained from the U.S. Geological Survey (USGS), with a spatial resolution of 30 m. The lake boundary was extracted using Landsat8 OLI data (https://earthexplorer.usgs.gov/), and the lake basin boundary was extracted using DEM data and the ArcGIS Arc-SWAT plugin. For more information on the specific methods used for LSWT and water boundary extraction, please refer to the Appendix. The world map, China map, and provincial administrative boundaries of the Yunnan-Guizhou Plateau were downloaded from the Chinese Academy of Sciences Resource and Environmental Science and Data Center. The specific description of the data source is shown in Appendix Table 2.

3. Methods

3.1. Trend analysis

The *Theil-Sen slope (TS_{slope})* is a robust non-parametric estimation method that is insensitive to measurement errors and outlier, making it suitable for trend analysis of long time series data (Sen, 1968). This method has obvious advantages, especially for data with chaotic properties. Therefore, this study combines Theil-Sen slope estimation model and Mann-Kendall non-parametric test method to explore the variation characteristics of major lakes in the Yunnan-Guizhou Plateau at the annual, seasonal, and monthly scales (Hipel and McLeod, 1994). The first step is to use the Theil-Sen slope estimation model to calculate the trend of the time series data. When the slope is positive, it indicates an upward trend, and vice versa for a negative slope. The larger the value $|TS_{Slope}|$, the more pronounced the trend. In this study, the Mann-Kendall non-parametric test method was used to determine the significance of the trend. A confidence level of 95 % was selected, which means that the data series has undergone significant changes when $|Z|>1.96$ (Libiseller and Grimvall, 2002).

In addition, to avoid the limitations of a single dimension and weaken the influence of local extremes on the overall level, and to comprehensively analyze the overall trend of each time series data set, this study referred to the TS_C constructed by the research team in a previous study to reflect the comprehensive change rate of variables (Yang et al., 2020), which is calculated as shown in formula (1).

$$TS_C = mean(TS_{year} + TS_{season} + TS_{month}) \quad (1)$$

The comprehensive change rate is the average of the annual average change rate TS_{year}, the seasonal change rate (TS_{season}), and the monthly change rate (TS_{month}), where is the mean function. In contrast to the previous study, this study simultaneously considers the warming rate and cooling rate to calculate the comprehensive change rate.

3.2. Quantification of anthropogenic impacts on LSWT

The key to quantifying the anthropogenic impacts on LSWT is whether a model can be built to remove the interference of air temperature on LSWT. Air2water is a model developed based on physical energy exchange (Piccolroaz, 2016; Piccolroaz et al., 2017), which only considers the heat exchange of LSWT with natural variables such as air temperature in natural processes, and disregard the influence of human activities such as thermal runoff on water temperature (Piccolroaz et al., 2013; Piccolroaz et al., 2015). Please refer to the Appendix and relevant references for the calculation formula of Air2water. We thus believe that the water temperature predicted by the Air2water model can characterize the water temperature under direct impact (DI). For each lake, we define the comprehensive change rate as comprehensive forcing (CF), which includes DI and anthropogenic impact (AI).

$$AI = CF - DI \quad (2)$$

The sensitivity of LSWT to anthropogenic impact represents the overall change in LSWT when anthropogenic impact causes a 1℃ change, which is the ratio of the derivatives of these two variables. Since the rate of change is essentially a derivative, this paper uses the ratio of the rate of change in the impact of temperature warming to the rate of change in temperature to represent the sensitivity of water temperature to anthropogenic impact (Anthropogenic Impact Sensitivity, AS), which is calculated as shown in formula (3). The abbreviations used in this paper are listed in Table 1.

$$AS = \frac{d_{AI}}{d_{CF}} \quad (3)$$

4. Result

4.1. Analysis of the change characteristics of LSWT

We used MODIS11A2 data to construct the LSWT dataset from 2001 to 2023 to reveal the characteristics of LSWT changes (Fig. 2). From 2001 to 2023, the eleven lakes in the Yunnan-Guizhou Plateau showed different varying rates (as shown in Appendix Table 4), all lakes showing a warming trend, with an average warming rate of 0.60℃/decade. Xingyun Lake had the highest annual warming rate of LSWT (TSC_{XYL} = 0.85℃/decade), and Fuxian Lake had the smallest annual warming rate of LSWT (TSC_{FXL} = 0.44℃/decade).

From the seasonal change characteristics, the LSWT of the eleven lakes in the Yunnan-Guizhou Plateau all showed a warming trend, with the highest growth rates in summer and autumn (0.60℃/decade and 0.67℃/decade, respectively). The warming rate in spring was higher than that in winter. From the monthly change characteristics, the LSWT in the Yunnan-Guizhou Plateau showed a warming trend was observed with an average warming rate of 0.62℃/decade. Overall, from 2001 to 2023, the LSWT in the Yunnan-Guizhou Plateau showed a warming trend, with fluctuation in the rate ranging from 0.38 to 0.95℃/decade.

4.2. Analysis of the anthropogenic impacts on LSWT changes from 2001 to 2023

From 2001 to 2023, anthropogenic impact had different impacts on the LSWT of various lakes in the Yunnan-Guizhou Plateau. From the trend analysis (see Fig. 3), Dianchi Lake, Xingyun Lake, Yilong Lake, Qilu Lake, Erhai Lake, Yangzonghai Lake, Chenghai Lake and Fuxian Lake showed an increasing trend (0.11℃/yr), while Caohai Lake, Lugu Lake and Qionghai Lake showed a decline trend (−0.06℃/yr). The significant anthropogenic impact on the LSWT of each lake is shown in Fig. 3. The greatest impact in 2023 was observed in Dianchi Lake, Qilu Lake, Xingyun Lake, Chenghai Lake, Erhai Lake, Fuxian Lake, Yangzonghai Lake, and Yilong Lake, which were the warmest; Caohai Lake and Lugu Lake were the coldest. Among them, the impact on Caohai is decrease rapidly, while the impact on Xingyun Lake is increased rapidly in 2023.

We analyzed the anthropogenic impact on LSWT of different types of lakes. Previously, our team combined various factors (such as GDP, impervious cover, and NASA data) and used the K-means algorithm to classify the Yunnan-Guizhou Plateau lakes at the basin scale into three types: urban lakes (NL), semi-urban lakes (SUL), and natural lakes (NL). Previous research classified Fuxian Lake and Xingyun Lake into the same lake type. Based on current research results and the impervious cover of the Xingyun Lake basin, we believe that Xingyun Lake should be included in the urban lake category. As a result, there are three types of lakes are urban lakes (Dianchi Lake, Qilu Lake, and Xingyun Lake), five semi-urban lakes (Erhai Lake, Yilong Lake, Qionghai Lake, Yangzonghai Lake, and Caohai Lake), and three natural lakes (Fuxian Lake, Lugu Lake, and Chenghai Lake).

As shown in Fig. 3, for urban lakes, the impact of anthropogenic impact on Qilu Lake and Xingyun Lake has been increasing year by year. For semi-urban lakes, the anthropogenic impact on Yangzonghai and Yilong has been increasing, while the impact on the other three lakes

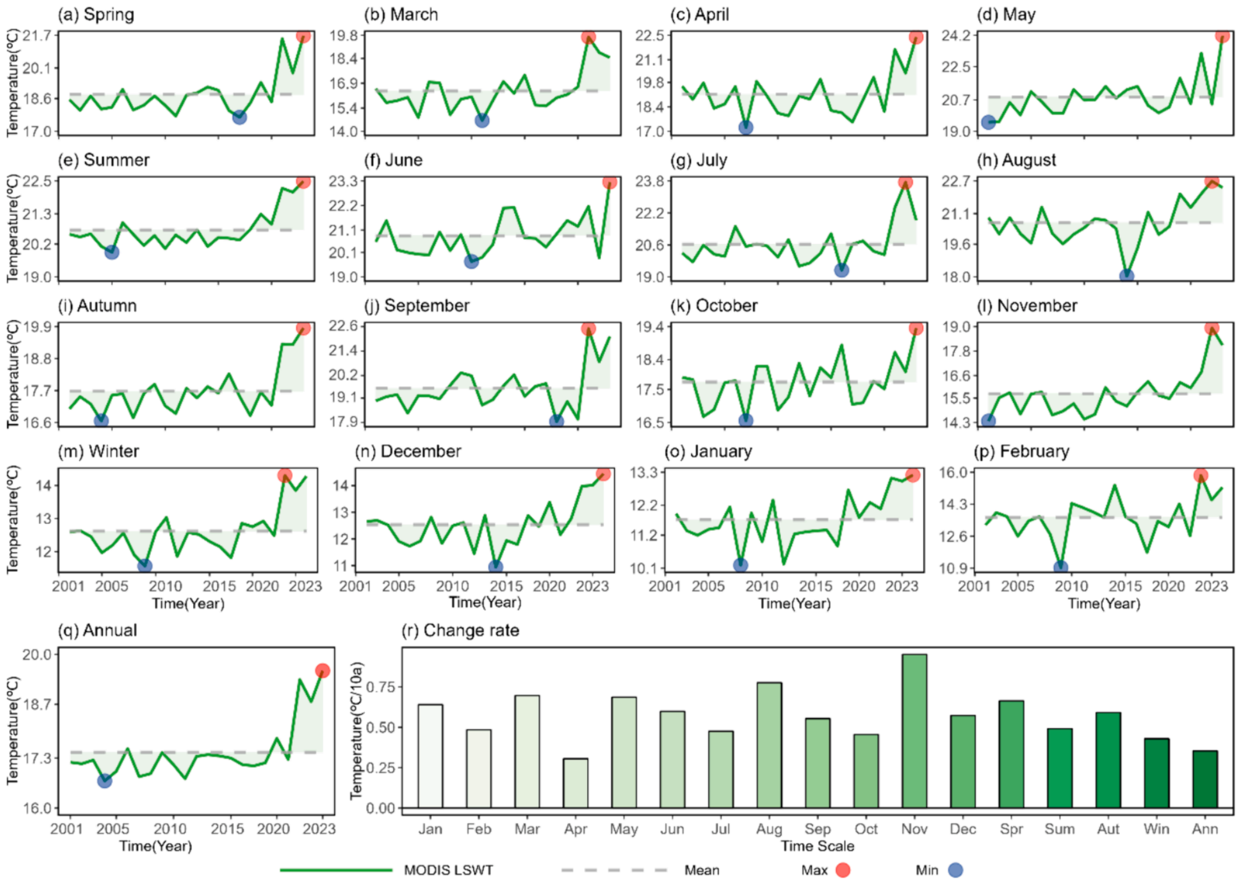

Fig. 2. Characteristics of LSWT changes in lakes on the Yunnan-Guizhou Plateau over 2001–2023.

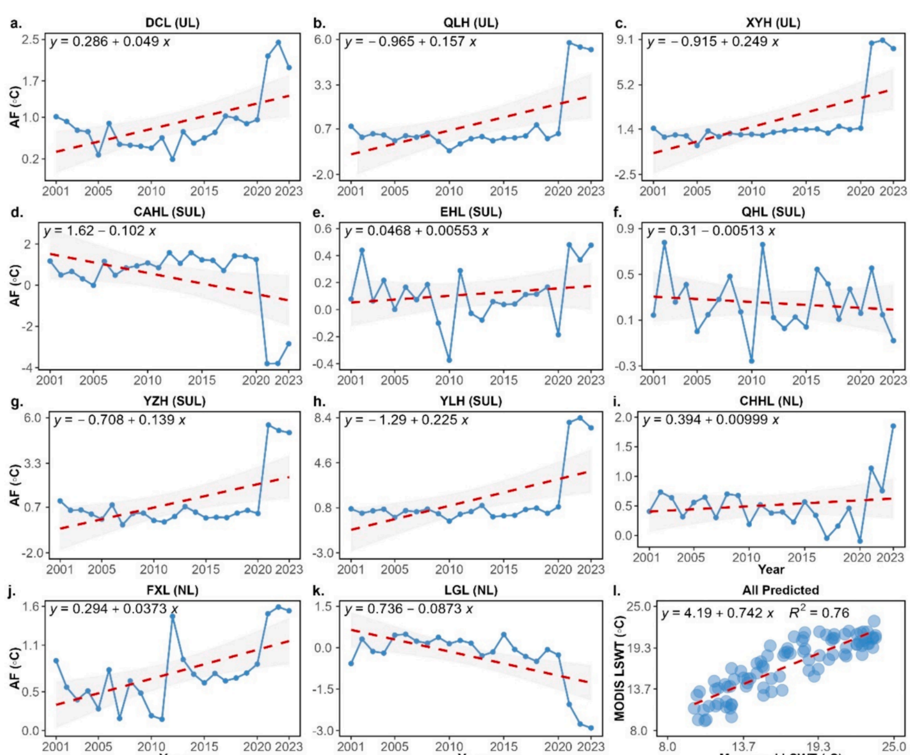

Fig. 3. The trend of anthropogenic impact on LSWT in the Yunnan-Guizhou Plateau (Data are tested for time series smoothness, DCL indicates Dianchi Lake, QLL indicates Qilu Lake, XYL indicates Xinyun Lake, CAHL indicates Caohai Lake, EHL indicates Erhai Lake, QHL indicates Qionghai Lake, YZHL indicates Yangzonghai Lake, YLL indicates Yilong Lake, FXL indicates Fuxian Lake, LGL indicates Lugu Lake, CHEL indicates Chenghai Lake).

(Erhai, Qionghai, and Caohai) has been decreasing. For natural lakes, the anthropogenic impact has a greater warming effect on the LSWT of Fuxian and Chenghai Lake and cooling effect on Lugu Lake. The rate of change anthropogenic impact has the most significant impact on urban lakes (0.15℃/yr), followed by semi-urban lakes (warm:0.05℃/yr; coling:-0.06℃/yr), and the least effect on natural lakes (warm:0.02℃/yr; coling:-0.09℃/yr).

4.3. Spatial heterogeneity analysis of the anthropogenic impacts on LSWT changes in the Yunnan-Guizhou Plateau

As shown in Fig. 4, the anthropogenic impact exhibits significant spatial heterogeneity. The most significant cooling effect on LSWT is observed in Lugu Lake (−0.31℃/yr), while the most significant warming effect on LSWT is observed in Xingyun Lake(2.08℃/yr). The central plain of the Yunnan-Guizhou Plateau includes Dianchi, Fuxian, Xingyun, Yangzonghai, Qilu, and Yilong Lakes; the northwestern part includes Lugu, Chenghai, Erhai, and Caohai Lakes. The lake group in the central plain of the Yunnan-Guizhou Plateau shows a significant warming effect on LSWT with an average increase 1.12℃/yr. In contrast, the lakes in the northern part of the plateau have varied changes, the northwestern part experienced both cooling and warming. Lugu Lake cooled by −0.31℃/yr, and Erhai, Chenghai, Caohai, and Qionghai Lakes warmed by 0.32℃/yr.

From a spatial analysis perspective, the sensitivity of LSWT in the lakes of the Yunnan-Guizhou Plateau to anthropogenic impact shows the same pattern with anthropogenic impacts themselves. Regarding the sensitivity of LSWT in the lakes of the Yunnan-Guizhou Plateau to anthropogenic impact, when the anthropogenic impact causes LSWT to rise by 1℃, the LSWT of Lake Luguhu and Caohai Lakes decreases, with Luguhu Lake showing the most significant cooling (−1.37℃). The LSWT of the other ten lakes (Ehai, Chenghai, Xingyun, Dianchi, Fuxian, Yilong, Yangzonghai, Qionghai, and Qilu) increases, with Dianchi, and Fuxian lakes showing the most significant warming (0.76℃ and 0.73℃, respectively).

4.4. Critical years with abnormal changes in the anthropogenic impact on LSWT

From 2001 to 2023, LSWT experienced abrupt changes in2005, 2015 and 2023. To analyze these types of temperature changes, we combined the Mann-Kendall Test method to investigate the impact of anthropogenic impact on LSWT changes (Fig. 5) and explain the process of abnormal temperature changes caused by anthropogenic impact. From the impact of anthropogenic impact on LSWT, there was an abnormal change in the impact of anthropogenic impact on LSWT in four lakes (Caohai, Erhai, Qionghai) from 2001 to 2010. The impact of anthropogenic impact on LSWT in nine lakes (Dianchi, Qiluhu, Xingyun, Caohai, Qionghai, Yilong, Chenghai, Fuxian, and Luguhu) experienced an abnormal change from 2011 to 2023. These results are consistent with the abnormal changes in LSWT, indicating that anthropogenic impact is an important factor in the abrupt changes in LSWT. Among them, the research results indicate that the most significant abnormal changes in anthropogenic impact on LSWT across all lakes primarily occurred during 2011–2023, especially in 2020. Another period of abnormal changes was observed from 2001 to 2010, particularly in semi-urban lakes.

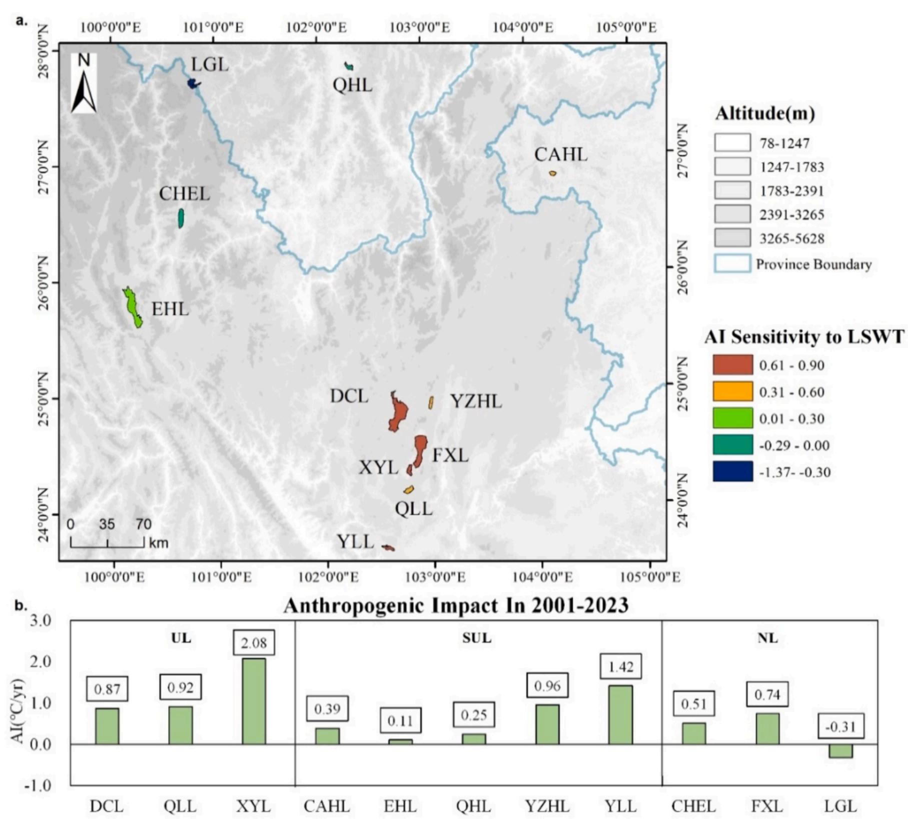

Fig. 4. Contribution and sensitivity of anthropogenic impact to LSWT (DCL indicates Dianchi Lake, QLL indicates Qilu Lake, XYL indicates Xinyun Lake, CAHL indicates Caohai Lake, EHL indicates Erhai Lake, QHL indicates Qionghai Lake, YZHL indicates Yangzonghai Lake, YLL indicates Yilong Lake, FXL indicates Fuxian Lake, LGL indicates Lugu Lake, CHEL indicates Chenghai Lake, UL indicates the lake type is urban, SUL indicates the lake type is semi-urban, and NL indicates the lake type is natural).

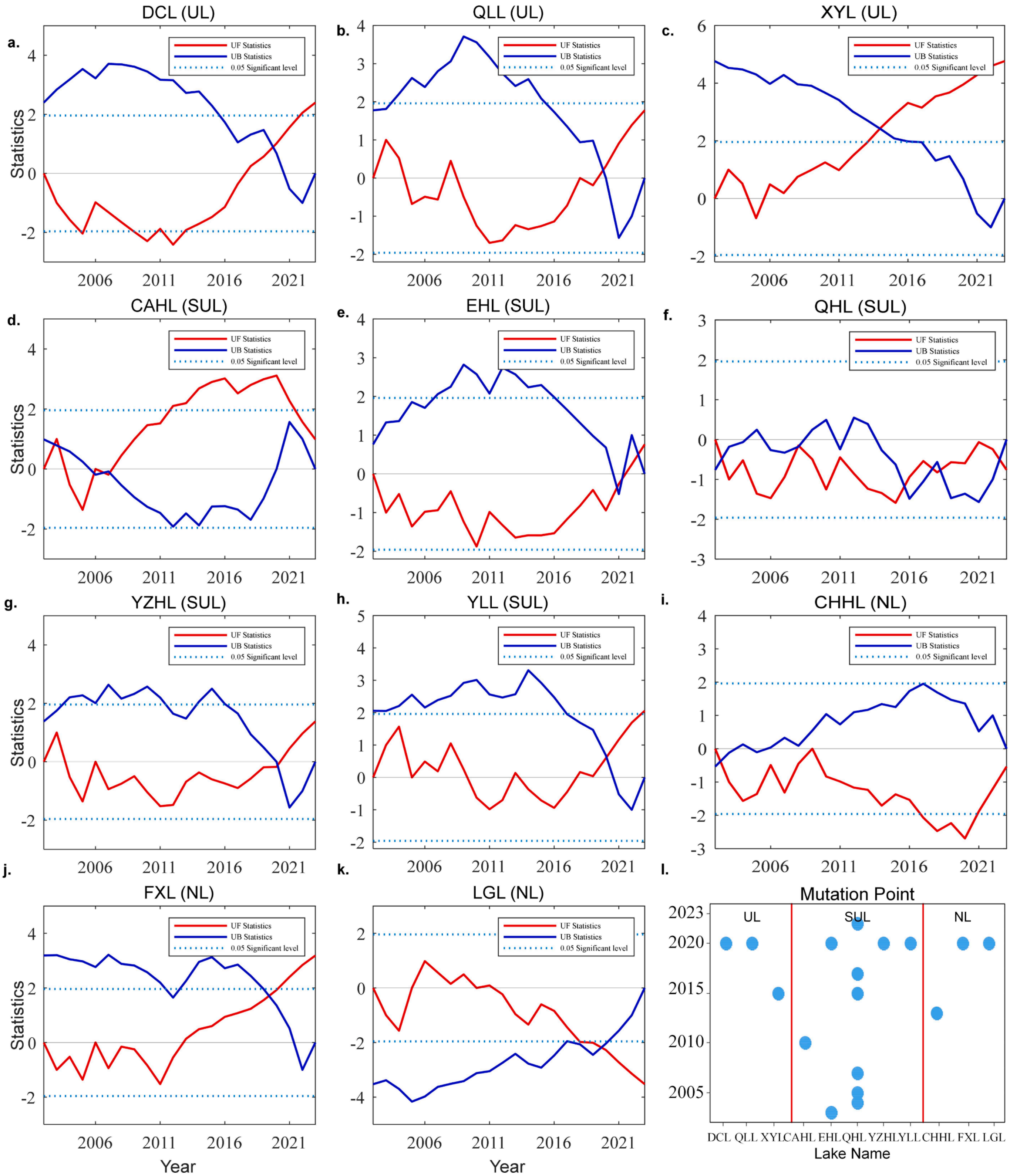

Fig. 5. Mutational analysis of the effects of anthropogenic impact on the LSWTin the Yunnan-Guizhou Plateau (DCL indicates Dianchi Lake, QLL indicates Qilu Lake, XYL indicates Xinyun Lake, CAHL indicates Caohai Lake, EHL indicates Erhai Lake, QHL indicates Qionghai Lake, YZHL indicates Yangzonghai Lake, YLL indicates Yilong Lake, FXL indicates Fuxian Lake, LGL indicates Lugu Lake, CHEL indicates Chenghai Lake, UL indicates the lake type is urban, SUL indicates the lake type is semi-urban, and NL indicates the lake type is natural).

5. Discussion

5.1. Main findings of the present study

Anthropogenic activities have impacted lake surface water temperatures (LSWT). Temporally, from 2001 to 2023, the influence of anthropogenic factors on the lakes of the Yunnan-Guizhou Plateau has progressively intensified, with the annual rate of change in the impact on LSWT fluctuating between −0.06 and 0.11℃ per year. Spatially, the impact of anthropogenic activities on LSWT shows a trend of increasing from north to south. Lakes in the northern part are less affected by anthropogenic activities compared to those in the southern part. LSWT is sensitive to changes in anthropogenic activities; a 1℃ increase in LSWT due to anthropogenic factors typically results in an overall temperature variation of −0.37 to 0.76℃. From 2001 to 2023, anthropogenic activities had a significant effect on LSWT, with several mutations occurring around the year 2020.

5.2. Comparison with other studies

At present, there are few studies available on the Web of Science or Google Earth Engine that address the impact of anthropogenic activities on lake surface water temperatures. Existing research generally considers the impact of anthropogenic activities as just one of several factors influencing changes in lake surface temperatures. The methodologies employed include linear regression and machine learning, which are used to quantify the impact together with various other factors. For instance, research by Yang attributes 35 % of the change in lake surface temperatures to anthropogenic activities(Yang et al., 2020c), while Peng report a contribution of 25 %()(Peng et al., 2022). These studies quantify the impact of anthropogenic activities using GDP/POP data, but they do not fully account for cultural factors and overlook influences such as urban heat runoff. Therefore, based on previous research, this study recognizes that the impact of anthropogenic activities on LSWT is significant and should not be overlooked. It focuses on quantifying the influence of anthropogenic activities and explores the relationship between these activities and social policies, providing essential support for the development of ecological and environmental policies for lake basins.

5.3. Implication and explanation of findings

From 2001 to 2023, the impact of anthropogenic activities on lake surface water temperatures (LSWT) exhibited mutations over time. Social policies impose certain constraints on human activities. The analysis integrating the years when social policies were enacted with the mutation points in the impact of anthropogenic activities on LSWT can illustrate how these policies, centered around the lake basins, influence LSWT. This provides a theoretical basis for government agencies to protect and manage lake water quality. From 2020 to 2023, the impact of anthropogenic activities on LSWT was the most significant, with notable mutations. This period coincided with the COVID-19 pandemic, during which anthropogenic influences altered local air temperatures, leading to the "urban heat island" effect that indirectly increased water temperatures.

As shown in the Fig. 5 and Supplementary Material Fig. S12, LSWT of lakes can experience abnormal changes due to interference from social policies. For example, the Mann-Kendall mutation test shows that the LSWT of Dianchi Lake underwent a mutation in 2018, and the anthropogenic impact on the LSWT of Dianchi Lake underwent a mutation in 2016 and 2018. This result shows that the mutation in the LSWT of Dianchi Lake in 2018 was caused by human activities. This mutation may be related to the Niulanjiang water diversion project in Dianchi Lake in 2013 (Liu et al., 2014). This might be due to slow impact of human activities on LSWT. Water has a large heat capacity, so it takes a relatively longer time to change its temperature. Therefore, the water diversion project started running in 2013, and the water temperature changed in 2018. The impact of human activities on Xingyun Lake's LSWT underwent a mutation in 2013. The LSWT of Xingyun Lake underwent a mutation around 2013, which may be related to the opening of the gate in Jiangchuan County, Yuxi City, causing the diversion of the outflow of water. The LSWT of Caohai Lake underwent a mutation point in 2010. The impact of human activities on Caohai Lake's LSWT underwent a turning point in 2010, which may be due to the comprehensive plan for the overall treatment of Caohai issued by Beijing in 2008, and the ecological environmental management of Caohai started in November 2008. The reduction in human activities changed LSWT of Caohai Lake. Information on other lake LSWT mutations related to social policies is shown in Table 2.

5.4. Contributions and limitations

Based on the above analysis, this study has made three main contributions. Firstly, considering the limitations in current quantitative analysis methods for the anthropogenic impact on LSWT, we have proposed a new approach to quantitatively measure the anthropogenic impact on LSWT. Secondly, we used the sensitivity concept and proposed a new method to explain the anthropogenic impact on LSWT. Finally, the combined anthropogenic impact on LSWT, the sensitivity of LSWT to anthropogenic impact changes, and the MK mutation test reveal the potential relationship between human social policies and LSWT, as well as the potential crisis of the lake ecosystem under the influence of human activities.

There is a limitation in using Air2water and MODIS data. Air2water and MODIS use two different data sources that can only partially quantify the anthropogenic impact such as urban expansion and climate change on LSWT. In future research, we will also adopt more comprehensive methods to quantify the anthropogenic impact on LSWT and explore the characteristics of LSWT changes with future scenarios.

5.5. Recommendation, and future direction

Anthropogenic activities influence on LSWT, and governmental policies can restrict these activities to a certain extent. Understanding the characteristics and driving mechanisms of anthropogenic impacts on LSWT can provide theoretical support for governmental bodies to protect and manage lake water quality, as well as deepen our understanding of changes in LSWT. Our study illustrates from a macro perspective the impact of anthropogenic activities on the LSWT of lakes on the Yunnan-Guizhou Plateau and the sensitivity of LSWT to anthropogenic activities. When intervention in the lake's surface temperature is necessary, regulating the temperature can be effectively achieved by controlling the length of the channel through which the river enters the lake. We confirm that anthropogenic activities impact LSWT; given that lakes are complex ecosystems where both warming and cooling can have significant effects, human intervention must be approached with careful consideration. Therefore, future research should investigate the extent and timing of anthropogenic activities that are beneficial for the lake ecosystem, and determine the thresholds at which anthropogenic activities must be forcibly curtailed to avoid ecological degradation.

6. Conclusion

In this paper, based on MODIS11A2, near-surface air temperature (NAST), and land use data, the Air2water model, this study quantifies the anthropogenic impact on LSWT warming and reveals the characteristics and interrelationships of LSWT anthropogenic impact for different types of lakes on Yunnan-Guizhou Plateau. This study offers new insights for future research on lake environments and quantifying the anthropogenic impact on LSWT, laying a foundation for subsequent investigations. The results of this study are as follows:

(1) The results of the temporal change rate due to anthropogenic impacts revealed that there were 8 lakes (Dianchi, Qilu, Xingyun, Chenghai, Erhai, Fuxian, Yangzonghai and Yilong Lake) were on the rise (the mean warming rate was 0.11℃ /yr), with 3 lakes (Caohai, Qionghai and Lugu Lake) showed a downward trend (the mean cooling rate was 0.06℃ /yr)
(2) LSWT is sensitive to changes in anthropogenic activities; a 1℃ increase in LSWT due to anthropogenic factors typically results in an overall average temperature variation fluctuates between −1.37℃ and 0.90℃. There were 8 lakes (Dianchi, Qilu, Xingyun, Chenghai, Erhai, Fuxian, Yangzonghai and Yilong Lake) were on the rise (the mean warming rate was 0.55℃), with 3 lakes (Caohai, Qionghai and Lugu Lake) showed a downward trend (the mean cooling rate was 0.39℃).
(3) During the three years of the COVID-19 pandemic, the surface water temperature (LSWT) of lakes on the Yunnan-Guizhou Plateau was significantly affected by anthropogenic activities.
(4) We emphasize that lakes, as complex ecosystems, experience significant impacts from both warming and cooling; therefore, human interventions must be carefully considered. Future research should focus on the lake ecosystems to discuss whether it is necessary to establish relevant policies to protect the thermal environment of the lakes.

CRediT authorship contribution statement

Haimei Duan: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kun Yang:** Writing – review & editing, Methodology, Conceptualization. **Chunxue Shang:** Writing – review & editing, Conceptualization. **Xiaolu Zhou:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Yi Luo:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated and/or analyzed during the current study are available at https://zenodo.org/record/7051209 under a specific license. Please note that there may be restrictions on the availability of these data due to the terms of the license. Further inquiries can be directed to the corresponding author. Restrictions apply to the availability of these data, which were used under license for this study. Please find Supplementary material at https://doi.org/10.5281/zenodo.7914591.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112165.

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