

Progress of remote sensing inversion research on surface temperature of lakes and reservoirs

Gang Xie^{1,*a}, Haoming Zhang^{1,b} and Quanfu Niu²

¹School of Petrochemical Engineering, Lanzhou University of Technology, Lanzhou 730050, Gansu, China;

²School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, Gansu, China

xiegang@lut.edu.cn^a, 505408676@qq.com^b

Abstract: Surface temperature of lakes and reservoirs is one of the important indicators of temperature change on the earth's surface, which not only reflects the impact of earth's climate change, but also has great significance for water resource management and ecological environmental protection. However, traditional temperature observation methods are limited by factors such as time, space and economic cost, which make it difficult to provide comprehensive and continuous temperature data. Therefore, the quantitative inversion of the surface temperature of lakes and reservoirs using remote sensing technology has become one of the hot spots in research. Based on this, this paper summarizes the relevant data sources and various research methods of remote sensing quantitative inversion of surface temperature of lakes and reservoirs in recent years, and elaborates and analyzes them, in order to provide reference for the ecological protection of lakes.

Keywords: Lake reservoir; surface temperature; inversion algorithm

1. Introduction

Lakes and reservoirs are important freshwater resources, which are significant for the stability of ecosystems and human life. Among them, the surface temperature of water bodies is an important parameter in the study of lakes and reservoirs' ecological environment, which can reflect the thermal characteristics of water bodies, hydrological processes, and the interaction between water bodies and the atmosphere. Remote sensing technology, on the other hand, can obtain large-scale, high-resolution surface temperature data through platforms such as satellites or unmanned aerial vehicles, which provides a new means of research on lakes and reservoirs[1-2]. Therefore, scholars have been focusing on the ecological environment of lakes and reservoirs in recent years. The surface temperature of lakes and reservoirs is an important indicator of their thermal structure and the ecological environment of water bodies, and how to accurately measure and monitor the surface temperature of lakes and reservoirs is of great scientific and practical significance[3-4]. Traditional methods of monitoring surface temperatures in lakes and reservoirs rely mainly on in situ observation and sampling, which is associated with high labour, time and space costs[5]. Remote sensing, however, has become an important technique for surface temperature inversion studies of lakes and reservoirs due to its efficiency, economy and unmanned nature.

2. Basis for remote sensing study of lake water surface temperature inversion

Lake water surface temperature inversion usually relies on remotely sensed data, including multispectral and thermal infrared images. However, obtaining high-quality remotely sensed data is still a challenge, especially regarding the monitoring of large-scale lakes. In addition, it is also a challenge to properly handle disturbances such as noise and cloud cover in remotely sensed data [6-8]. In this section, a detailed summary of remote sensing data sources for lake surface temperature inversion is presented.

2.1 Landsat TM data

The Landsat series of satellites is a tool that provides rich thermal infrared data for inversion studies of lake water surface temperatures [9-10]. Research on lake surface temperature measurements using Landsat-5 TM thermal infrared images has progressed since 1996. Subsequently, Matheus Henrique Tavares introduced the Landsat-7 ETM+ and MODIS sensors, which provide more options and higher accuracy for inversion of lake water surface temperatures, in particular the MOD11 LST and MOD28 SST products, which have been shown to provide high accuracy in certain cases [11-12].

With the development of machine learning methods, K. Dyba, S. Ermida [13] let Some new algorithms such as Random Forest (RF) models are used for inversion of lake water surface temperature. These methods show high efficiency and accuracy when dealing with large-scale datasets. For example, using Landsat 8 data, the RF method applied on 28 lakes in Poland showed a low root mean square error (RMSE = 1.83°C) compared to the RMSE of 3.68°C for the LST-L2 method.

In addition, for specific regions or specific types of lakes, Chen Qiang, Wang Wei, Zhang Zhen et al. [14] researchers also explored different inversion methods. For example, in the case of Lake Taihu, the SW2 algorithm was found to provide the best inversion results with absolute errors ranging from 0.1 to 1.4 K. This suggests that different algorithms may be applicable to different types of lakes, and therefore lake-specific characteristics need to be considered when selecting an inversion method.

In recent years, the Enhanced Single Channel Algorithm (SCen) has become the latest Landsat TM data in inversion of lake water surface temperature. Mengmeng Wang; Zhao-ming Zhang et al. [15] shown that SCen, an improved single-channel algorithm for Landsat series data (from Landsat 4 to Landsat 8), improves the retrieval accuracy of LST (Land Surface Temperature) by introducing three Atmospheric Functions (AFs) and taking into account the latitude and month of acquisition of the Landsat images. The validation of the algorithm on simulated and field data shows a root mean square error (RMSD) of 1.363 K and 1.04 K, respectively, which exhibits high operability and accuracy.

2.2 NOAA/AVHRR data

Since the 1980s, NOAA/AVHRR has been used to monitor temperature changes at the Earth's surface, including lake surface water temperatures (LSWT), which are critical for assessing aquatic ecosystems and studying the response of lakes to climate change [16].

Currently, methods and techniques for lake water surface temperature inversion for NOAA/AVHRR data include the use of Random Forest (RF) models and Linear Regression (LM) models. These methods use Landsat 8 satellite imagery to estimate lake water surface temperatures and verify their accuracy by comparing them to actual measurements.

In recent years, Derek K. Gray, S. Hampton et al. [17] use data from 28 lakes were analysed the Random Forest Model and the results showed that the method has high accuracy. Its Root Mean Square Error (RMSE) was 1.83°C and Coefficient of Determination (R^2) was 0.89, indicating that the Random Forest Model is effective in predicting the surface water temperature of lakes with high reliability. In addition, the study found systematic errors in the Landsat Level-2 Surface Temperature Science Product (LST-L2) data, especially in the coastal region, but such errors can be corrected to improve the quality of the estimates.

In addition, K. Kumari and M. Mrunalini [18] use a linear regression model to estimate lake surface water temperature, although it was slightly less accurate than the random forest model. Its root mean square error was 3.68°C and the coefficient of determination was 0.8. This suggests that although the linear regression model may not be as accurate as the random forest model in some cases, it is still an effective tool. These studies provide important references and lessons for lake

water temperature monitoring and prediction, and contribute to a better understanding and management of lake ecosystems.

2.3 EOS MODIS data

MODIS is a satellite remote sensing sensor with a broad spectrum covering a wide range and multiple bands, capable of capturing information on different surface features and possessing many advantages, such as high resolution, high temporal resolution, multi-channel observation and free reception, which makes it widely applicable and valuable in the field of remote sensing applications. Therefore, MODIS can be used to invert sea surface temperature (SST) and land surface temperature (LST).

Vitor S. Martins, Alexei Lyapustin, Yujie Wang et al [13] analysing the radiometric information from EOS MODIS data and combining it with measured data from surface temperature observation sites, a series of lake water surface temperature inversion algorithms have been developed for estimating lake water surface temperatures and further analysing the changes in water surface temperatures. In addition, Hongxiao Jin et al [14] used EOS MODIS data to analyse remote sensing data in different time periods to reveal the interannual and seasonal patterns of change in lake water surface temperatures, which helps to understand the long-term trends and seasonal changes in lake water temperatures, and provides an important reference for lake management and protection. In addition, EOS MODIS data can be used for environmental monitoring of lake water bodies, such as obtaining chlorophyll concentration, dissolved oxygen and other related data. By analysing these data, S. V. Afonin [15] explored the relationship between lake water surface temperature and climate change and predicted future trends, and these studies provide more scientific evidence and predictions about the dynamics of lake ecosystems.

3. Remote sensing inversion method for surface temperature

Surface temperature is one of the important meteorological parameters of water bodies, such as oceans and lakes, and is of great significance for understanding the thermodynamic properties of water bodies, environmental changes and ecosystems. And the surface temperature inversion and monitoring techniques are dominated by remote sensing. In this section, the remote sensing inversion methods for water surface temperature will be summarised, and the commonly used algorithms and techniques for remote sensing data, as well as the problems and challenges, are presented.

3.1 Single window algorithm

The transmission of thermal radiation in the atmosphere can be described by the thermal radiation transport equation, based on which Qin et al [16] the basic principle of the single window algorithm is to obtain the surface temperature by selecting the appropriate thermal band. The thermal radiative transfer equation describes the relationship between radiant energy and temperature at the surface of a feature [17-20]. Among the single-window algorithms, Hu, D. Y. et al [21] based on Landsat 8 TRS band 10 (TIRS10), worked out the algorithm that can analyse the inversion process in terms of its accuracy in relation to the sensitivity of key parameters such as atmospheric and surface emissivities, i.e., the TIRS10 single-window algorithm (TIRS10_SC). In addition, they used the algorithm to analyse the spatial and temporal distribution characteristics of imperviousness and surface temperature in Xining area, and their findings are of great significance for understanding the urban thermal environment and formulating corresponding policies.

3.2 Splitting window algorithm

In order to accurately obtain information about features, scientists need to be able to eliminate atmospheric interference with remotely sensed data. The split window algorithm is one method that has been widely used in this regard. The basic principle of this algorithm is that there are two

neighbouring channels within the atmospheric window of 10-13 μm that have similar spectral bandwidths but different atmospheric absorption effects. Based on this, the atmospheric absorption of radiation can be inferred by comparing the differences in the measurements of these two channels. Wen Yafei et al [22] on the other hand, combined this algorithm with the TIRS10_SC algorithm to optimise the Landsat 9 data and invert the surface temperature. In addition, they further verified that the accuracy of the split-window algorithm model is relatively high with a low value of error (RMSE) and the TIRS10_SC algorithm has an even lower value of accuracy by using the measured data from the SURFRAD site. The results show that the split-window algorithm model is less sensitive to parameters compared to the single-window algorithm model.

3.3 Multichannel algorithm

Traditional single-channel algorithms use data from only one thermal infrared channel to estimate surface temperature, but they are susceptible to errors due to the complexity of surface properties and atmospheric effects. However, the multi-channel algorithm can simultaneously invert the surface temperature and specific emissivity using data from multiple thermal infrared channels. This means that it can provide information not only on surface temperature but also on specific radiance. In the past research, Peng Jida, Ma Zhiguo et al [23] chose the offshore of Fujian as the study area and used MODIS remote sensing data for the inversion of offshore surface temperature (SST), which obtained more stable and accurate data for the algorithm. However, the multi-channel algorithm also faces some challenges and problems. First, the algorithm needs to establish multiple equations to calculate SST, which increases the computational complexity [24-25]. In order to accurately invert the SST, several factors need to be considered, such as atmospheric correction, water vapour content, cloud cover, etc., which makes the algorithm relatively complex to design and implement. Secondly, it is difficult to obtain ground truth data during satellite transit, which has an impact on the accuracy of the assessment algorithm. Due to the scarcity of measured data, it is difficult to obtain ground-based measured data matching the time and space of the satellite transit, thus limiting the accurate assessment of the algorithm's accuracy. Therefore, the evaluation of the accuracy of the algorithm will be the focus of future research. The accuracy assessment of the multichannel algorithm can be further improved by collecting more measured data and comparing and verifying them with satellite data.

4. Research Outlook

The remote sensing quantitative inversion of surface temperature in lakes and reservoirs is a complex and important research field. By using remote sensing technology to obtain large-scale and high-resolution temperature data, it can provide important references for water resource management and ecological environmental protection of lakes and reservoirs. To this end, three outlooks are proposed:

Current inversion methods often rely on specific sensor data and algorithmic models, limiting their applicability and accuracy. Therefore, there is a need to develop more versatile and accurate inversion methods that can be adapted to different types of lakes and reservoirs and improve the reliability of inversion results.

Existing inversion methods have limitations in dealing with atmospheric disturbances and other errors. The effects of atmospheric disturbances on the observed data may lead to bias in the inversion results. Therefore, further improvements in atmospheric correction and pre-processing techniques are needed to reduce these disturbances and improve the accuracy of the inversion results.

Current research has focused on surface temperature inversion in lake waters, with relatively little research on deep temperatures. However, deep temperature changes in lakes and reservoirs have an important impact on the ecological environment and water quality. Therefore, we need to

explore the methods and techniques for deep temperature inversion to gain a more comprehensive understanding of the temperature dynamics of lakes and reservoirs.

Future research can also combine other remote sensing data and ground observation data for multi-source data fusion to improve the accuracy and reliability of the inversion results. At the same time, the inversion results can be compared and verified with model simulation data to further enhance the accuracy and application value of the inversion method.

Reference

- [1] Wang Xingshun. Progress of lake eutrophication management and EM technology[J]. *Leather Making and Environmental Protection Technology*,2023,4(20):39-41.
- [2] SING Tong, LI Hui, LI Yunling. Evolution of landscape pattern and driving factors in Liangzi Lake Basin[J]. *South-to-North Water Diversion and Water Science and Technology (in English)*,2023,21(5):951-961..
- [3] He Huacheng. Study on remote sensing inversion of surface temperature change in Liuzhou city based on Landsat-8[J]. *Science and Technology Innovation and Use*,2023,13(34):100-104.
- [4] WAN Fang,YANG Lulu,ZHOU Zu'an. Radiation outgoing degree of a blackbody at Planck length[J]. *Journal of Hunan Institute of Science and Technology*,2022,43(3):5-7.
- [5] Cui Yan, Li Desian, Zhou Ye, et al. Influence of ice clouds on the polarisation pattern of the sky[J]. *Journal of Photonics*,2023,52(11):318-329.
- [6] NIE Q,SHI K,GONG Y,et al.Spatial-temporal variability of land surface temperature spatial pattern:Multifractal detrended fluctuation analysis[J].*IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*,2020,13:2010-2018.
- [7] HU J,YANG Y,PAN X,et al.Analysis of the spatial and temporal variations of land surface temperature based on local climate zones:A case study in Nanjing,China[J].*IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*,2019,12(11):4213-4223.
- [8] SARAFANOV M,KAZAKOV E,NIKITIN N O,et al.A machine learning approach for remote sensing data gap-filling with open-source implementation:An example regarding land surface temperature,surface albedo and NDVI[J].*Remote Sensing*,2020,12(23):3865.
- [9] YIN Z,LI J,LIU Y,et al.Water clarity changes in Lake Taihu over 36 years based on Landsat TM and OLI observations[J] *International Journal of Applied Earth Observation and Geoinformation*,2021,102:102457.
- [10] HENITS L,JÜRGENS C,MUCSI L.Seasonal multitemporal land-cover classification and change detection analysis of Bochum,Germany,using multitemporal Landsat TM data[J].*International Journal of Remote Sensing*,2016,37(15):3439-3454.
- [11] LI S,SUN D,YU Y,et al.A new short-wave infrared(SWIR)method for quantitative water fraction derivation and evaluation with EOS/MODIS and Landsat/TM data[J].*IEEE Transactions on Geoscience and Remote Sensing*,2012,51(3):1852-1862.
- [12] CHEN Y,QU L,LI Z,et al.Retrieval of Sea Surface Skin Temperature from the High Resolution Picture Transmission Data of the National Oceanic and Atmospheric Administration Series Satellites[J].*Remote Sensing*,2023,15(15):3723.
- [13] K. Dyba, S. Ermida et al. “Evaluation of Methods for Estimating Lake Surface Water Temperature Using Landsat 8.” *Remote Sensing* (2022). 3839.
- [14] Chen Qiang, Wang W, Zhang Z et al. Comparison of Landsat 8 water surface temperature inversion algorithms based on measured values--Take Taihu Lake as an example[J]. *Science, Technology and Engineering*,2020,20(32):13317-13326.
- [15] Matheus Henrique Tavares, A. Cunha et al. “Comparison of Methods to Estimate Lake-Surface-Water Temperature Using Landsat 7 ETM+ and MODIS Imagery: Case Study of a Large Shallow Subtropical Lake in Southern Brazil.” *Water* (2019).
- [16] G. Lieberherr and S. Wunderle. “Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes.” *Remote Sensing* (2018). 990.

- [17] Derek K. Gray, S. Hampton et al. “How do data collection and processing methods impact the accuracy of long - term trend estimation in lake surface - water temperatures?.” *Limnology and Oceanography: Methods* (2018).
- [18] K. Kumari and M. Mrunalini. “A SURVEY ON BIG DATA PROCESSING: TECHNIQUES, ISSUES AND CHALLENGES.” (2018). 540-569.
- [19] TAN Guirong, CAI Zhe, XU Yongming. Heat island effect in Nanjing based on Landsat images[J]. *Anhui Agricultural Science*,2009,37(13):6050-6052+6066.
- [20] SOBRINO J A,JIMÉNEZ-MUÑOZ J C,PAOLINI L.Land surface temperature retrieval from LANDSAT TM 5[J].*Remote Sensing of environment*,2004,90(4):434-440.
- [21] HU De-Yong, QIAO Kun, WANG Xing-Ling, et al. Single window algorithm combined with Landsat8 thermal infrared data for inversion of surface temperature[J]. *Journal of Remote Sensing*,2015,19(6):964-976.
- [22] WEN Yafei, LIU Yu, WANG Guanghui, et al. Optimisation of surface temperature inversion algorithm for Landsat 9 data[J]. *Optimisation of surface temperature inversion algorithm for Landsat 9 data*[J]..
- [23] PENG Jida, MA Zhiguo, ZHANG Chungui, et al. Study on the ecological quality change of Pingtan Island based on RSEI model[J]. *Strait Science*,2023,(5):3-7.
- [24] MARKOVIĆ M,CHEEMA J,TEOFILOVIĆ A,et al.Monitoring of Spatiotemporal Change of Green Spaces in Relation to the Land Surface Temperature: A Case Study of Belgrade, Serbia[J].*Remote Sensing*,2021,13(19):3846.
- [25] MOSER G,DE MARTINO M,SERPICO S B.Estimation of air surface temperature from remote sensing images and pixelwise modeling of the estimation uncertainty through support vector machines[J].*IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*,2015,8(1):332-349.