Changes in Near-Surface Freezing State in the Source Region of the Yellow River and Its Impact on Runoff (Postprint)

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Abstract

Based on the 0–40 cm soil temperature data in the Source Region of the Yellow River (SRYR) from 1982 to 2020, this study analyzes the variation characteristics of near-surface soil temperature and soil freezing status. Combined with meteorological and vegetation datasets, random forest and SHAP (Shapley Additive Explanations) methods were employed to analyze the impact of changes in near-surface soil freezing status on runoff.

The results indicate that the annual runoff in the SRYR underwent a significant transition in 2002, shifting from a significant decrease in the early period to a significant increase in the later period. During the same period, the soil warming patterns at 0–40 cm depth underwent certain transitions in the vertical direction, seasonal scale, and spatial pattern, manifested as a significant reduction in the area of stratified soil freezing and a marked shallowing of the freezing depth in winter.

Based on random forest and SHAP analysis, it was found that the response of runoff to changes in stratified soil freezing status exhibits distinct non-linear characteristics. Among the factors characterizing the stratified soil freezing status, runoff from 1982 to 2002 was primarily influenced by the freezing areas at 0 cm and 10 cm depths, with relative influence proportions of 8.3% and 7.2%, respectively; whereas from 2002 to 2020, the primary factors were the freezing areas at 0 cm and 40 cm depths, with relative influence proportions of 10.6% and 8.4%, respectively. Furthermore, the interannual fluctuations of runoff are sensitive to the interannual fluctuations of the soil freezing status at 0–10 cm depth. This study reveals the changes in near-surface soil temperature and the resulting changes in freezing status in the SRYR under the context of climate warming, as well as their impacts on runoff, providing a basis for the study of hydrological processes in cold regions.

Full Text

Changes in Near-Surface Freezing Status and Their Impact on Runoff in the Source Region of the Yellow River

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Abstract

The Source Region of the Yellow River (SRYR) is a critical water conservation area in China, characterized by extensive permafrost and seasonally frozen ground. Based on soil temperature data from 0 to 40 cm in the SRYR from 1982 to 2020, this study analyzes the variations in near-surface soil temperature and soil freezing states. The results indicate that the soil temperature in the SRYR has exhibited a significant upward trend over the past four decades. This warming trend is consistent across different depths, although the magnitude of temperature increase varies spatially and vertically. Furthermore, the duration of the soil freezing period has shortened, characterized by a delayed start of the freezing process and an earlier onset of the thawing period.

Using Random Forest and SHAP (SHapley Additive exPlanations) methods, this study analyzes the impact of these changes on runoff. The results indicate that annual runoff in the SRYR underwent a significant shift in 2002, transitioning from a period of significant decline to a subsequent period of significant increase. During the same period, the warming patterns of the 0–40 cm soil layer underwent significant shifts across vertical dimensions, seasonal scales, and spatial distributions. The response of runoff to changes in the stratified soil freezing state exhibits distinct non-linear characteristics. From 1982 to 2002, runoff was primarily influenced by the frozen area at depths of 0 cm and 10 cm, with relative impacts of 8.3% and 7.2%, respectively. From 2002 to 2020, the primary driving factors shifted to the frozen area at depths of 0 cm and 40 cm, with relative impact proportions of 10.6% and 8.4%, respectively. This research provides a scientific basis for water resource management and ecological protection in the Yellow River basin under a changing climate.

1 Introduction

The Source Region of the Yellow River (SRYR), located in the northeastern part of the Qinghai-Tibet Plateau, is a critical region for water conservation and is highly sensitive to climate change. As the "Water Tower of China," it contributes significantly to the total runoff of the Yellow River basin, accounting for approximately 38% of the total annual average runoff. The region is characterized by high altitude and the widespread presence of permafrost and seasonally frozen ground. The freezing and thawing of the near-surface soil act as a "valve" that regulates the exchange of water and energy between the land surface and the atmosphere.

In recent years, global warming has accelerated the degradation of permafrost and seasonally frozen ground in the SRYR. According to the IPCC Sixth Assessment Report (AR6), global surface temperature was 1.09°C higher in the decade 2011–2020 than in 1850–1900. This warming trend directly influences the variations in near-surface soil temperature, which in turn significantly alters soil permeability and moisture storage capacity. Understanding the long-term spatiotemporal characteristics of soil temperature and the transition of freezing states is essential for predicting future water resource availability and assessing ecological risks.

2 Data and Methods

2.1 Data Sources

The primary data used in this study consist of soil temperature measurements at depths of 0 cm, 5 cm, 10 cm, 15 cm, 20 cm, and 40 cm, covering the period from 1982 to 2020. These data were obtained from the National Meteorological Science Data Center and validated for the SRYR ($R^2 = 0.94$, $RMSE = 1.89$). Runoff data consist of natural monthly runoff volumes restored from the Tangnaihai hydrological station, provided by the Hydrological Bureau of the Yellow River Conservancy Commission. Additional datasets include: - **Meteorological Data:** Precipitation and air temperature generated via thin-plate spline interpolation. - **Evapotranspiration:** Sourced from the Global Land Evaporation Amsterdam Model (GLEAM). - **Vegetation Index:** GIMMS NDVI (3G+, version 1.2) at 0.0833° resolution.

2.2 Analysis Methods

2.2.1 Random Forest (RF) Random Forest is an ensemble statistical learning theory that utilizes bootstrap sampling to generate multiple training sets to train individual decision trees [**?**]. It is highly effective for solving complex nonlinear problems and is resistant to overfitting. In this study, the RF model was used to construct a runoff regression model using 10 input variables, including frozen area at various depths, precipitation, temperature, and NDVI .

2.2.2 SHAP Interpretability Analysis To address the "black box" nature of machine learning, we employ SHAP (SHapley Additive exPlanations) based on cooperative game theory [**?**]. SHAP assigns an importance value to each

Figure 2

Figure 1: Figure 2

feature by calculating its marginal contribution:

$$\phi_i = \sum_{S \subseteq F \setminus \{i\}} \frac{|S|!(p - |S| - 1)!}{p!} [f_{S \cup \{i\}}(x_{S \cup \{i\}}) - f_S(x_S)]$$

This allows for a quantitative assessment of how variations in soil freezing depth and duration influence runoff.

2.2.3 Time-Lag Analysis To account for the "memory" of hydrological systems, runoff sequences were lagged by 0 to 3 months. Pearson correlation analysis at a 99% confidence level was used to identify the optimal response time of runoff to environmental factors.

3 Results and Analysis

3.1 Spatiotemporal Variation of Hydrometeorological Factors

From 1982 to 2020, soil temperature in the SRYR warmed at a rate of approximately $0.4^{\circ}\mathrm{C} \cdot (10\mathrm{a})^{-1}$. Before 2002, warming was concentrated in spring and summer; after 2002, intense warming shifted to autumn and winter, with 65.5% of the region exceeding a warming rate of $1^{\circ}\mathrm{C} \cdot (10\mathrm{a})^{-1}$ in winter.

Runoff at the Tangnaihai station reached a minimum in 2002. From 1982 to 2002, annual runoff declined at a rate of $6.11 \times 10^8\ \mathrm{m}^3 \cdot \mathrm{a}^{-1}$. From 2002 to 2020, it increased significantly at a rate of $6.02 \times 10^8\ \mathrm{m}^3 \cdot \mathrm{a}^{-1}$

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3.2 Soil Freezing State Changes

The frozen area at depths of 0–40 cm showed a significant decreasing trend. The rate of reduction was most pronounced at the 0 cm depth ($-297.9\ \mathrm{km}^2 \cdot \mathrm{a}^{-1}$). At 40 cm, the reduction intensified during the later stage (2002–2020), particularly in autumn and winter. The winter soil freezing depth in the SRYR has shown a clear shallowing trend [FIGURE:4].

3.3 Impact of Soil Freezing Status on Runoff

The SHAP analysis reveals that the stratified freezing state of the soil significantly influences runoff processes, though the primary drivers shifted over time. - **1982–2002:** Runoff was most sensitive to the frozen area at 0 cm and 10 cm. A larger frozen area generally exerted a negative impact on runoff by obstructing infiltration. - **2002–2020:** The primary drivers shifted to the 0 cm and 40 cm depths. The relative importance of the 40 cm frozen area increased to 8.4%.

Figure 1

Figure 2: Figure 1

The analysis indicates a threshold effect: when the frozen area is small (representing a thawed state), it contributes positively to runoff generation. As the frozen area increases, it acts as an impermeable barrier, eventually reducing the total runoff volume.

4 Discussion and Conclusion

The study reveals that under climate warming, the near-surface soil in the Source Region of the Yellow River is warming rapidly, leading to a significant reduction in the frozen area and a shortening of the freezing period. These cryospheric changes have fundamentally altered the regional hydrological regime. The shift in runoff trends around 2002 coincides with a shift in the seasonal patterns of soil warming.

The integration of Random Forest and SHAP provides a robust framework for quantifying these non-linear interactions. The findings suggest that as the soil freezing depth continues to shallow, the basin' s storage and regulation capacity will change, potentially increasing winter baseflow while altering the timing of spring freshets. This research provides a scientific foundation for predicting future water resource availability and developing ecological protection strategies in the high-altitude cold regions of the Yellow River basin.

Figures

Source: ChinaXiv —Machine translation. Verify with original.