Li et al. present an interesting study that employs deep learning models to predict groundwater levels during freezing and thawing periods, as well as to classify the underlying dynamic drivers. The paper is mostly well-written. Still, considerable issues require significant revision to make the paper clearer. The most important ones are related to the current structure; the results and discussion are in the same chapter, which is recommended for modification. The authors are encouraged to include a separate discussion section to discuss the main groundwater level types and the most significant implications from these different types. Second, some issues should be more precisely defined in the method. Finally, the authors should consider to present the conclusion in a more structured and clear way.

Response: We sincerely thank you for your recognition of our work and for your valuable comments. We have carefully studied your suggestions and made corresponding revisions to the manuscript. Regarding your comment about merging the "Results" and "Discussion" sections, we would like to clarify that in our study, the LSTM-based simulation results are closely integrated with the explanation provided by the Expected Gradients (EG) method. The two components are interdependent and difficult to present completely separately; thus, we initially adopted a combined section format to maintain content coherence and logical consistency. That said, we fully understand that a standalone "Discussion" section facilitates a deeper interpretation of the scientific significance. In response, we have added more discussion content in the relevant part of the manuscript, enhancing the analysis of the major groundwater level dynamics and their critical implications by incorporating insights from previous studies. These additions aim to improve the depth and academic value of the paper. Additionally, in response to your comment about the inaccuracy in the methodology section, we have thoroughly reviewed and revised the relevant descriptions to ensure greater precision and scientific rigor. For the conclusion section, we have also optimized its structure following your suggestion, making the summary clearer, more organized, and better aligned with the key findings and contributions of our study. Once again, we sincerely thank you for your detailed comments and insightful suggestions, which have significantly contributed to improving the quality of this manuscript. We look forward to your further guidance.

General comments:

1. Abstract:

It would be worth rephrasing to make the message clear and better reflect the key findings and the value of this study.

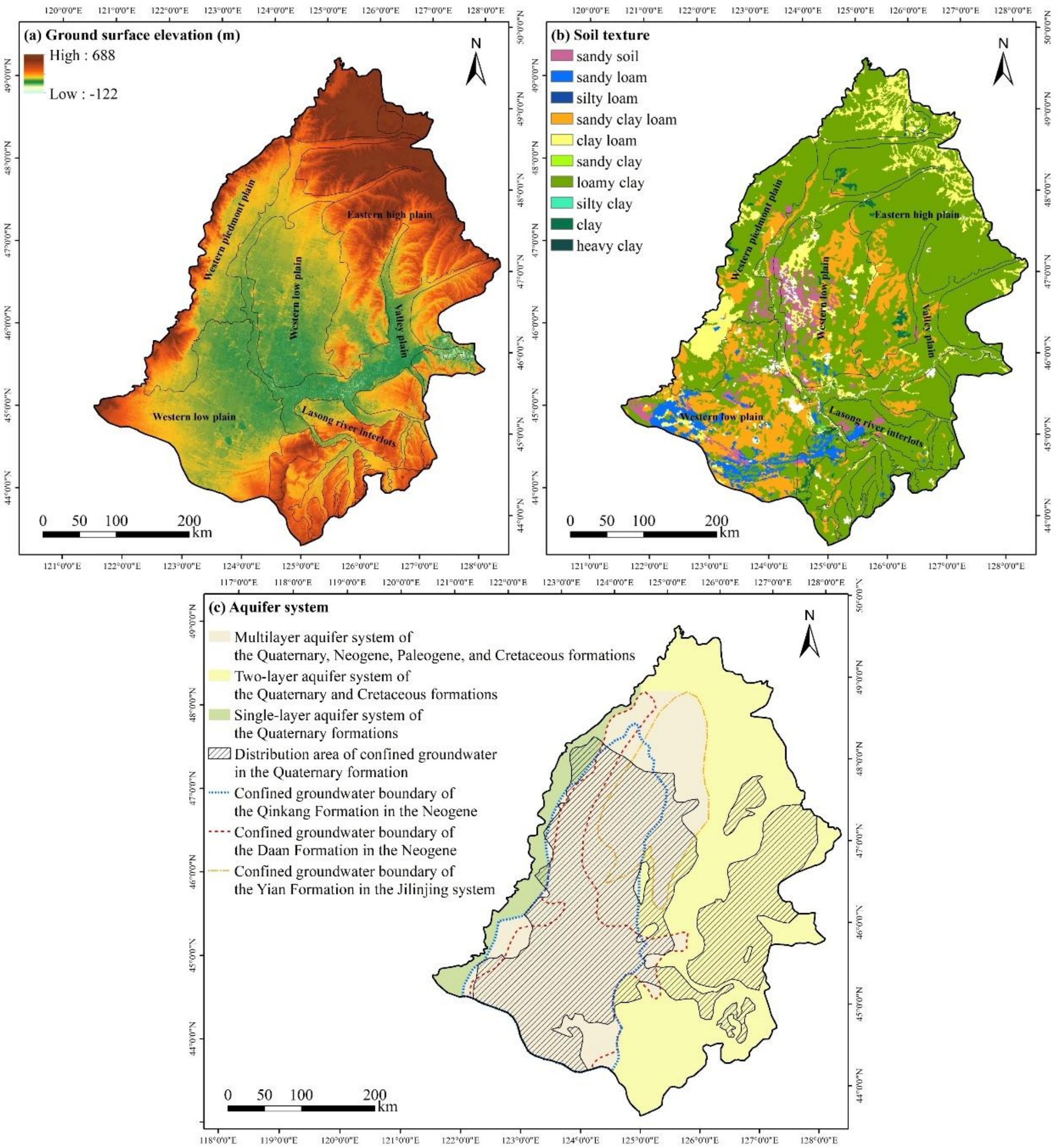
Response: We sincerely thank the reviewer for the valuable comments on the abstract. We have revised the abstract accordingly. The revised version is as follows:

"Accurately characterizing groundwater level dynamics in seasonal frozen soil regions is of great significance for water resource management and ecosystem protection in cold areas. Taking the Songnen Plain in China as the study area, this paper constructs a Long Short-Term Memory (LSTM) model to simulate daily groundwater levels for 138 monitoring wells. The Expected Gradients (EG) method is introduced to interpret the model results, thereby identifying the dominant factors and underlying mechanisms of different groundwater level variation types. The results show that the LSTM model performs well on the test set, with the Nash-Sutcliffe Efficiency (NSE) exceeding 0.7 at 81.88% of the monitoring sites, effectively capturing the temporal dynamics of groundwater levels. At the annual scale, three typical groundwater level variation types are identified: precipitation infiltration–evaporation type (29.0%), precipitation infiltration–runoff type (18.1%), and extraction type (52.9%). The first two types are mainly controlled by natural processes, with water level variations depending on climatic conditions, while the extraction type is significantly influenced by human activities, characterized by frequent water level fluctuations. During the frozen-thaw period, groundwater level dynamics can be classified into three major types: "V"-shaped variation (decline during freezing, rise during thawing, accounting for 38.4%), continuous decline (23.2%), and continuous rise (38.4%). EG analysis indicates that the "V"-shaped dynamics are mainly governed by climatic factors such as air temperature, precipitation, and snow thickness, clearly reflecting the dominant role of the frozen-thaw process. Further analysis reveals that when the initial groundwater level depth at the start of the freezing period is shallower than the sum of the “frozen-thaw influence depth plus capillary rise height,” a hydraulic connection is established between the frozen soil layer and the aquifer, enabling frequent conversion between soil water and groundwater and resulting in the characteristic “V”-shaped fluctuation. Conversely, when the groundwater level depth exceeds this critical threshold, the frozen-thaw process has limited influence on the aquifer. Groundwater level variations are then mainly driven by groundwater extraction or the recovery process following prior recharge from precipitation, exhibiting continuous decline or continuous rise, respectively. This study establishes an integrated framework of “simulation–classification–interpretation,” which not only improves the accuracy of groundwater level dynamic simulation and prediction but also provides new methods and perspectives for revealing the underlying mechanisms. The findings offer theoretical support and technical basis for regional groundwater resource management, regulation strategy optimization, and climate change response assessment in cold regions.”

2. Method:

a) Figure 2 What do the solid circles in Fig. 2(a) represent? Additional description on these labels should be added to the figure caption. Since some similar information is presented in panels (a), (b), and (c), consider merging some of them.

Response: We thank the reviewer for the comment. Regarding the solid circles in Figure 2(a), we have confirmed that this marker was mistakenly added during the typesetting process and has been removed in the revised version. In addition, in response to the suggestion concerning the redundancy of certain information across the subplots in Figure 2(a), (b), and (c), we have merged and adjusted the figure contents accordingly. The revised figure is shown below:



Spatial distribution of the ground surface elevation (a), topography (b) and aquifer system (c) in the Songnen Plain, China.

b) Lines 147-149 How do you determine the exact timing of the beginning and end of the freezing period for each well? A precise definition of the freezing period should be provided, similar to the one you gave for the 'Beginning of winter' in Lines 194-198.

Response: Thank you very much for your comments. Based on meteorological data from 2018 to 2021 and relevant studies (Lyu et al., 2023), we found that after the "Beginning of Winter" solar term (around November 7–8), air temperatures steadily declined and a thin ice layer began to form on the ground surface. Following the "Rain

Water" solar term (around February 18–20), temperatures began to rise, and the frozen soil started to gradually thaw. By the "Grain Rain" solar term (around April 19–21), most areas in the study region had experienced complete thawing of the frozen soil. Accordingly, we defined a uniform freezing and thawing period for all monitoring wells in the study area. Specifically, the freezing period is defined as the time span from "Beginning of Winter" to "Rain Water", and the thawing period is from "Rain Water" to "Grain Rain" each year. We will provide additional clarification in the manuscript regarding the start and end times of the freezing and thawing periods.

c) Lines 167-169 Please detail the method to estimate the groundwater extraction volume. Given that the groundwater extraction volume is a key component of the proposed mechanism, its estimation accuracy may have an impact on the results. Also, the well depth and screened interval of the monitoring wells might also influence the response rate of the observed groundwater levels, but this aspect does not appear to be addressed in the paper.

Response: Thank you very much for your comments. In the Songnen Plain, approximately 70% of groundwater extraction is used for agricultural irrigation; therefore, in this study, groundwater extraction was approximated based on crop water deficits. Using spatial distribution data of the region's major crops, ten-day period crop water requirements, and precipitation data, we estimated groundwater extraction at a fine resolution, ultimately generating ten-day period groundwater extraction data with a spatial resolution of 25 km × 25 km. Specifically, based on the water requirements of the main crops (rice, soybean, and maize), we calculated the total crop water demand for each ten-day period within each grid cell. These values were then weighted according to the crop planting area to obtain the total water demand per grid. By comparing precipitation with crop water demand, we determined whether precipitation could meet the crop water needs. When precipitation was sufficient, crops relied entirely on natural rainfall, and the effective precipitation equaled the water demand. When precipitation was insufficient, effective precipitation was limited by actual rainfall, and the remaining crop water deficit was assumed to be supplemented by other water sources. Finally, the difference between crop water demand and effective precipitation was calculated as the crop water deficit, which was assumed to be primarily supplied by groundwater. This allowed us to approximate ten-day period groundwater extraction. To ensure consistency with the temporal resolution of other variables used for model training, the ten-day period data were converted to daily averages by dividing by the number of days in each period. We will provide additional clarification in the manuscript regarding the method used to estimate groundwater extraction.

We fully acknowledge that the depth of monitoring wells and the distribution of screened intervals may affect the groundwater level response. However, due to limited data availability, we were unable to obtain relevant structural parameters for all wells and thus could not conduct a detailed analysis in this study. In future work, we will further explore the impact of these factors when sufficient data become available.

3. Result and discussion:

a) Lines 313-314 This statement is unclear or lacks significance. Could you provide a quantitative indicator to support it?

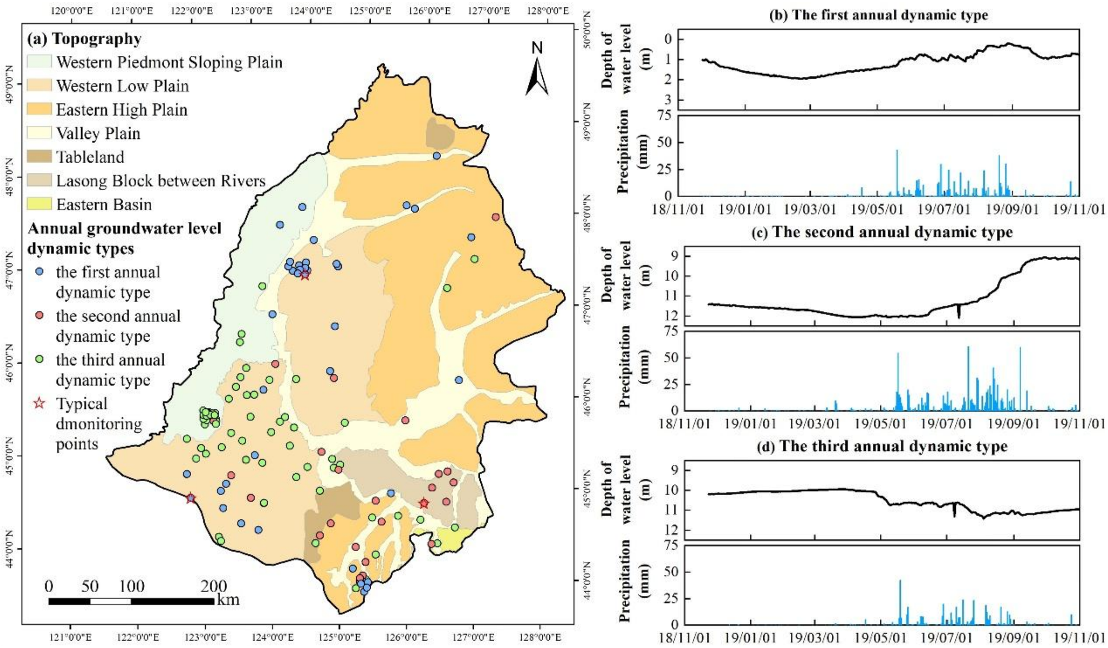
Response: We thank the reviewer for the comment. As suggested, we have revised the sentence accordingly. The updated version is as follows:

“The LSTM model is capable of accurately capturing the variation trend of groundwater levels, and no significant lag is observed between the simulated and observed values (Figure 4). The Pearson correlation coefficients at the four representative monitoring wells shown in the figure are 0.86, 0.81, 0.87, and 0.85, respectively. Moreover, the correlation coefficients reach their maximum values without applying any time lag, indicating that the simulated values can effectively and promptly reflect the actual variation trend of groundwater levels.”

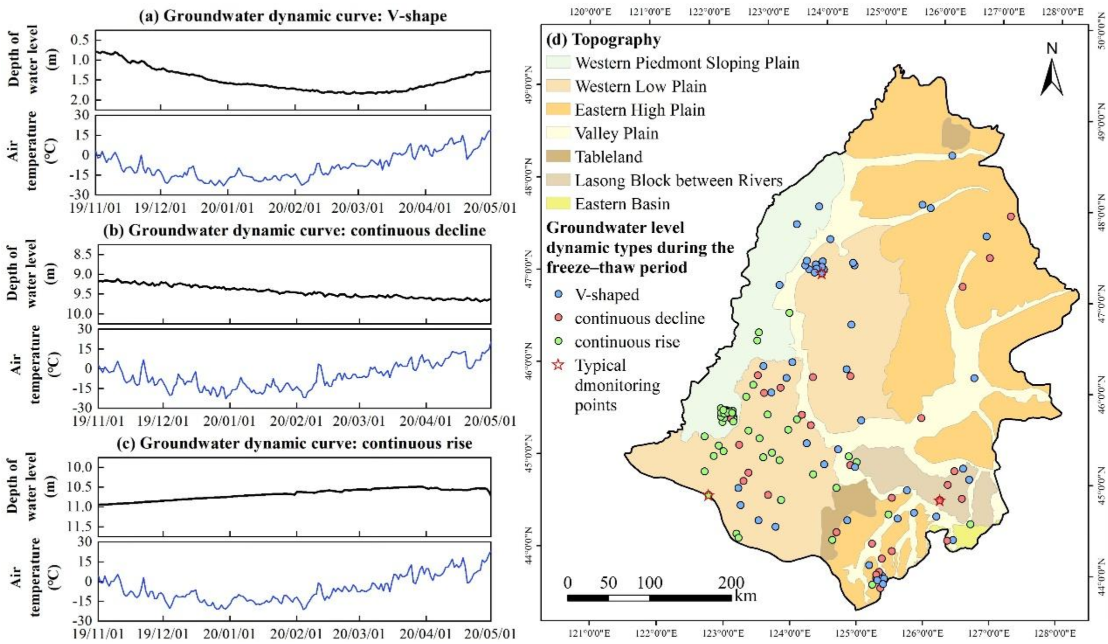
b) Lines 359 The authors are strongly recommended to label the three monitoring wells representing the three types of groundwater level dynamics (panels b, c, and d) in

Figure 5a. The well numbers mentioned here are not very informative since the locations of the wells are not indicated. There are similar cases later on as well.

Response: We thank the reviewer for the suggestion. We have marked the locations of the three representative monitoring wells in Figure 5a. In addition, the locations of the representative wells have also been added to Figure 6. The revised figures are as follows:



(a) Spatial distribution of different annual groundwater level dynamic types in the Songnen Plain, China; (b–d) Dynamic curves of different annual groundwater types and their corresponding precipitation variations. (b) The first annual dynamic type is represented by an unconfined aquifer monitoring well, numbered 230204210070, located in the western low plain; (c) The second annual dynamic type is represented by an unconfined aquifer monitoring well, numbered 220182210411, located in the Lasong Block between rivers; (d) The third annual dynamic type is represented by an unconfined aquifer monitoring well, numbered 220802210145, located in the western piedmont sloping plain.



(a–c) Dynamic curves of different groundwater types during the freeze–thaw period and corresponding changes in air temperature; (d) Spatial distribution of different groundwater level dynamic types during the freeze–thaw period in the Songnen Plain, China. The dynamic curves of the groundwater level exhibiting patterns of (a) V-shaped, (b) continuous decline, and (c) continuous rise correspond to the unconfined aquifer monitoring wells numbered 230204210070, 220182210411, and 220802210145, respectively.

c) Lines 388-395 I am not sure I fully understand the authors' meaning here. They state that continuous groundwater level decline mostly occurs in areas with deep groundwater level, but actually, the groundwater depth is greater in areas where the groundwater level shows a continuous rise. Moreover, I think some of the mechanism for the "continuous rising" type should be discussed further, that could enhance the implication of this study.

Response: We sincerely thank the reviewer for the constructive suggestion. The original statement that "sustained declines in groundwater levels mostly occur in areas with greater groundwater depths" could indeed be misleading, as some areas with sustained rising trends actually have even deeper groundwater levels. We have revised and rephrased this section The revised content is as follows:

“Monitoring points with the continuous decline in the groundwater level were mainly distributed in areas, such as the eastern high plain and the Lasong Block between rivers, where the groundwater level depth ranged from 4.52 to 11.51 m at the start of the freezing period (Fig. 6d).”

In addition, we have further discussed the mechanism underlying the formation of the “sustained rising” groundwater level trend. The revised content is as follows:

“Groundwater monitoring points exhibiting the precipitation infiltration-runoff type were mainly distributed in the eastern high plain and the Lasong Block between rivers. In these areas, the groundwater level is deeper, typically ranging from 5 to 12 m (Fig. 11b), and runoff is the primary mode of groundwater discharge. The deeper groundwater level prolongs the infiltration time of precipitation, resulting in a delayed response of the groundwater level dynamics to precipitation recharge. Groundwater level peaks typically occur between August and October (Fig. 11d), lagging behind the precipitation peak by approximately one month (Fig. 11f). Due to the low recharge rate, groundwater level fluctuations are relatively moderate, with annual variations generally within 4 m (Fig. 11c). During the freeze–thaw period, groundwater monitoring points with continuously declining trends have greater initial groundwater level depths, ranging from 4.52 to 11.51 m at the beginning of the freezing period (Fig. 12d). This pattern is primarily attributed to the sharp reduction in groundwater extraction following the end of the irrigation season. As agricultural activities cease, the regional groundwater system gradually enters a recovery phase, during which the groundwater depression cones formed by intensive earlier pumping begin to be replenished, leading to a gradual rise in groundwater levels. Due to the previously high pumping intensity and the relatively deep groundwater table, the recovery process does not occur instantaneously; instead, it is jointly constrained by the delayed response of the groundwater system and the regional recharge conditions. As a result, the groundwater level exhibits a steady and sustained upward trend. In addition, the soil freezing depth in this dynamic type was shallower (between 1.6 and 1.8 m), and the soil was still primarily silty clay (Fig. 12b and c). The greater groundwater level depth and shallower soil freezing depth prevented a complete hydraulic connection between the frozen soil and groundwater (Fig. 12a), resulting in the groundwater level being unaffected by the soil freeze–thaw process. Therefore, under conditions where no groundwater extraction occurs during the freeze–thaw period and the groundwater level is not influenced by freeze–thaw processes, the groundwater system continues the post-irrigation recovery process, presenting a "sustained rising" groundwater level pattern."

d) Line 427 It is confusing to see the sentence "Precipitation directly recharged the groundwater" here.

Response: We thank the reviewer for pointing out the issue with the statement "Precipitation directly recharged the groundwater." We acknowledge that this expression was logically ambiguous and lacked terminological rigor. We have revised the sentence by linking it more clearly to the preceding one. The revised version is as follows:

" When a pronounced precipitation peak occurred (Figure 9b), the EG score increased significantly (exceeding 0.15), corresponding to a rise in groundwater level (Figure 9e), indicating that precipitation infiltration made a substantial contribution to the groundwater level increase."

e) Some subheadings are a bit too long and very similar, e.g., Sections 3.2, 3.2.1, and 3.2.2, as well as 3.3, 3.3.1, and 3.3.2, I suggest the authors refine them.

Response: We thank the reviewer for the suggestion. We have simplified and refined the subheadings of Sections 3.2 and 3.3 by removing redundant words and highlighting the core content. The revised subheadings are as follows:

3.2. Dynamic Characteristics of Regional Groundwater Level and their Distribution Laws

3.2.1. Annual Dynamics Variations and Spatial Distribution

3.2.2. Freeze–Thaw Period Dynamics Variations and Spatial Distribution

3.3. Main Controlling Factors and Identification of Causes for Various

Groundwater Level Dynamic Types

3.3.1. Annual Dynamics: Influencing Factors and Dynamics Mechanisms

3.3.2. Freeze–Thaw Dynamics: Influencing Factors and Dynamics Mechanisms

f) The authors are encouraged to strengthen the discussion by connecting this research to relevant studies and highlighting its potential implications.

Response: In response to the reviewer's suggestion, we have strengthened the discussion by incorporating relevant existing studies to better support our conclusions and highlight the practical value of this research. The specific revisions include:

In the analysis of the first intra-annual groundwater dynamics type, we have added a citation to the findings of Xu et al. (2024) in the Songnen Plain, which demonstrated that precipitation is the primary source of shallow groundwater recharge. This indirectly supports our proposed "precipitation infiltration–evaporation" mechanism.

In the analysis of the third intra-annual dynamics type, we have included a reference to the study by Wu et al. (2025) on groundwater level variations in the Songnen Plain, which pointed out that significant groundwater declines are mainly related to excessive agricultural extraction—particularly in large-scale rice cultivation areas in Jilin Province. This finding is highly consistent with our identified "extraction-driven" mechanism.

4. Conclusion:

The conclusion section is considerably longer than necessary and could be more concise.

Response: We sincerely thank the reviewer for the valuable suggestions regarding the conclusion. In response, we have revised the conclusion as follows:

"This study applies an interpretable deep learning approach to reveal the driving mechanisms behind groundwater level dynamics in seasonally frozen soil regions. High-precision simulations were conducted at 138 monitoring wells using an LSTM model. The main controlling factors and underlying mechanisms of different groundwater level variation types were identified using the EG (Expected Gradients) method. The main findings are as follows:

First, the LSTM model demonstrated high accuracy in simulating groundwater level variations in seasonally frozen areas, with NSE values on the test set ranging from 0.53 to 0.96, indicating its effectiveness in capturing complex groundwater dynamics.

Second, by applying the EG method, three dominant intra-annual groundwater dynamic types in the Songnen Plain of China were identified: precipitation infiltration–evaporation type (29.0%), precipitation infiltration–runoff type (18.1%), and extraction type (52.9%). Correspondingly, during the freeze–thaw period, these types are reflected as V-shaped, continuously declining, and continuously rising patterns, accounting for 38.4%, 23.2%, and 38.4% of the monitoring wells, respectively.

Third, while all three intra-annual types are primarily recharged by precipitation infiltration, their discharge pathways differ: evaporation, surface runoff, and groundwater extraction, respectively. During the freeze–thaw period, changes in the soil water potential gradient due to freezing and thawing lead to interactions between soil water and groundwater, resulting in the V-shaped variation. In contrast, the continuously declining and rising types reflect gradual water level changes primarily driven by groundwater extraction and precipitation recharge, without strong influence from freeze–thaw processes. These dynamic types represent groundwater fluctuations jointly driven by multiple factors across different temporal scales.

Groundwater dynamics in seasonally frozen regions are complex, influenced by both climate variability and human activities. Deep learning models require more sophisticated architectures and broader input variables to improve simulation accuracy, but this increases the difficulty of interpreting their internal mechanisms. Therefore, this study introduces the EG method to identify the key drivers and formative mechanisms of groundwater level dynamics. The results demonstrate the great potential of the EG method to bridge model accuracy and interpretability, offering a new perspective for analyzing complex hydrological processes. Future research may incorporate more advanced interpretability techniques to further enhance understanding of deep learning models. The significance of deep learning lies not only in high-accuracy simulations, but also in advancing the discovery of hydrological mechanisms. This study provides new methodological support and theoretical insights for groundwater resource management and ecological protection in seasonally frozen soil regions."

Minor comments:

Line 49 There are formatting issues with some references, which also appear throughout the rest of the paper.

Response: We sincerely thank the reviewer for the review. We have conducted a comprehensive check of all references cited in the manuscript and have standardized their formatting in accordance with the journal's guidelines to ensure accuracy and consistency.

Line 137 delete "topography of the"

Response: Thank you for the suggestion. We have removed "topography of the" in Line 137 to make the expression more accurate and concise.

I'm not sure if it's due to image resolution, but some of the colors in the figures are difficult to distinguish. For example, in Fig. 2a, the colors of the solid circles are too similar to those used in the base map.

Response: We thank the reviewer for the comment. Regarding the solid circles in Figure 2(a), we have confirmed that this marker was mistakenly added during the typesetting process and has been removed in the revised version. In addition to Fig. 2(a), we also noticed a similar issue with insufficient color contrast in Fig. 11(a) of the original manuscript. To improve the readability and visual clarity of the figure, we have adjusted the color of the solid circles in Fig. 11(a) to enhance their contrast against the background map and minimize potential misinterpretation.

References:

Xu, L., Cui, X., Bian, J., et al.: Dynamic change and driving response of shallow groundwater level based on random forest in southwest Songnen Plain, J. Hydrol. Reg. Stud., 53, 101800, https://doi.org/10.1016/j.ejrh.2024.101800, 2024.

Wu, H., Ye, X., Du, X., et al.: Assessing groundwater level variability in response to climate change: A case study of large plain areas, J. Hydrol. Reg. Stud., 57, 102180, https://doi.org/10.1016/j.ejrh.2025.102180, 2025.