Response to Reviewer #2

The work presented by Xie et al. (2021) investigated the interaction of soil water and groundwater mainly via the lateral groundwater flow and freezing or thawing induced water migration during the freezing-thawing cycle in a semi-arid region with shallow groundwater. They conducted field observations and numerical experiments and further analyzed the water budget components. The role of lateral groundwater flow and the freezing-thawing process was demonstrated important in the tested area. I found this work is interesting while there are some concerns about the current version of the manuscript necessary to be addressed from my perspective.

First, the existence of freezing-induced water gain and lateral groundwater flow is mostly postulated from the observations and not directly measured. This renders that you have to demonstrate the reliability and uncertainties of your observations (e.g., liquid water content, the occurrence of thawed water infiltration, frost depth, …).

Response: Thanks for your comments. We will add more details of the reliability of our observations in the revision. The 5TM sensors, which measure the soil dielectric permittivity to represent liquid soil water content, have an accuracy of ±2% volumetric water content. It has been reported that the 5TM sensor was accurate enough to measure the liquid water content under frozen condition (Yang et al., 2013; Zhang et al., 2019; Xue et al., 2021). The 5TM sensors have an accuracy of ±1℃ for soil temperature, which is used to infer the frost depth. In the manuscript, Figure 4 also shows that the measured liquid water content is sensitive to the temperature drop from above 0℃ to below 0℃, which well demonstrates that 5TM sensors can be used to monitor liquid water content and temperature during the freezing period. Because there are increases in liquid soil water content during the thawing stage, we believe that the increased liquid soil water content is caused by the infiltration of thawed water.

Second, as most of the analysis part is based on the SHAW model simulations. I think the authors should put a bit more words on the SHAW model setup (e.g., bottom boundary condition settings, how groundwater is considered), model performance, and uncertainty (e.g., simulation of freezing/thawing dates, statistical performance). Thus, I suggest more dedicated efforts should be made before its publication in the HESS journal.

Response: Thanks for your suggestions. We will add more detailed description of the SHAW model setup, model performance and uncertainty in the revision.

My specific comments are as follows:

Abstract:

Line 22-23: I notice that in your figures (Figure 4) the unit of soil water content is cm3/cm3, please keep consistent.

Response: Thanks for your suggestions; we will add the unit cm3/cm3 in the revision.

1 Introduction:

Line 44: "… and further decrease the hydraulic conductivity of frozen soils" please explain or clarify.

Response: Thanks for your comments. When there is groundwater migrated into the freezing front, the porosity might be decreased to be as low as 0.13. In this case, the permeability is considered to be 0 in the SHAW model. Therefore, we wrote the sentence "Soil freezing also generated cryosuction, which causes migration of water from the unfrozen zone to the freezing front and further decrease the hydraulic conductivity of frozen soils". Now we realize that it is not appropriate to add "… and further decrease the hydraulic conductivity of frozen soils" before mentioning freezing-induced groundwater migration. We will modify it in the revision.

Line 99-103: these sentence does not belong here, I think it should better be in the Introduction part.

Response: Thanks for your suggestions. We will consider to put them in a proper place in the revision.

2 Method

Please clearly present the soil texture (fraction of sand, clay, silt, organic matter) information.

Response: We have measured particle size by the Mastersizer 2000 instrument (Malvern Instruments, England), the measured fraction of sand, clay, silt shown in the Table 1. However, we have not measured the organic matter and did not consider the influence of organic matter in our model.

Table 1 The measured fraction of sand, clay, silt

Depth (cm)	Clay (%)	Silt (%)	Sand (%)
10	1.5	9.4	89.1
20	1.6	9.5	88.9
30	1.5	9.5	89.0
40	2.0	9.5	88.5
50	2.5	9.1	88.3
60	2.7	9.7	87.6
70	5.5	13.5	81.0
80	6.4	11.2	82.4
90	6.1	9.2	84.7
100	7.7	10.4	81.9
110	3.0	9.4	87.6
120	1.7	9.7	88.6

Are the 5TM sensors calibrated on this site? What about the measuring accuracy of 5TM sensors regarding the soil moisture and temperature?

Response: We have performed site-specific calibration for the sensors by the comparing the volumetric water content measured by the 5TM sensors and by the gravimetric method. The 5TM sensors have an accuracy of around ±2% for the volumetric water content and around ±1℃ for the temperature.

Line 112-114: From my understanding, Figure 1 cannot directly tell us that the increase of groundwater table depth is due to the freezing-induced water migration. Please carefully rephrase this sentence.

Response: Thanks for pointing out this. We totally agree that "Figure 1 cannot directly tell us that the increase of groundwater table depth is due to the freezing-induced water migration". We will modify it into "As shown in Fig. 1, water table depth changes from 115 cm on 28 NOV 2015 to 143 cm on 29 JAN 2016, which corresponds to the stage with an increasing frost depth."

2.3 Model inputs

Line 174: "… soil column is set to be 155 cm." I can understand that you want to use the measured soil temperature (150 cm) as the bottom boundary condition. While for the other numerical scenarios, you use 200cm for the soil column. I think either you keep all the numerical scenarios as 200cm, or you should explain a little bit the potential uncertainties regarding the results.

Response: It is true that it is appealing to use a soil column with the same length for all simulations. However, we do not have soil temperature measurement deeper than 150 cm below surface. When there is no soil temperature measurement at the lower boundary, the temperature can be estimated the by the force-restore approach, which is shown by the following expression (Hirota et al., 2002):

$$\left(1+\frac{2z}{d_d}\right)\frac{\partial T}{\partial t}=\frac{2}{C_S d_d}G-\omega\left(T-T_{AVG}\right) \tag{1}$$

where z is the depth [L] below the surface, ω is the frequency [Θ^{-1}] of fluctuation period, d_d is damping depth [L] corresponding to ω, which is expressed as $d_d=\left(\frac{2k_T}{C_S\omega}\right)^{1/2}$, k_S is the is volumetric heat capacity of soil [M L^{-2} T^{-2} Θ^{-1}], k_T is thermal conductivity of soil [M L^2 T^{-3} Θ^{-1}] , and T_{AVG} is the average annual air temperature. Equation 1 is embedded in the SHAW model. Unfortunately, we find the estimated soil temperature at 150 cm deviates slightly from the observed values.

Here, we briefly introduce how we decide to treat the bottom boundary condition. We will use a soil column with a length of 150 cm as the base case for model calibration and calculating water budget. Because we find numerically that groundwater level is not influenced by freezing when the water table depth equals 220 cm, we will use a soil column with a length of 250 cm in all other simulations for sensitivity analysis (initial water table depth equals 220 cm and 170 cm).

Line 176: Please explain in more detail about the lateral groundwater flow in SHAW. And how did you calibrate the lateral groundwater flow as 1.03mm/d?

Response: The lateral groundwater inflow is added to the saturated zone of the 1D soil column. Specifically, we assign a constant horizontal hydraulic gradient at one node within the saturated zone. The SHAW model calculates the lateral flow rate based on the assigned horizontal hydraulic gradient and saturated hydraulic conductivity. The rate of lateral groundwater inflow was estimated by Jiang et al. (2017) to range from 0.96 mm/d to 1.16 mm/d based on water table fluctuations in the unfrozen period. In the current study, the rate of lateral groundwater inflow is estimated by fitting the simulated and measured water level during the freezing-thawing stage. We find a lateral inflow rate of 1.03 mm/d leads to the best fit of water table depth (with the lowest RMSE).

Line 187: For the bottom boundary conditions, I have a sense that the setting of the bottom boundary condition can affect the simulations. Please explain why you set the bottom as the no-flux boundary condition. Is it the more realistic condition for that site or for the better simulations?

Response: To account for the effect of groundwater, a saturated zone should be included in the soil column. As we pointed out in the manuscript, a constant head lower boundary condition would overestimate freezing-induced groundwater migration toward the freezing front. Because the water level fluctuations are not independent from the atmospheric conditions, a specified-head lower boundary condition is not justified. Therefore, a closed soil column with a no-flow lower boundary condition is the best choice to identify how the groundwater level responds to freezing-induced water migration, lateral groundwater flow, and infiltration of thawed water. This lower boundary condition leads to an accurate estimation of freezing-induced groundwater level decline as well as freezing-induced water gain in the frozen zone.

Line 204: For presenting the different simulation scenarios (A, B, C, D), I would suggest that you include them as a table, listing the main difference among all the simulation scenarios (or numerical experiments).

Response: Thanks for your suggestions. We will include a table to show the main difference among all the simulation scenarios in the revision. We will also add more numerical experiments in the revision.

Table 2: I think the row with "Calibrated parameters" should be below the row with "Initial parameters".

Response: We will exchange positions of the two rows in the revision.

3 Results and discussion

Figure 4: the scale of soil temperature should be finer (e.g., [-5, 10] oC) for Figure 4d, e, f. In addition, I think there also be freezing or thawing periods for 90cm. Please zoom in and clarify.

Response: Thanks for your suggestions. We will modify the scales of soil temperature in Figure 4. According to our measurements, the temperature of 90 cm never drop below 0℃, therefore, there is no freezing or thawing periods in the 90cm. We will zoom in the scale of temperature in the revision.

Line 248: please explain how to define the "occurrence of thawed water infiltration".

Response: In the manuscript, we wrote "From 29 JAN, there is a trend of rising water level, which is one month earlier than the occurrence of thawed water infiltration during the thawing stage." If there is no lateral groundwater inflow, the only possible cause of groundwater level rise is infiltration of thawed water. However, as we observed, the water level rises before the thawing stage. Therefore, we interpret that the water level rise before the thawing stage is caused by lateral groundwater inflow.

Figure 5: I suggest that the statistical performance should be added here to demonstrate the capability of the SHAW model in simulating soil moisture and temperature.

Response: We agree and will add the statistical performance on the Figure 5 in the revision.

Section 3.2: please also add some text to describe how the model captures the observed freezing or thawing dates.

Response: Thanks for your suggestions. We will add some text to describe how the model captures the observed freezing or thawing dates in the revision.

Figure 6: for better comparison, please present the observed frost depth and water table depth for all four subplots. In addition, how is the frost depth measured?

Response: The measured frost depth is determined by the dates of start of freezing and end of thawing as shown in Figure 4 in the manuscript. We will add the observed frost depth and water table depth for all the subplots in the revision.

Table 3: please clarify the frozen zone and how you calculate TWC.

Response: In Table 3, the frozen zone represents the zone from the surface to the maximum frost depth. The mean TWC is calculated by total water content in the frozen zone (S_{FZ}) divided by the maximum frost depth (FD), while the ΔTWC is calculated by total water content change in the frozen zone (ΔS_{FZ}) divided by the maximum frost depth (FD). We will explain in more detail in the revision.

Section 3.3: as you present two subplots in Figure 8, it is better to say what you want to say about the comparison here. The effect of snow can be clearly identified (Figure 8), the role or the amount of snowfall should be stated from the water budget closure perspective.

Response: Thanks for your suggestions. We will add the purpose of comparison in the revision. As pointed out by Reviewer #1, we did not correctly simulate the effect of snow in the current version. We have fixed this problem and find the amount of infiltration from snowmelt should be 3.23 mm. We will describe the effect of snow in detail in the revision.

4 Conclusions

I suggest adding some text describing that how well the SHAW model can capture the observed soil moisture, temperature, frost depth, and groundwater table depth.

Response: We will follow your suggestions in the revision.

Line 380: "a model is built…" should better be "a series of numerical experiments were set up to …" or something similar.

Response: Thanks for your suggestions. We will revise this sentence in the revision.

References

Hirota, T.: An extension of the force-restore method to estimating soil temperature at depth and evaluation for frozen soils under snow, Journal of Geophysical Research, 107, 4767, 10.1029/2001jd001280, 2002.

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