Response to Reviewer #1

It's my pleasure to review hess-2020-657 "Interaction of soil water and groundwater during the freezing-thawing cycle: field observations and numerical modeling" by Xie et al. The authors quantified the impact of freezing-induced groundwater migration and lateral groundwater inflow on soil moisture profile and groundwater level dynamics at site scale using the SHAW model. This is a very specific study at a single site, and the broad implication of this study to the relevant research community is unknown and needs to be justified. In addition, additional numerical experiments should be included to better quantify the impact of freezing-induced groundwater migration and lateral groundwater inflow, and additional descriptions of the measurements and methods are also necessary. According to these, a major revision is recommended. My comments are as follows.

Response: Thanks for your comments. We will introduce the broad implication of this study, add additional numerical experiments in the revision and give more detailed description of the measurements and methods in the revision.

Major Comments:

1. This paper describes a specific case of observing and simulating the impact of freezing-induced groundwater migration and lateral groundwater inflow on soil moisture profile and groundwater level dynamics at a single site with very shallow water level ranging from 90-143cm. I think this is a very special case for the frozen areas that the water level is generally much deeper. As such, the broad implication of this study to the relevant research community should be justified. In addition, the authors are suggested to include additional numerical simulations to investigate the impact of different water level depths.

Response: It is true that we have only one site with detailed measurements of time series of groundwater level and soil liquid water content, which is shown in the current study. However, this is not a special case. Shallow groundwater tables widely occur in river valleys and coastal regions, as well as in regions with large-scale topographic relief

(Gleeson et al., 2011; Fan et al., 2013). In our study area covered mainly by sand, numerical results show that when the water table depth equals 2.2 m, groundwater level is not influenced by freezing (Fig. 1d). We find the region with water table depth smaller than 2 m accounts for around one third of the total area of the current catchment. As shown in Fan et al.(2013), the regions with water table depth below 2 m account for around 31% of the global land area.

Thanks for the suggestion of adding additional numerical simulations. Because we found the extinction depth of freezing-induced groundwater table decline is 2.2 m in our study area, we will show the simulation results when initial water table depth equals 1.7m and 2.2 m (with and without lateral groundwater flow) in the revision, which are shown below (Figure 1).

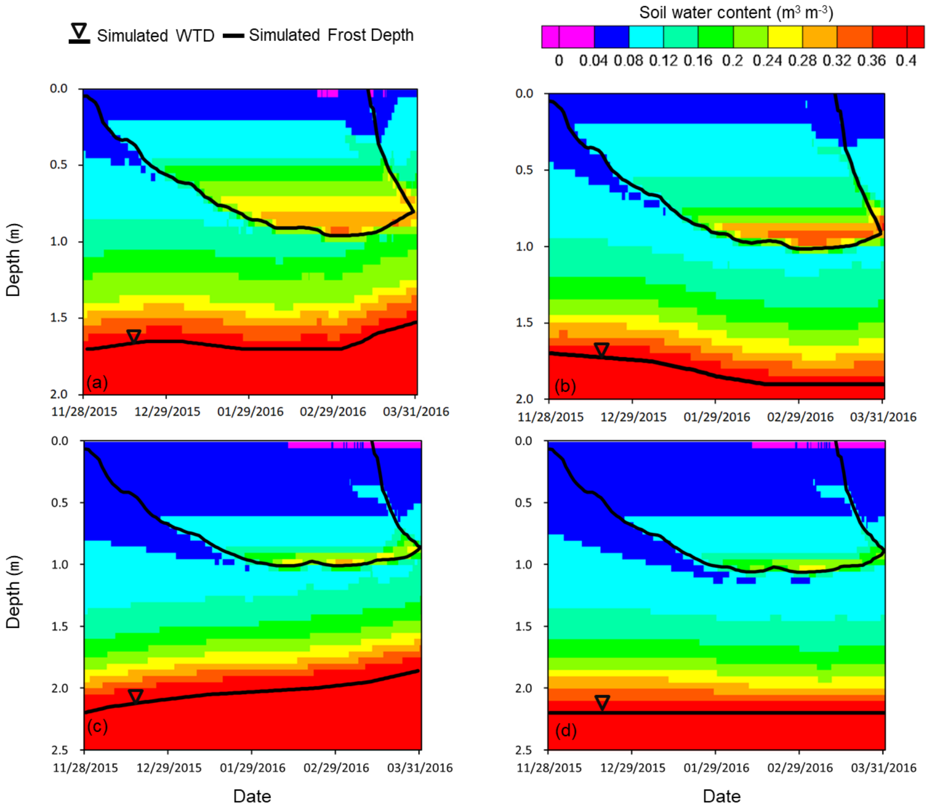

Figure 1. The frost depth, groundwater level and total water content under four scenarios. (a-b) initial water table depth equals 1.7 m with a lateral flow rate of 1.03 mm/d (a) and without lateral flow (b); (c-d) initial water table depth equals 2.2 m with a lateral flow rate of 1.03 mm/d (c) and without lateral flow (d).

2. Related to comment #1, I think detailed descriptions of the study site and all the available measurements are necessary as these given in Jiang et al. 2017,2018 cited in this paper. I found that there are at least two experimental wells and several other kinds of wells shown in Jiang et al. 2017, 2018. Why only one experimental well is investigated in this study? What's the typical depth of groundwater level found across the whole Wudu lake catchment? How far is the Otak meteorological station from the monitoring site? What's the accuracy of precipitation and soil moisture measurements? Did the authors perform site-specific calibration for the 5TM sensor? And how accurate can the 5TM sensor measure the liquid water content under frozen condition? What's the typical vegetation and soil types? The measurements of soil texture and soil temperature are also suggested to include in the supplement.

Response: Thanks for your suggestion of providing detailed descriptions of the study site and all the available measurement. In the revision, we will add the typical vegetation (*Achnatherum splendens*), soil type (loamy sand), and range of water table depths across the whole Wudu lake catchment (from less than 0.5 m to more than 15 m), as well as measurements of soil texture at 12 depths.

Although we have another monitoring well (DK 1 as shown in Jiang et al., 2018), the water table depth is as deep as around 15 m. Due to the deep water table depth, there is no interaction of soil water and groundwater induced by freezing. All other wells shown on the map of water table elevation in Jiang et al. (2018) are domestic wells.

The Otak meteorological station, which is a national meteorological station, is around 35 km away from the study site. The accuracy of precipitation measurements is ±0.1 mm. The 5TM capacitance sensors, which measure the soil dielectric permittivity to represent liquid soil water content, have an accuracy of around ±2% volumetric water content (VWC). It has been reported that the 5TM sensor was accurate enough to measure the liquid water content under frozen condition (Yang et al., 2013; Xue et al., 2021). We have performed site-specific calibration for the sensors by the comparing the VWC measured by the 5TM sensors and by the gravimetric method.

3. The authors indicated that "we find snowfall did not infiltrate into the soil column due to the low permeability of frozen soil", which I think is questionable. If the permeability of frozen soil is so low that the snowmelt cannot infiltrate into the soil, how can the freezing-induced groundwater migration enter the soil column? What's the mechanism behind this? I am curious how the authors simulate the snow process? What's the accuracy of snowfall measurements and snowmelt simulations?

Response: Thanks for pointing out the problem of the sentence "we find snowfall did not infiltrate into the soil column due to the low permeability of frozen soil". After referring to several references (Iwata et al., 2008; Zhao et al., 2013; Mohammed et al., 2018), we realize that although infiltration of snowmelt would be impeded by the low permeability of frozen soil, the majority of snowmelt can be infiltrated into the frozen zone. Unfortunately, because we did not set the parameter representing "ponding for rainfall and snowmelt" correctly, our model results led to the wrong conclusion that snowfall could not infiltrate into the soil column. We have fixed this problem and will re-run all models in the revision.

In the meteorological station, the amount of snowfall is determined by weighting water equivalent of snowfall, which has an accuracy of ±0.1 mm. The total snowfall during the freezing-thawing period is found to be 11.7 mm. In the SHAW model, precipitation is assumed to be snow if the air temperature is below 0℃, and snow would be melted when the temperature is increased to above 0℃. However, snow could be easily blown away by wind in a bare ground before melting (Link and Marks, 1999; Zhao et al., 2013). After correcting the parameter representing "ponding for rainfall and snowmelt", we find the amount of infiltration from snowmelt equals 3.23 mm, which accounts for 28% of the total snowfall. Because the infiltration of snowmelt is limited, the wrong treatment on snowmelt does influence other conclusions drawn in the current study. We will re-calculate the water budget and update all figures in the revision.

Concerning the question of "If the permeability of frozen soil is so low that the snowmelt cannot infiltrate into the soil, how can the freezing-induced groundwater migration enter the soil column?", we want to clarify that due to cryosuction at the freezing front, groundwater migrates through the unfrozen zone and gets frozen near the freezing front. As shown in Fig.5 in the manuscript, as the freezing front moves down, the total water content in the frozen zone changes little.

4. Detailed descriptions of how the authors determine the hydraulic parameters are necessary. Did the authors measure the soil texture and other relevant hydraulic parameters such as porosity, bulk density and saturated hydraulic conductivity? Why the saturated hydraulic conductivity estimated for the second layer (0.7-1.0 m) is so different from other two layers? How the authors determine the permeability of aquifer?

Response: We measured particle size by the Mastersizer 2000 instrument (Malvern Instruments, England) and the bulk density of the different layers in the study site with the cutting-ring method. The measured soil parameters are shown in the Table 1. Based on the contents of clay, silt and sand, the profile is divided into three layers. Based on the average contents of clay, silt and sand in each layer, initial estimates of hydraulic parameters (θr, θs, α, n) are estimated by the Rosetta pedotransfer function (Schaap and Leij 1998; Zhang and Schaap 2017). We further calibrated the hydraulic parameters by fitting the simulated and measured soil water content.

Table 1 The measured soil texture

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density(g/cm^3)
10	1.5	9.4	89.1	1.638
20	1.6	9.5	88.9	1.673
30	1.5	9.5	89.0	1.628
40	2.0	9.5	88.5	1.672
50	2.5	9.1	88.3	1.655
60	2.7	9.7	87.6	1.613
70	5.5	13.5	81.0	1.562
80	6.4	11.2	82.4	1.518
90	6.1	9.2	84.7	1.549
100	7.7	10.4	81.9	1.598
110	3.0	9.4	87.6	1.652
120	1.7	9.7	88.6	1.733

We also measured the saturated hydraulic conductivity of soil samples from each layer by HYPROP (www.metergroup.com/environment/products/hyprop-2/). The soil samples with low clay content above 70 cm and below 100 cm were measured to be around 18.0 cm/h, while that with higher clay content at the depth ranging between 70 and 100 cm is measured to be 0.8 cm/h. The different saturated hydraulic conductivity is caused by the slight difference in clay and silt. The permeability of aquifer is the same as saturated hydraulic conductivity of soils below 100 cm.

5. Detailed descriptions of the SHAW model and its implementation are necessary. For instance, how the model compute the permeability of frozen soil? How the authors include the lateral groundwater inflow into the SHAW model? How the authors determine the temperature at the lower boundary? What are the state variables need to be determined before the simulations? What's the time step of simulations? How the authors consider the impact of vegetation processes?

Response: We will give more detailed description of the SHAW model in the revision. Here, we briefly answer the questions.

The permeability of both unfrozen soil and frozen soil is computed by the van Genuchten and Mualem equation. However, when the porosity of frozen soil is decreased to 0.13, the permeability is assumed to be zero.

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.

For scenarios A and B which have the length of the soil column is 155 cm), we use the measured temperature in 150 cm at the lower boundary. When there is no temperature measurement at the lower boundary, the temperature at the lower boundary 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 [$M\ L^{-2}\ T^{-2}\ \Theta^{-1}$], k_T is thermal conductivity of soil [$M\ L^{2}\ T^{-3}\ \Theta^{-1}$] , and T_{AVG} is the average annual air temperature. Equation 1 is embedded in the SHAW model.

Because we find the soil temperature estimated at 150 cm by using equation 1 deviate slightly from soil temperature measured at 150 cm, to insure the accuracy of model calibration, we use the measured temperature at 150 cm to represent the bottom temperature for the base case model. After model calibration, we change the length of the soil column into 200 cm to account for the scenarios with deeper water table depths, and use equation 1 to obtain temperature at the lower boundary. In the revision, we will extend the length of the soil column into 250 cm to account for more scenarios of freezing-induced groundwater migration.

The stable variables of the model include soil temperature and soil water content. We use the initial conditions of soil water content and soil temperature on 29 OCT 2015 for spin-up, which is run for 30 days to obtain the initial conditions before the start of freezing (28 NOV 2015). The time step of simulations is one hour.

Because the grass in our study site fades during the freezing and thawing stages, we don’t consider the influence of plants in the model.

6. Four numerical experiments are conducted to investigate the impact of soil heterogeneity and lateral groundwater on the simulations. I do not find the necessary to quantify the impact of soil heterogeneity. Instead, I think the authors can consider following additional experiments such as simulations without impact of groundwater, simulations with deeper water level depth, and simulations with changing rates of lateral groundwater inflow. It’s not clear why the authors fix the rate of lateral groundwater inflow.

Response: Thanks for the suggestions, we will add some additional simulations with deeper water table depth (Figure 1 in the current file), and some simulations without impact of groundwater.

Although we have shown the water level fluctuations under different rates of lateral groundwater inflow (Figure 7 in the manuscript), we will add plots to show how different rates of lateral groundwater inflow would influence total water content and frost depth. Because lateral groundwater flow is mainly controlled by regional-scale water table undulation, we assume that rate of lateral groundwater flow is constant during the whole freezing-thawing period.

Because the vertical distribution of soil water content in the profile is influenced by the low-permeability layer from 70 to 100 cm, we prefer to keep the scenarios with homogeneous soil to explain how a middle layer with low-permeability influence freezing-induced groundwater migration as well as evaporation during the freezing-thawing stage .

Minor Comments:

1. The authors are suggested to merge Figures 4 and 5, and the info of precipitation is suggested to include in the figure. The scale for the temperature can be set at 10~-20.

Response: Thanks for your suggestions. We will add the information of precipitation into the figure. However, we respectfully disagree to merge figures 4 and 5. Figure 4 shows the sensitivity of measured liquid water content to temperature drop from above 0℃ to below 0℃, and well demonstrates that 5TM sensors can be used to monitor liquid water content during the freezing period.

2. Why there is not increase found for the simulation of total water content at 10 cm as shown in Figure 5?

Response: The low total water content in the shallow part (from the surface to 20 cm) of the soil profile is caused by the low initial soil water content at these depths as well as the long distance away from the water table.

3. It’s suggested to plot the measured frost depth and WTD in all the subplots of Figure 6. In addition, how the authors determine the frost depth?

Response: We will add the measured frost depth and WTD into all subplots as suggested. The measured frost depth is determined by the dates of start of freezing and end of thawing as shown in the figure below.

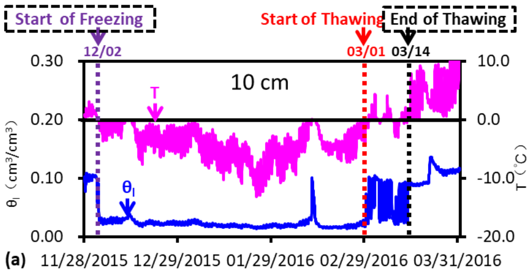

Figure 2.The dates of start of freezing and end of thawing to determine frost depth

4. For all the simulations, it’s suggested to show how they affect both soil liquid water content and temperature simulations, as well as to list the corresponding error statistics.

Response: The simulated liquid water content and temperature for the four scenarios are shown in Figure3 and 4. We will incorporate these plots in the revision.

The error statistics for all of the four scenarios are listed in Tables 2 and 3. We will add the results in the revision.

Table 2 The RMSEs of simulated liquid water content under different scenarios

Parameters	10 cm	20 cm	30 cm	50 cm	70cm
Scenario A	0.0213	0.0205	0.0289	0.0175	0.0231
Scenario B	0.0237	0.0300	0.0322	0.0321	0.0761
Scenario C	0.0224	0.0332	0.0297	0.0352	0.0425
Scenario D	0.0253	0.0361	0.0273	0.0497	0.0825

Table 3 The RMSEs of simulated soil temperature under different scenarios

Parameters	10 cm	20 cm	30 cm	50 cm	70cm
Scenario A	0.95	0.67	0.69	0.41	0.37
Scenario B	1.06	0.78	0.79	0.47	0.41
Scenario C	1.24	0.91	0.88	0.55	0.54
Scenario D	1.30	1.03	0.99	0.68	0.64

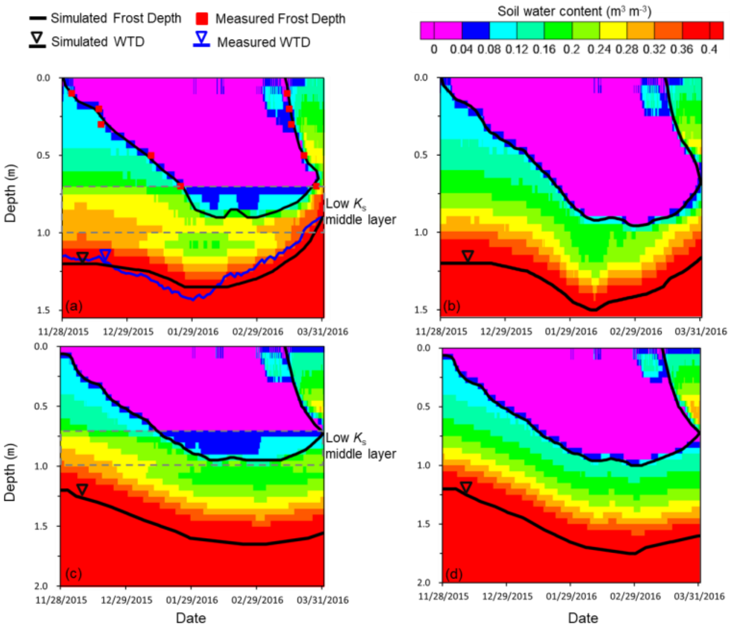

Figure 3 The frost depth, groundwater level and liquid water content under the four scenarios. (a) Scenario A, heterogeneous soil profile with a lateral flow rate of 1.03 mm/d; (b) Scenario B, homogeneous soil profile with a lateral flow rate of 1.03 mm/d; (c) Scenario C, heterogeneous soil profile without lateral inflow; (d) Scenario D, homogeneous soil profile without lateral inflow.

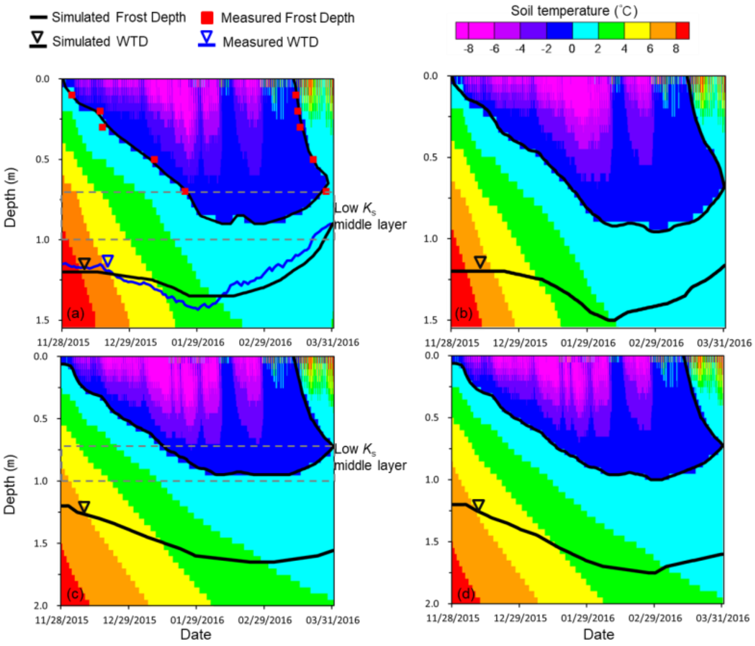

Figure 4 The frost depth, groundwater level and temperature under the four scenarios. (a) Scenario A, heterogeneous soil profile with a lateral flow rate of 1.03 mm/d; (b) Scenario B, homogeneous soil profile with a lateral flow rate of 1.03 mm/d; (c) Scenario C, heterogeneous soil profile without lateral inflow; (d) Scenario D, homogeneous soil profile without lateral inflow.

5. For the description of soil evaporation in Section 3.3, can the authors provide validation data? If not, I don't find the necessary to include this subsection. Instead, the impact of different numerical experiments on both soil liquid water content and temperature simulations can be shown in detail.

Response: Thanks for your suggestions. It is a pity that we do not have measured data to validate simulated results of soil evaporation, so we agree to delete subsection 3.3. We will incorporate plots of simulated soil liquid water content and simulated temperature in the revision.

6. For the Table S1, it's suggested to remove 110cm and 150cm since there are not measurements recorded for these two depths. Besides, it's suggested to add the measured soil temperature and lateral groundwater inflow in the supplement.

Response: Thanks for your suggestions. We will remove 110 cm and 150 cm in Table S1. In fact, the measured soil temperature is already listed in Table S2 of supplement material.

We want to clarify that we don't have measured lateral groundwater inflow data. The rate of lateral groundwater inflow was initially estimated by Jiang et al. (2017) based on water table fluctuations in the unfrozen period. In the current study, we estimated the rate of lateral groundwater inflow by fitting the simulated water level and measured water level during the freezing-thawing stage.

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