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Soil hydrological process and migration mode influenced by the freeze-thaw process in the activity layer of permafrost regions in Qinghai-Tibet Plateau

Cao Wei [a], Sheng Yu [a,*], Wu Jichun [a], Chou Yaling [b], Peng Erxing [a], Gagarin Leonid [a,c]

[a] State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Key Laboratory of Disaster Prevention and Mitigation in Civil Engineering of Gansu Province, Lanzhou University of Technology, Lanzhou 730000, China
[c] Melnikow Permafrost Institute, Siberian Branch Russian Academy of Sciences, Yakutsk 677010, Russia

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ABSTRACT

It hasn't yet fully understood the influence of freeze-thaw action on hydrological processes in the active layer of permafrost regions. So this article investigated one permafrost cross-section at the northern slope of Bayan Har Mountains in the Source Area of the Yellow River in Qinghai-Tibet Plateau. According to the data of field monitoring, seasonal variability of soil hydrological processes in the active layer of permafrost regions was studied and simulated by the freeze–thaw module of HYDRUS-1D software. The results show that: 1) The soil moisture and the suprapermafrost water-level are divided into four stages based on the freeze-thaw process. Rainfall infiltration is the main driving force of soil hydrological processes, and the freeze-thaw front are the main limiting factors. 2) The active layer thickness (ALT) is greater on the upslope than that on the downslope due to the influence of terrain slope. It leads to that the change variation of the soil moisture and the suprapermafrost water-level on the upslope is also more gently than that on the downslope. 3) Temperature is the key factor that affects soil hydrologic process of the active layer in permafrost regions. Soil temperature and soil moisture showed a significant exponential linear correlation at different depths. The relationship between soil temperature and suprapermafrost water level shows Boltzmann function relations. 4) Soil moisture has a downward migration trend after a freeze-thaw cycle. It will result in the formation of underground ice near the permafrost table. Driven by the temperature gradient, the unfrozen water in the active layer moves from bottom to top during the freezing stage.

1. Introduction

Due to its sensitivity to temperature and water content changes, permafrost is a special geological environment in cold regions. As a major part of the cryosphere, permafrost is a key factor of earth-atmosphere exchange, surface processes and the hydrological cycle. Under the influence of climate change, permafrost will greatly degrade. And the change of permafrost will significantly affect the change of earth's surface in cold regions. Permafrost change will further affect the physical, chemical and biological processes of ecological and hydrological systems in cold regions (Cheng and Wu, 2007; Jorgenson et al., 2010; Zhang, 2012). Especially, soil moisture movement is the important carrier and main form of material energy transfer between surface layers in permafrost regions. And it is also one of the main causes for the deterioration of water resources and the degradation of ecological functions (Woo et al., 2008). Permafrost degradation will lead to the thawing of ground ice and an increase of depth of seasonal thawing. It will ultimately trigger a decline of the water table. Especially, the change of hydrogeological condition in permafrost regions will lead to the degradation of overlying vegetation and the decrease of biodiversity (Bibi et al., 2018; Oliva et al., 2018). It will further cause the degradation of alpine meadows and desertification. It thus leads to a series of ecological problems and environmental problems in permafrost regions (Jin et al., 2009; Jorgenson et al., 2010; Wang et al., 2000).

Recently, an extended period of observation has been carried out both at home and abroad to study the hydrological process in permafrost regions (Ding et al., 2000; St St Jacques and Sauchyn, 2009; Yang et al., 2000). More and more evidence has shown that the permafrost

* Corresponding author.
E-mail addresses: caowei@lzb.ac.cn (C. Wei), sheng@lzb.ac.cn (S. Yu).

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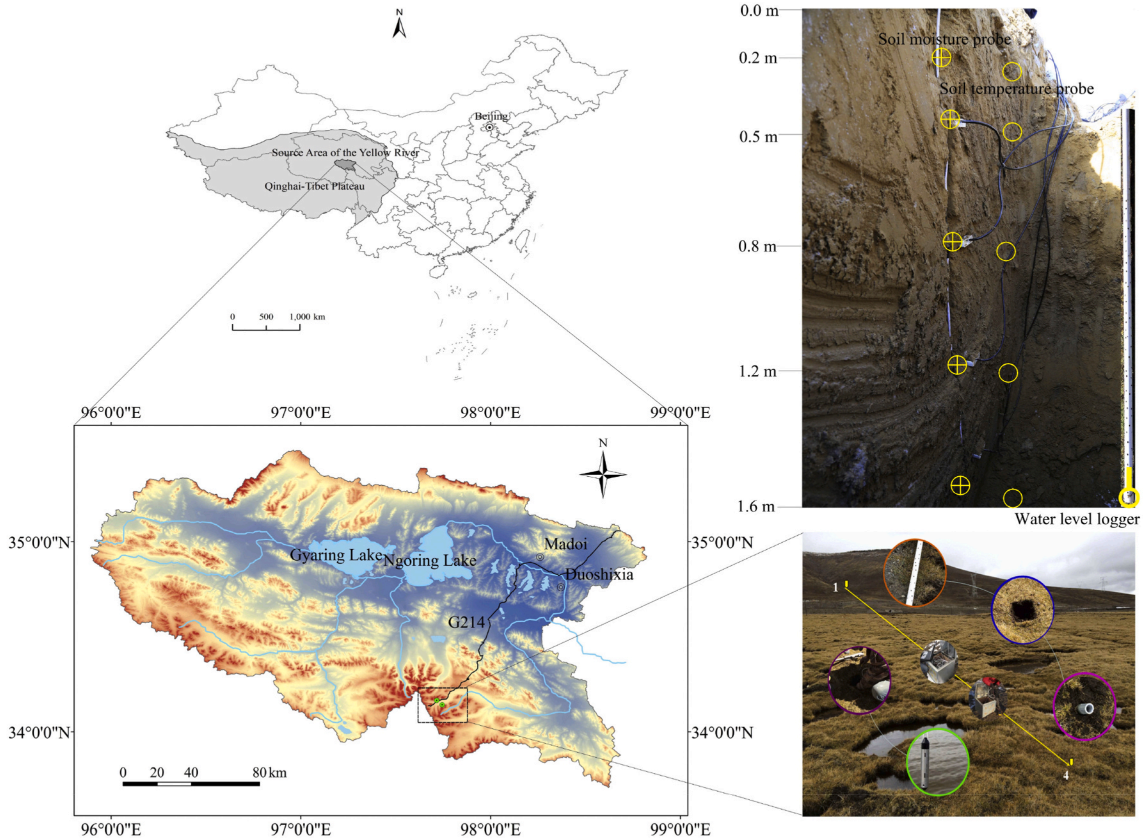


Fig. 1. Field monitoring site of the study area.

degradation will have a direct impact on the flow of surface water and groundwater (Cheng and Jin, 2013; Frampton et al., 2013; Quinton et al., 2011). Freeze-thaw action of the active layer also has a significant influence on the hydrological process. Some researchers have analyzed the influence of seasonal thawing of the active layer on the runoff. And they found that the bedrock topography is the main factor controlling subsurface flow (Wright et al., 2009). Some domestic and foreign scholars have discussed the effect of the active layer on hydrological processes. The researchers have focused on the permafrost in Fenghuo Mountain Basin of Qinghai-Tibet Plateau and Binggou Basin of Qilian Mountain. They analyzed the seasonal dynamic changes of suprapermafrost water and the effect of freeze-thaw action in the active layer on the seasonal dynamic changes of suprapermafrost water (Chang et al., 2015; Yang et al., 1993). In general, research in this field is relatively limited. It only discusses the relationship between the freeze-thaw action and the hydrological process in the active layer, which cannot thoroughly reveal the mutual relationship and the functional mechanism between the freeze-thaw action and hydrological processes in the active layer. Thus, we haven't yet fully understood the influence of freeze-thaw action on hydrological processes in the active layer.

In recent years, the global climate has been remarkably warming. Permafrost in Qinghai-Tibet Plateau is in the process of accelerated degradation (Wang et al., 2000; Wu and Zhang, 2008). Permafrost degradation also appears in the Source Area of the Yellow River in the northeast of the Qinghai-Tibet Plateau (Sheng et al., 2020). Due to permafrost degradation, water recharge, runoff and discharge processes in this region have remarkably changed (Jin et al., 2009). Stability of the water resources and the ecological environment in the source area has been seriously damaged (Chang et al., 2007; Liang et al., 2008; Wang et al., 2001). Water quantity in the source area is very important to the stability of water resources in the basin of the Yellow River. However, permafrost distribution is considerably complicated in the source area. Permafrost interacts with surface water and groundwater. The topography, active fault and permafrost degradation control the distribution of groundwater (Jin et al., 2010; Luo et al., 2014). Permafrost degradation will change the continuity and distribution of permafrost in 3D space. This will damage the recharge and drainage conditions of surface water and groundwater. It will have a profound impact on hydrological processes (Niu et al., 2011; Zhang et al., 2004). Thus, this study attempts to understand the influence of freeze-thaw action in the active layer on hydrological processes. The permafrost change and hydrological process were investigated at the Northern Slope of Bayan Har Mountains in the Source Area of the Yellow River. In view of investigation data, this research analyzed seasonal variation of rainfall, soil moisture in the active layer and suprapermafrost water. And based on hillslope scale, this study studied seasonal variation characteristics of soil hydrological process in the active layer. And it will provide an important reference for understanding the relationship between freeze-thaw action and hydrological processes from the perspective of hillslope scale.

2. Materials and methods

2.1. Study area

The study area is located at the Northern Slope of Bayan Har Mountains in the Source Area of the Yellow River in Qinghai-Tibet Plateau. The altitude of this region is between 4500 m and 5200 m. This region is affected by the typical continental semi-arid climate of Plateau. Due to influences of the altitude, this region is dominated by permafrost. Continuous permafrost is interlaced with the discontinuous permafrost, island permafrost, and talik. The terrain is dominated by mountains and hills. This region is largely covered with the alpine swamp meadow. The region is covered by the continuous permafrost. The region is mainly distributed with icy permafrost and saturated permafrost. The mean annual ground temperature (MAGT) is about −1.0 °C. Influenced by climatic and geological factors, the permafrost

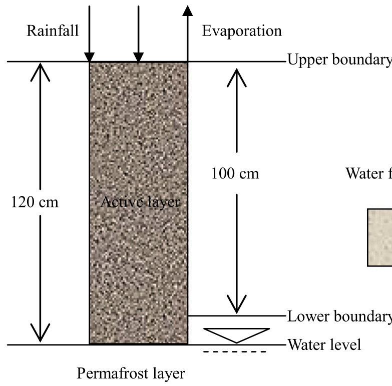


Fig. 2. Freeze–thaw module of HYDRUS-1D software.

thickness is about 40 m. The permafrost degradation results in the permafrost table reaching to about 1.5 m.

2.2. Field monitoring

A vertical section is chosen to reveal the seasonal variation characteristics of soil hydrological process in the active layer (Fig. 1). The vertical section is located in North Slope of Bayan Har Mountains. It is close to the national road of G214. Two slope positions are selected in the vertical section. They are the upper slope position (1#) and the lower slope position (4#), respectively. A lot of monitoring instruments produced by the Onset Corporation of America are installed inside the slope positions. These instruments include the soil temperature probes and the soil moisture probes. These probes are embedded at the depths of 20 cm, 50 cm, 80 cm, 120 cm, and 160 cm in the upper slope position (1#). And they are also embedded at the depths of 20 cm, 50 cm, and 80 cm in the lower slope position (4#). Different embedded depth is mainly due to the different active layers of permafrost on different slopes. The measuring precision of soil temperature probe (S-TMB-M006) is less than 0.2 °C. The operating temperature of soil temperature probe is from −40 °C to 70 °C. And the observation accuracy of soil moisture probe (S-SMC-M005) is 3%. The operating temperature of soil moisture probe is from 0 °C to 50 °C. Data acquisition instrument of U30 series can acquire the soil temperature and soil moisture data once every 4 h. At the same time, the observed wells of groundwater level are set up near the permafrost boreholes. The pipe of groundwater level is made of aluminum-plastic PPR (polypropylene random) pipe. It is due to that this pipe is made of better material. Especially, it is frost-resisting and wear-resisting in high altitude and alpine region. And the inner diameter of this pipe is 45 mm. The diameter of drilled hole on the tube wall is 5–10 mm. And the pipe of groundwater level is embedded in the two observed wells. In order to prevent the fine sand and clay from falling into the pipe of groundwater level, a plastic filter screen is wrapped outside the pipe of groundwater level. And HOBO U20 Water Level Logger is used to monitor the change of suprapermafrost water. The data logger is made by the American onset Corporation. The product model of data logger is U20-001-04, whose measuring precision is less than 0.3 cm. The range of operating temperature is −20–50 °C. The water level logger is together fixed by the nylon rope and the wire rope. Two water level loggers are placed at the lower part of the pipe of groundwater level in the upper slope and the lower slope position, respectively. Their monitoring frequency is also 4 h/time. This article chooses a monitoring-period data from September 2015 to September 2016. The data of atmospheric temperature and precipitation are from the nearest observation station in Madoi County.

2.3. Simulation methods

The soil hydrological process in permafrost regions is mainly simulated by the freeze–thaw module of HYDRUS-1D software (Dagois et al., 2017); Hansson et al., 2004; Lai et al., 2016; Li et al., 2013; Zhao et al., 2016; Wu et al., 2014). Fig. 2 shows the freeze–thaw module of HYDRUS-1D software.

2.3.1. Equation of soil moisture movement and heat flow

This module can calculate the soil moisture movement in the freeze–thaw period by improving the Richards equation and coupling the soil hydrothermal process. The formula can be written as follow:

$$\frac{\partial\theta_u(h)}{\partial t}+\frac{\rho_i}{\rho_w}\frac{\partial\theta_i(T)}{\partial t}=\frac{\partial}{\partial z}\left[K_{Lh}(h)\frac{\partial h}{\partial z}+K_{Lh}(h)+K_{Lh}(h)\frac{\partial T}{\partial z}+K_{vh}(\theta)\frac{\partial h}{\partial z}+K_{vT}(\theta)\frac{\partial T}{\partial z}\right]-S \tag{1}$$

where θ_u is the volumetric unfrozen water content (including volumetric liquid and vapor water content), cm^3/cm^3; θ is the volumetric liquid content, cm^3/cm^3; θ_i is the volumetric ice content, cm^3/cm^3; t is time, s; z is the spatial coordinate, cm, and upward is positive; ρ_i is the ice density, kg/m^3, taking 931 kg/m^3; ρ_w is the density of liquid water, kg/m^3, taking 1000 kg/m^3; h is the pressure head, cm; T is the temperature, K; S is a sink or source term, s^{-1}, which is normally root extraction. K_{Lh}, K_{LT}, K_{vh} and K_{vT} is respectively liquid hydraulic conductivity under the action of water potential, liquid hydraulic conductivity under the action of temperature, gaseous hydraulic conductivity under the action of water potential and gaseous hydraulic conductivity under the action of temperature.

The heat flow equation in the model is expressed as follows:

$$\frac{\partial C_pT}{\partial t}-L_f\rho_i\frac{\partial\theta_i}{\partial t}+L_0(T)\frac{\partial\theta_v(T)}{\partial t}=\frac{\partial}{\partial z}\left[\lambda(\theta)\frac{\partial T}{\partial z}\right]-C_w\frac{\partial q_1T}{\partial z}-C_v\frac{\partial q_vT}{\partial z}-L_0(T)\frac{\partial q_v}{\partial z}-C_wST \tag{2}$$

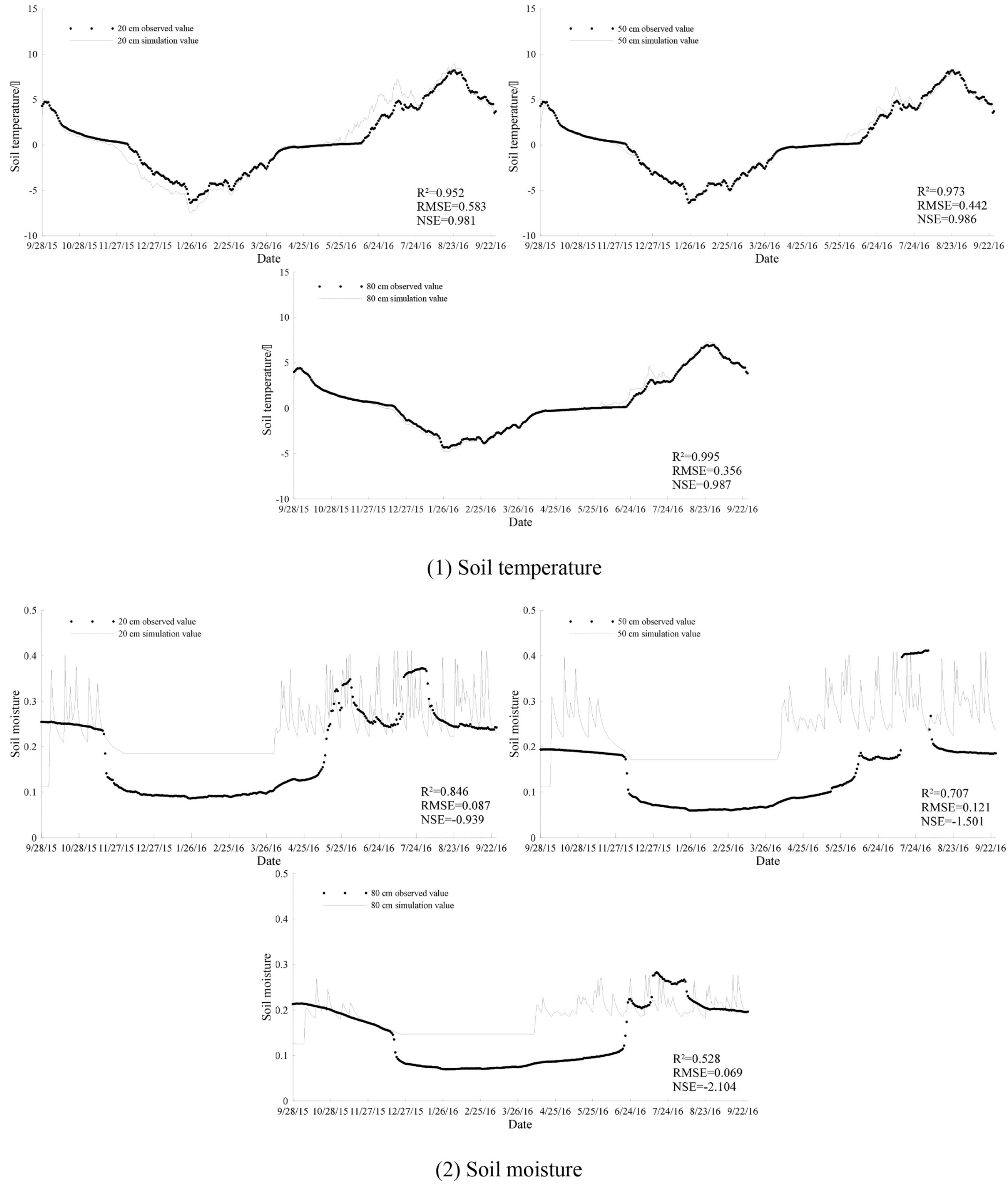


Fig. 3. Comparison of simulation results of soil temperature and moisture at different depths.

where θ_v is the gaseous water content, cm^3/cm^3. $L_0 = L_w \rho_w$, L_w is the latent heat of water gasification, where the value is taken as $2.501 \times 10^6 - 2369.2T$, J/kg. L_f is latent heat of water freezing, where the value is approximately taken as 3.34×10^5, J/kg. $\lambda(\theta)$ is the soil thermal conductivity, $W/(m \cdot ^\circ C)$. q_1 is the liquid water flux, m/s. C_p is the soil volume heat capacity, $J/(m^3 \cdot K^{-1})$, which is the sum of the heat capacity of each phase (solid phase C_n, liquid phase C_w, vapor phase C_v and ice phase C_i) in the soil.

Eqs. (1) and (2) are closely coupled. Both equations depend on water content, pressure head and temperature, and are interrelated in solving process. The finite difference method is used to solve the motion equations of water and heat flow respectively. And the coupling relationship between water and heat flow is considered to solve the model iteratively. When the soil is unfrozen, the thermal conductivity can be expressed as:

$$\begin{cases} \lambda(\theta) = \lambda_0(\theta) + \beta_t C_w |q_w| \\ \lambda_0(\theta) = C_1 + C_2\theta - (C_1 - C_4)exp\left[-(C_3\theta)^{C_5} \right] \end{cases} \quad (3)$$

where $\lambda_0(\theta)$ is the thermal conductivity of the porous medium without flow, β_t is the longitudinal thermal dispersivity, L. $C_i(i = 1, 2, 3, \dots 5)$ are constants. Eq. (3) can only be used for the calculation of liquid water content. This is mainly due to the fact that below zero degrees Celsius, water will become ice, and the conductivity of ice is stronger than that of water. Due to the nonlinear characteristics of soil thermal conductivity, θ is replaced by $\theta + F\theta_i$ in Eq. (3), where $F = 1 + F_1\theta_i^{F_2}$, $\lambda_0(\theta)$ can be expressed as:

$$\lambda_0(\theta) = C_1 + C_2(\theta + F\theta_i) - (C_1 - C_4)exp\left\{ -\left[C_3(\theta + F\theta_i)^{C_5} \right] \right\} \quad (4)$$

The thermal conductivity of water and ice in soil can be distinguished through F. Thus, when the soil is frozen, the thermal conductivity of ice can be calculated.

2.3.2. Initial and boundary conditions

Initial conditions are obtained by linear interpolation of measured soil moisture at the beginning of simulation period. The upper and lower boundary conditions of heat flow are that temperature varies with time.

Since there is almost no surface runoff during the freezing period, the upper boundary condition of the model is the atmospheric boundary. In the simulation period, the upper boundary flux values, including rainfall and evaporation, are input daily in the model. The lower boundary is set at 100 cm. Considering that the permafrost table is 120 cm and the corresponding suprapermafrost water level is 120 cm, the free drainage boundary is adopted. The boundary conditions can be expressed as:

$$\begin{cases} K(h)\dfrac{\partial h}{\partial z} - K(h) = q_0(0,t) - \dfrac{dh}{dt} \quad h_a \le h \le h_s & z = 0, t > 0 \\ h = h_a \quad h < h_a \qquad h < h_a & z = 0, t > 0 \\ \left[\dfrac{\partial h}{\partial z}\right]_{z=100} = 0 & t > 0 \end{cases} \quad (5)$$

where q_0 is the net infiltration rate, that is, the difference between rainfall and evaporation, cm/d. h_a is the minimum pressure water head on the surface, which is set as −100,000 cm in this study. h_s represents the maximum stagnant depth of surface water, and is taken as 0 cm in the model.

Because the water content of surface soil in active layer of permafrost varies with time during the thawing period, the upper boundary condition of the model must consider surface water accumulation in this period. In this paper, the maximum stagnation depth of surface water is set at 10 cm. When the rainfall exceeds the maximum stagnation depth, the stagnation depth will not increase, and the excessive seepage water will form surface runoff. In the simulation period, the upper boundary flux values, including rainfall and evaporation, are input daily in the model. The lower boundary is set at 100 cm. Considering that the permafrost table is 120 cm and the corresponding suprapermafrost water level is 120 cm, the free drainage boundary is adopted. The boundary conditions can be expressed as:

$$\begin{cases} K(h)\dfrac{\partial h}{\partial z} - K(h) = q_0(0,t) - \dfrac{dh}{dt} \quad h_a \le h \le h_s & z = 0, t > 0 \\ h = h_a \quad h < h_a \qquad h < h_a & z = 0, t > 0 \\ \left[\dfrac{\partial h}{\partial z}\right]_{z=100} = 0 & t > 0 \end{cases} \quad (6)$$

where q_0 is the net infiltration rate, that is, the difference between rainfall and evaporation, cm/d. h_a is the minimum pressure water head on the surface, which is set as −100,000 cm in this study. h_s represents the maximum stagnant depth of surface water, and is taken as 10 cm in the model.

Table 1
Soil thermodynamic parameters.

Soil layer/cm	λ(θ)/(W/(m·°C))	C_n/(J/(kg·°C))	C_w(J/(kg·°C))
0–20	1.33	1157	2518
20–50	1.39	1215	2646
50–80	1.18	1026	2235
80–100	2.20	1920	4180

Table 2
Soil hydraulic properties.

Soil layer/cm	θ_r/(cm^3/cm^3)	θ_s/(cm^3/cm^3)	n	K_s/(cm/d)	l
0–20	0.09	0.37	1.73	20.54	0.5
20–50	0.06	0.42	1.73	28.80	0.5
50–80	0.07	0.29	1.65	49.86	0.5
80–100	0.08	0.31	1.60	98.56	0.5

2.3.3. Soil hydrothermal parameters

Van-Genuchten-Mualem model was used to describe soil water characteristic curve $\theta(h)$ and unsaturated hydraulic conductivity $K(h)$.

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h < 0 \\ \theta_s & h \ge 0 \end{cases} \quad (7)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (8)$$

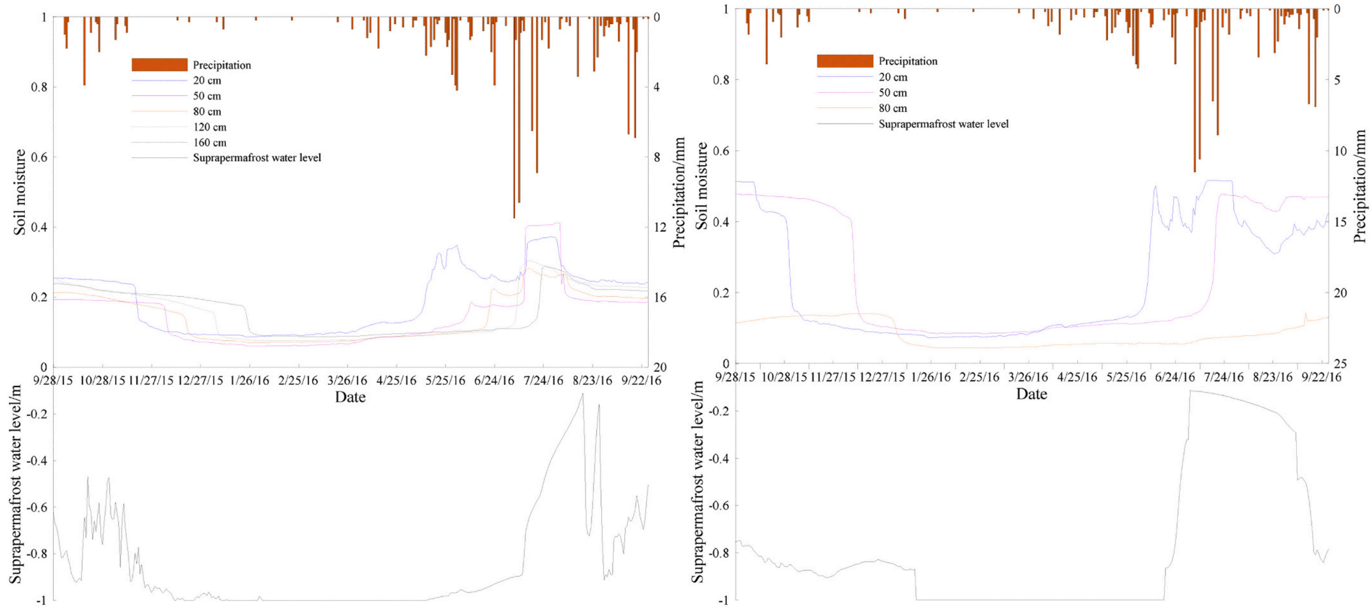
$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, m = 1 - \frac{1}{n}, n > 1$$

where θ_s represents saturated soil water content, cm^3/cm^3. θ_r represents residual water content in soil, cm^3/cm^3. $K_s$is saturated hydraulic conductivity, cm/d. α(cm^{-1}), n are the shape parameter. l *is* bending parameter.

In the simulation process, the soil is divided into four layers according to the soil genetic horizon in the permafrost (0–20 cm, 20–50 cm, 50–80 cm, 80–100 cm). The soil thickness is 100 cm, and the soil profile is divided into 100 units with equal spacing of 1 cm. The time step is variable. At the same time, it is assumed that the soil properties in the layer are uniform. Soil thermophysical properties of each layer were determined according to the reference value of national standard (GB50324-2001, 2014) and laboratory measurement. Based on the measured soil particle composition and bulk density of each layer, the hydraulic parameters of each layer were predicted by using the neural network module in HYDRUS-1D as the initial value.

Observed values of soil temperature and soil moisture of three soil layers (20 cm, 50 cm, 80 cm) were used to calibrate the soil thermodynamic parameters and soil hydraulic parameters in simulation model. In this study, correlation coefficient (R^2), root mean square error (*RMSE*), and nash efficiency coefficient (*NSE*) were used to evaluate the simulation results quantitatively. The equations for *RMSE* and *NSE* are as follows:

$$RSME = \sqrt{\frac{\sum_{i=1}^{N}(o_i - s_i)^2}{N}} \quad (9)$$



1# 4#

Fig. 4. Seasonal variation characteristics of soil hydrological processes in the active layer.

$$NSE = 1 - \frac{\sum_{i=1}^{N}(s_i - o_i)^2}{\sum_{i=1}^{N}(s_i - \overline{o})^2} \tag{10}$$

where s_i and o_i are the simulated and measured values of the i^{th} sample; $\overline{o}$ is the mean value of the measured value; N is the number of samples. *RMSE* reflects the average degree of absolute error between simulated value and measured value. *NSE* reflects the degree of agreement between the simulated value and the measured value with time. Fig. 3 shows the comparison results of soil temperature and soil moisture of three soil layers (20 cm, 50 cm, 80 cm) simulated by the model and the measured values. The simulation value is basically consistent with the measured value in the change trend, which shows that the simulation result of the model is good.

The calibration was carried out by multiple trial and error method. Table 1 and Table 2 show the calibrated soil thermodynamic parameters and hydraulic properties of each layer, respectively.

3. Results

3.1. Typical analysis of seasonal variation of soil hydrological process in active layer

This study compares with the relation among the atmospheric precipitation, soil moisture and suprapermafrost water table at the typical stage. It qualitatively analyzes the seasonal variation characteristics of soil hydrological processes in active layer. Fig. 4 show the seasonal variation of soil hydrological processes at the upper slope position (1#) and the lower slope position (4#), respectively.

1) The temperature begins to decrease at the rapid freezing phase. And the soil begins to enter the bidirectional freezing state of top-down and bottom-up. The temperature was only −9.7 °C in November 12, 2015. The rainfall was only 0.9 mm. And the rainfall is very small. When the rainfall passes through the surface and flows into the active layer, part of the rain water will supply the shallow soil moisture. Due to the influence of shallow-soil freezing, a freeze-thaw front will form in the active layer. The freezing soil will hinder the infiltration of soil moisture. The ability of shallow soil to retain the moisture will rapidly decline and reach the saturation. Part of the rainfall will flow laterally in the form of hillslope runoff. But because of less rainfall at this stage, the hillslope runoff is relatively weak. Thus, it can be seen from the diagram that the soil moisture at the depth of 20 cm is lower than the previous stage on the upper slope position (1#) and the lower slope position (4#). At the same time, the bidirectional freezing of soil occurs in the active layer. And the water content of shallow soil and deep soil will decrease due to be influenced by the soil freezing (Wang et al., 2016; Yang et al., 1993). Therefore, the soil moisture content at the depth of 50 cm is obviously higher than that at other depths. In addition, the soil temperature at the upper slope position (1#) is higher than that at the lower slope position (4#). The soil at the lower slope position begins to freeze earlier than that at the upper slope position. At this time, the decline rate of soil moisture at the depth of 20 cm on the upper slope position (1#) is significantly lower than that the lower slope position (4#). During this period, the supply ability of rainfall to soil water and groundwater reduces because of less rainfall. At the same time, due to the bidirectional freezing of soil in the active layer, the infiltration capacity of soil water weakens. During this period, the suprapermafrost water level thus decreases rapidly and gradually stabilizes. In addition, the soil at the lower slope position begins to freeze earlier than that at the upper slope position. It leads to that the decline of suprapermafrost water level at the lower slope position has gradually stabilized at this stage. But the suprapermafrost water level at the upper slope position is at a rapid decline stage.
2) The temperature is very low in the freezing stable stage and the soil in active layer enters the completely frozen state. The temperature was only −11.8 °C in January 30, 2016. The rainfall was only 0.2 mm. The rainfall infiltration process is relatively weak. Due to less rainfall, the lateral flow of the hillslope runoff is less. During this period, the soil in each layer of active layer is frozen and the soil moisture is mainly the volume content of unfrozen water. As can be seen from Fig. 4, the unfrozen water content at each layer is maintained at about 10% on the upper slope position (1#) and the lower slope position (4#). In addition, as can see from the figures, the soil

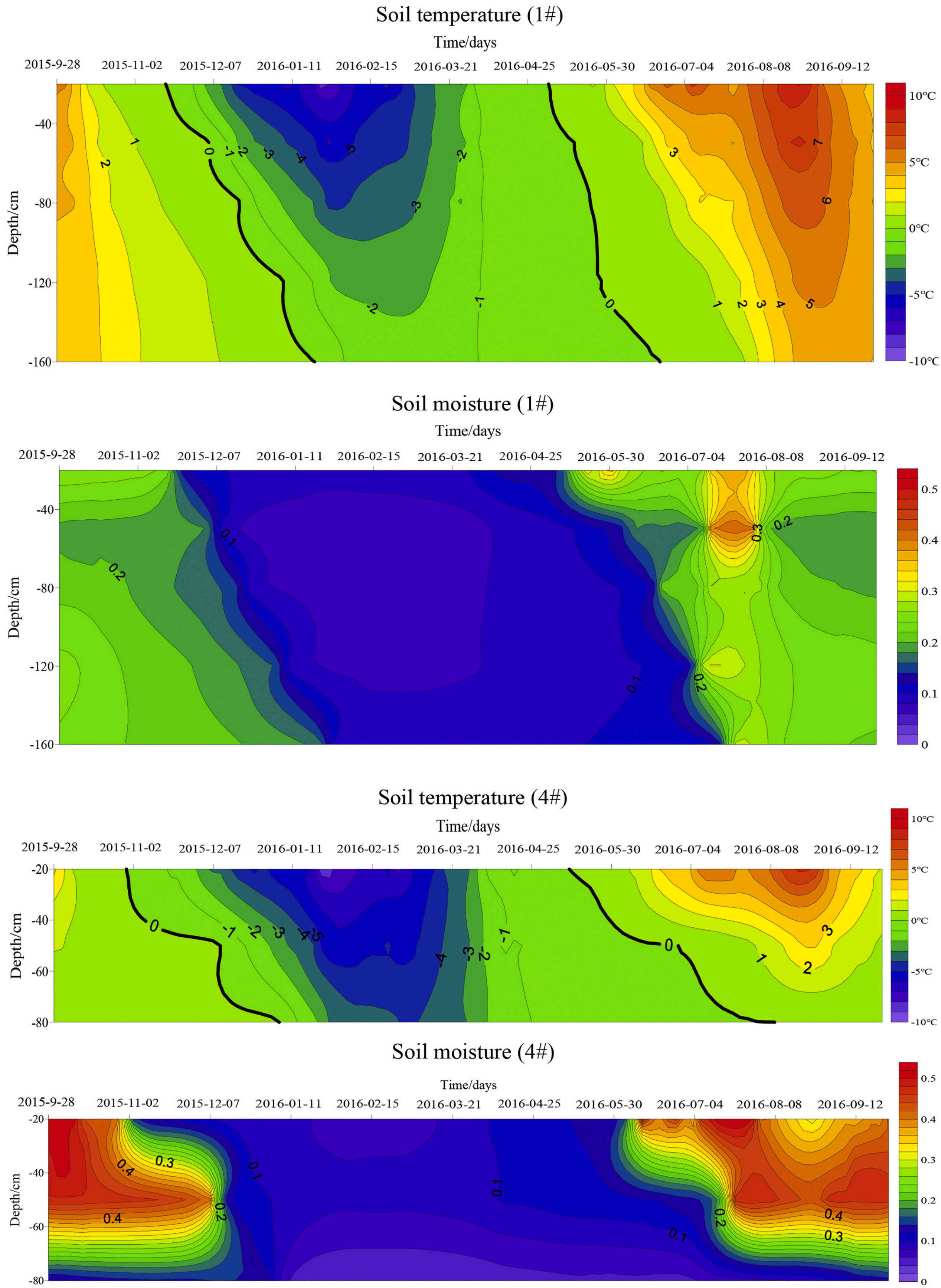
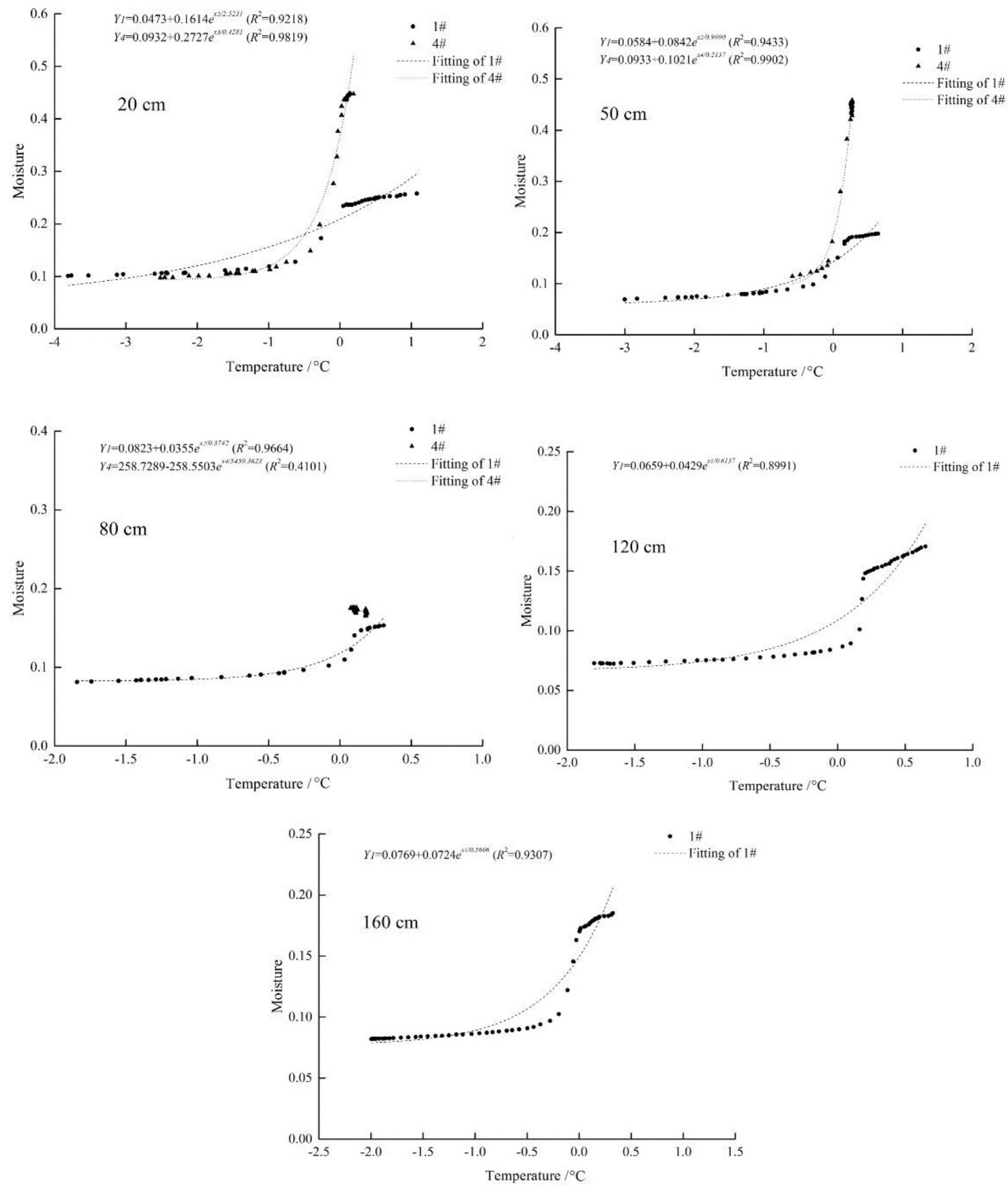


Fig. 5. Contour map of the soil temperature and soil moisture in the active layer



(1) Freezing process

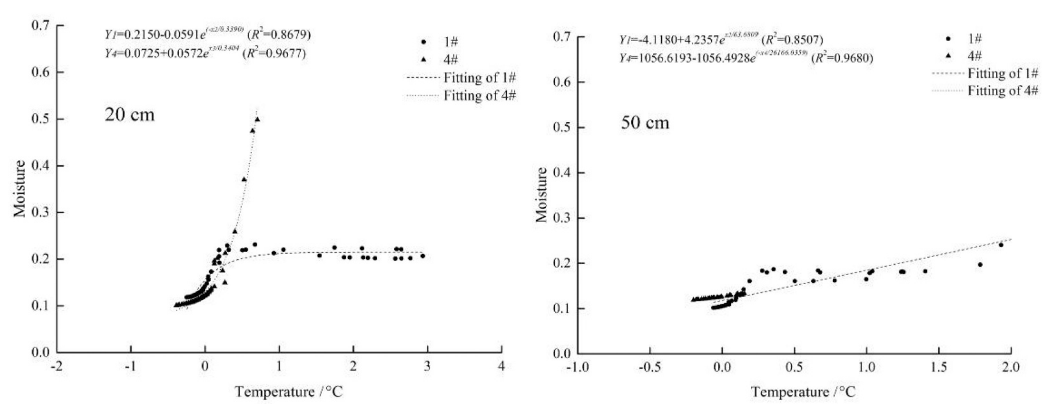
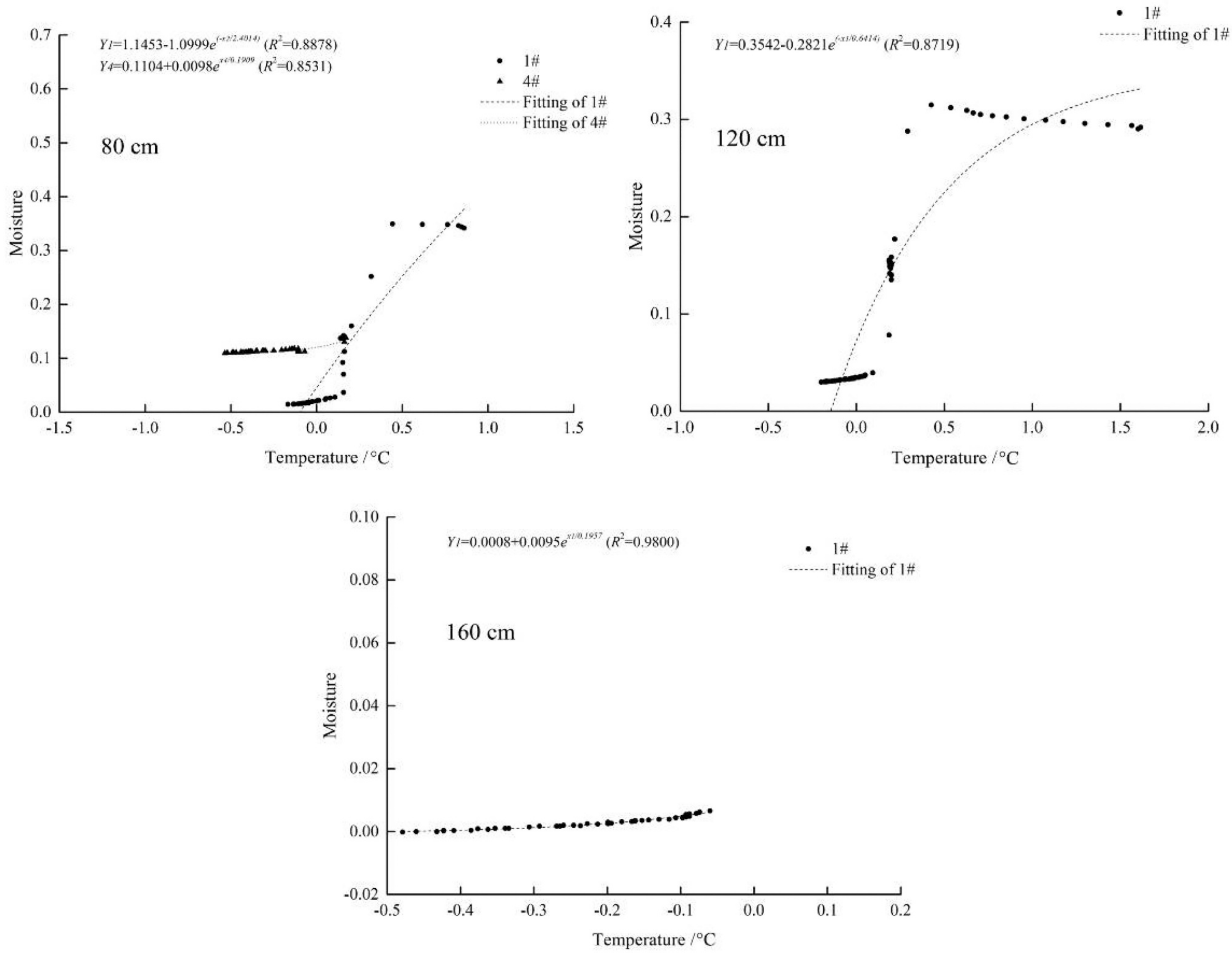


Fig. 6. Relationship between the soil moisture and the soil temperature in the freeze-thaw process.



(2) Thawing process

Fig. 6. (*continued*).

temperature at the upper slope position (1#) is lower than that at the lower slope position (4#). The soil at the upper slope position begins to freeze later than that at the lower slope position. It leads to that the unfrozen water content of all layers was just about 10% at the upper slope position (1#) in January 30, 2016. However, the unfrozen water content of all layers has reached about 10% in advance at the lower slope position (4#). As can be seen from Fig. 3, due to the influence of soil freezing during this period, the suprapermafrost water level has stabilized and is at its lowest level on the upper slope position (1#) and the lower slope position (4#).

3) During the period of rapid thawing, the temperature begins to rise gradually. The frozen soil in active layer begins to thaw from top to bottom. During this period, the upper part of the active layer is in a semi thaw state, while the lower part is in semi frozen state (Wang et al., 2016; Yang et al., 1993). The temperature was only −11.8 °C in June 24, 2016. The rainfall was 3.7 mm. Rainfall infiltration passes through the surface into the active layer. Precipitation, on the one hand, will recharge the shallow soil moisture. Because the shallow soil is semi thawed. When the capacity of shallow soil to retain water is saturated, the remaining precipitation will flow from uphill to downslope at the hillslope scale. Due to the gradual increase of rainfall during this period, the lateral flow of hillslope runoff will gradually increase. In addition, because of the semi-freezing state of soil in the lower part in this period, the effect of rainfall infiltration is increasing gradually. And soil volumetric water content is also increasing. But compared with the upper soil in semi-thawing state, its rise is less than that in the upper soil. Thus, as can be seen from Fig. 4, it is the largest vertical distance between the curve of soil water content at the depth of 20 cm and 50 cm on the upper slope position (1#) and the lower slope position (4#) during this period. It is mainly due to the influence of freeze-thaw process. In addition, the soil moisture content at the depth of 20 cm on the upper slope position (1#) is about 25%. Because of the influence of rainfall infiltration and lateral recharge of uphill overland flow, the soil moisture content at the depth of 20 cm on the lower slope position (4#) reaches about 50%. During this period, because of the increasing rainfall, the recharge capacity of soil water and ground water increases rapidly. At the same time, because the soil in active layer begins to thaw, it leads to the increase of soil water infiltration capacity. So the suprapermafrost water level increases rapidly during this period, and it is in the stage of rapid rise. In addition, the soil at the upper slope position (1#) begins to thaw earlier than that at the lower slope position (4#). So the suprapermafrost water level at the upper slope position (1#) begins to rise earlier than that at the lower slope position (4#). However, the source for the water is single at the upper slope position (1#) and it is mainly rainfall infiltration. So its rise cycle is longer, while the rise cycle is shorter at the lower slope position (4#).

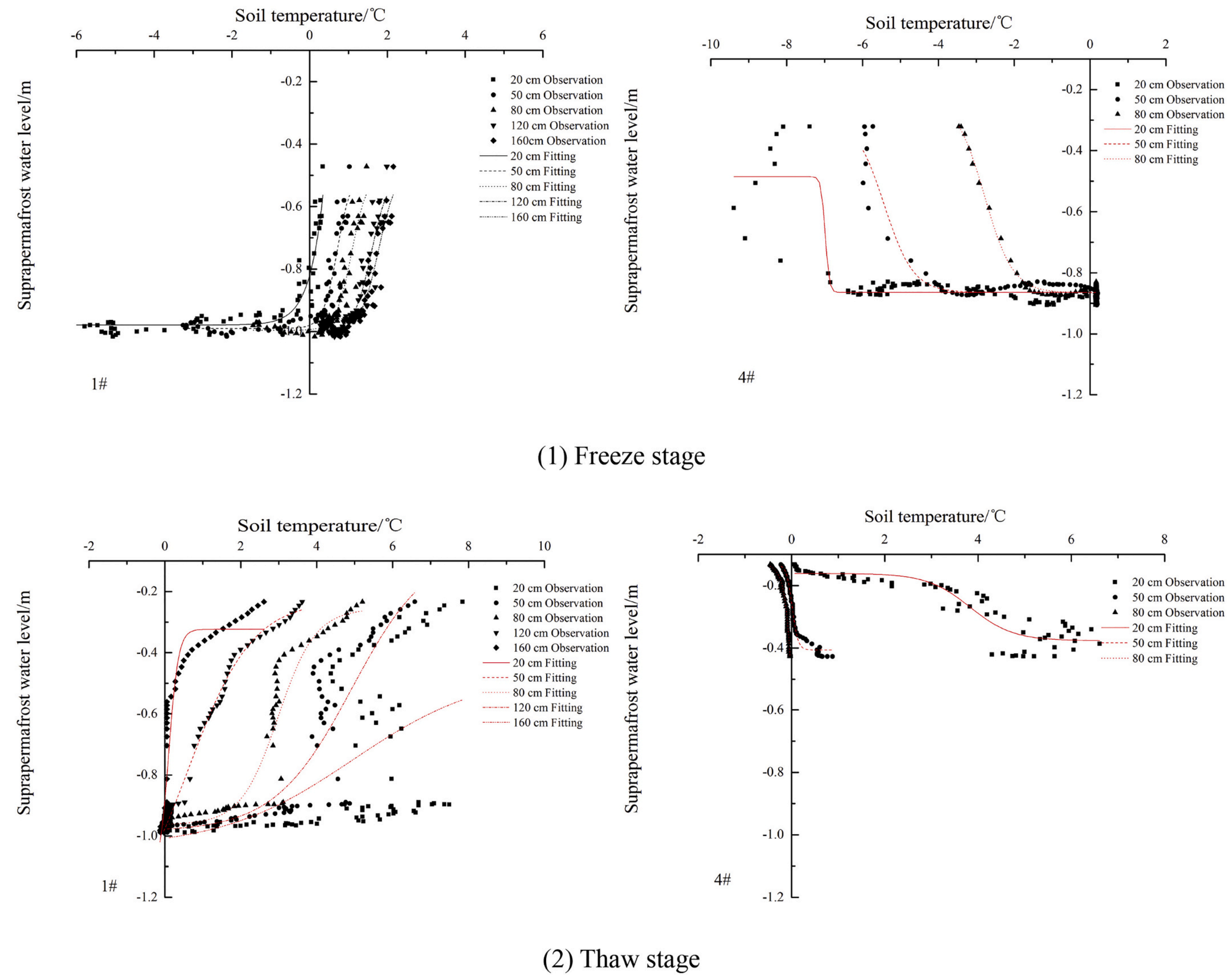


Fig. 7. Nonlinear fitting curve between soil temperature and suprapermafrost water level in the freeze-thaw stage.

4) During the thawing stabilization stage, the temperature is high. And the soil in active layer enters a state of complete thawing. The temperature was only 11.7 °C in August 14, 2016. The rainfall reached to 3.4 mm. The rainfall infiltration process is strong. Rainfall infiltration, on the one hand, supplies shallow soil moisture. Because of the abundant rainfall during this period, once the shallow soil reaches the saturation state, the rainfall will supply the surface soil moisture of the downstream by the form of overland flow. Due to the abundant rainfall during this period, the lateral flow of hillslope runoff is more frequent. The temperature is higher during this period, so the soil is in a state of complete thawing. And rainfall infiltration is the main source of soil water in the active layer. As can be seen from Fig. 4, the soil moisture in the upper and lower slopes will be saturated under the action of rainfall. So the soil moisture in each layer will be stable and show a certain level. In addition, the soil moisture content of each layer on the upper slope (1#) is maintained between 20% ~ 25%. Because of the influence of the rainfall infiltration and the lateral recharge from overland flow of the upper slope, the soil moisture content of each layer on the lower slope (4#) is between 40% ~ 50%. At the same time, it can be seen from Fig. 4 that soil moisture at 80 cm on the lower slope (4#) remained at around 10% at the freeze-thaw stage. It is mainly due to that the depth is at the bottom of the active layer. And the soil water content is unfrozen water content. A stable impermeable layer is formed in the lower part. During this period, because the rainfall is heavy, most of the rainfall will supply soil moisture and groundwater. At the same time, due to the full thawing of the soil in active layer, it results in the stronger infiltration capacity of soil water. So the suprapermafrost water level is higher and stable in this period. In addition, as can be seen from Fig. 4, because of the single-sourced water on the upper slope, it is mainly rainfall infiltration. Moreover, the soil layer on the upper slope is mainly coarse-grained soil and the vegetation coverage is low. So its water saturation capacity and water holding capacity are weak. This results in the poor stability of the groundwater level on the upper slope. And the lower slope is rich in water. In addition to rainfall infiltration, it can also receive the water from the upper slope. It may also be supplied by downstream rivers (lakes) and by upward infiltration of the thawing of the frozen layer. So the moisture is sufficient. Furthermore, the soil in active layer on the lower slope is mainly fine grained soil and the vegetation coverage is higher. So its water saturation capacity and water holding capacity are stronger, which results in relatively stable change of groundwater level.

Table 3
Nonlinear fitting parameters between soil temperature and suprapermafrost water level in the freeze stage.

Observation number	Depth/cm	Fitting result					
		R^2	Reduced Chi-Sqr	a_1	a_2	T_0	b
1#	20	0.8552**	0.0027	−0.9790	1242.9207	3.1952	0.3565
	50	0.8802**	0.0022	−0.9902	−0.4860	0.7131	0.1841
	80	0.8808**	0.0022	−0.9962	−0.4940	1.0841	0.2015
	120	0.8814**	0.0022	−0.9973	−0.4940	1.5892	0.2213
	160	0.8831**	0.0022	−0.9969	−0.4749	1.7790	0.2318
4#	20	0.8195**	0.0028	−0.4856	−0.8639	−6.9840	0.0513
	50	0.9168**	0.0013	−0.2898	−0.8641	−5.4960	0.3857
	80	0.9719**	0.0004	−0.2308	−0.8655	−2.7835	0.3769

Table 4
Nonlinear fitting parameters between soil temperature and suprapermafrost water level in the thaw stage.

Observation number	Depth/cm	Fitting result					
		R^2	Reduced Chi-Sqr	a_1	a_2	T_0	b
1#	20	0.8950**	0.0068	−1.1344	−0.3235	0.1003	0.1275
	50	0.9949**	0.0003	−1.3356	−0.2292	0.6139	0.8455
	80	0.8891**	0.0072	−0.9630	−0.2566	2.9841	0.4926
	120	0.7751*	0.0145	−0.9851	−0.0490	4.9255	1.0214
	160	0.2714*	0.0471	−1.0390	−0.4618	4.9544	1.7441
4#	20	0.8621**	0.0014	−0.1611	−0.3765	3.8272	0.4625
	50	0.9841**	0.0002	−0.1323	−0.4064	0.0156	0.0619
	80	0.9774**	0.0002	−0.1315	−5.4349	0.2844	0.1122

3.2. Influence of freeze-thaw processes on soil hydrological process in active layer

3.2.1. Change relationship between soil temperature and soil moisture

Fig. 5 shows the contour map of the soil temperature and soil moisture in the active layer at the upper slope position (1#) and the lower slope position (4#), respectively. It can be seen from Fig. 5 that the soil temperature isotherms are relatively dense in the freezing stage, indicating that the soil temperature drops rapidly. The gradient of the zero isotherm is small, which means that the time of complete freezing of soil in the active layer is short. And the gradient of the isotherm of soil moisture in the same period is roughly the same as that of the zero isotherm. The corresponding time of zero isotherm is slightly earlier than that of rapidly changing soil moisture. And compared with the upper slope (1#), the lag time on the lower slope (4#) is longer. With the increase of depth, the lag phenomenon is more obvious. In the stage of thawing, the gradient of the zero isotherm is large, which means that the time of complete thawing of soil is long. And the isotherm at this period is slightly sparse compared with the freezing stage, which means that the rate of temperature rise is slow. Compared with the freezing stage, the isoline of soil moisture is more dense, but the gradient is larger, which indicates that the thawing rate at the same depth is greater than the freezing rate. At different depths, the turning point of soil moisture thawing is slightly earlier than the boundary date when the soil temperature rises above zero, which indicates that when the soil temperature is still below zero, the thawing of frozen soil has started quietly.

Fig. 6 show the coupling relationship between soil temperature and soil moisture at different depths during the freeze-thaw process. In the process of freezing, with the decrease of soil temperature, the shallow soil moisture decreases faster, while the deep soil moisture changes slower. And the decrease rate and range of soil moisture in the lower slope (4#) are higher than that in the upper slope (1#). It can be seen from the figure that the soil temperature and soil moisture at different depths show a relatively significant exponential linear correlation. In the process of thawing, with the increase of soil temperature, the shallow soil moisture increases faster, while the deep soil moisture changes slower. Moreover, the rate and range of soil moisture decrease in the lower slope (4#) were significantly higher than that in the upper slope

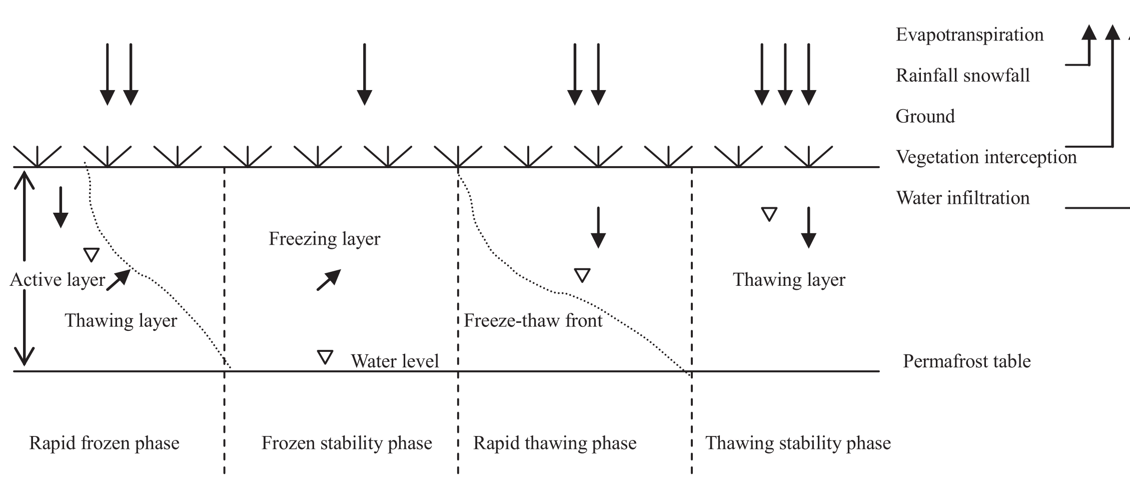


Fig. 8. Diagram of flow process in active layer at different stages.

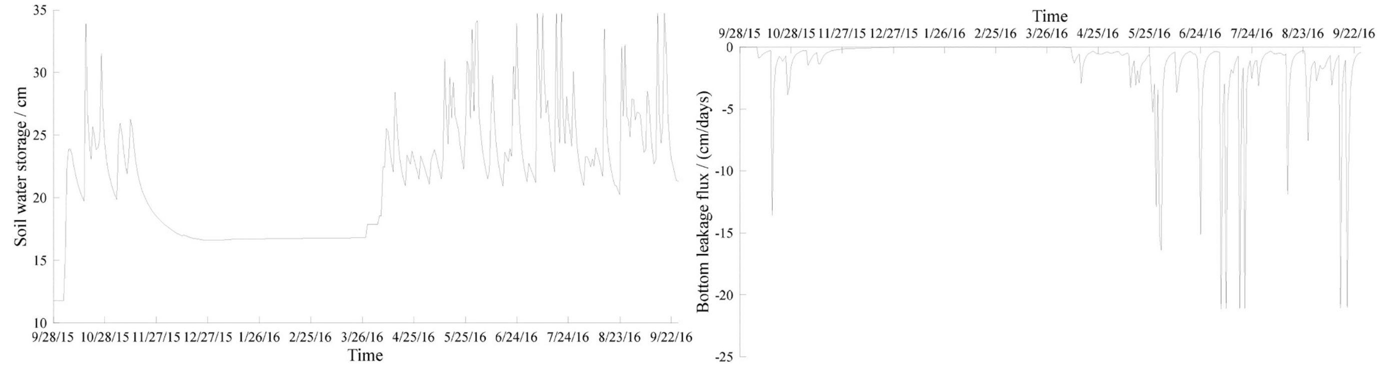


Fig. 9. Changes of soil water storage and bottom leakage flux in active layer.

(1#). Soil temperature and soil moisture showed a significant exponential linear correlation at different depths. The correlation coefficient is between 0.85 and 1.

3.2.2. *Change relationship between soil temperature and suprapermafrost water level*

We employed the method of non-linear least squares by fitting a statistical curve to deeply analyze the relationship between soil temperature and suprapermafrost water level in the freeze-thaw stage in Origin 9.0 software. The non-linear fitting results between soil temperature and suprapermafrost water level are shown in Fig. 7. Tables 3 and 4 show the parameters of non-linear fitting curve between soil temperature and suprapermafrost water level in the freeze-thaw stage.

As can be seen from Fig. 7 and Table 3-4, there are significant differences between soil temperature at different depths and suprapermafrost water level on the upper slope (1#) and on the lower slope (4#) during the freeze-thaw period. Values of Reduced Chi-Sqr are less than 0.01. The correlation coefficient (R^2) on the upper slope (1#) is higher than 0.27, respectively. The correlation coefficient (R^2) on the lower slope (4#) is higher than 0.81, respectively. The relationship between soil temperature and suprapermafrost water level shows Boltzmann function relations by fitting analysis of non-linear least square method (Chang et al., 2015). The relationship expression is as follows.

$$U = a_2 + (a_1 - a_2)/(1 + exp((T - T_0)/b))$$

where U is the suprapermafrost water level, m; T is the soil temperature at different depths, °C; T_0 is the initial soil temperature at different depths, °C; a_1, a_2, b are constants, which are related to the soil characteristics at different depths, and change with the change of soil depth. This means that during the freeze period, soil temperature with different depths is closely related to suprapermafrost water level in a statistical significance.

4. Discussions

4.1. *Seasonal variation characteristics of soil hydrological process in the active layer*

Due to the presence of permafrost, the hydrological process in permafrost regions is distinguished from other regions. It is because that permafrost is a cryogenic geological body and natural water-resisting layer in cold regions. At the same time, there is a formation of freeze-thaw front in the active layer due to the freeze-thaw affect. The upper part is a thawing layer and the lower part is a frozen layer. And the freeze-thaw front and the permafrost layer have the impermeable properties or weak permeability. As the permafrost is very sensitive to temperature, the freeze-thaw front would migrate in the active layer with the temperature change. And the permafrost table will also move down. It will change the infiltration capacity of soil water. It will also influence the migration pattern of overland flow and interflow. They all show the complexity and the particularity of permafrost hydrological process (Chang et al., 2015; Cheng and Jin, 2013). The flow process model of the active layer in different stages is shown in Fig. 8. Rainfall infiltration is the main driving force of the soil hydrological process in the hillslope scale. And the freeze-thaw front of active layer is the main limiting factor. Influenced by the freeze-thaw process, the rainfall decreases and the soil freezes in the freezing period. It leads to that the thickness of frozen layer is larger than that of thawing layer. The freeze-thaw front moves upward. So the soil water storage capacity decreases and the soil water infiltration stops. And the lateral flow of slope surface also decreases. Thus, the soil water content in the active layer is lower and the suprapermafrost water level is in a downward trend. The rainfall increases and the soil thaws in the thawing period. It leads to that the thickness of thawing layer is larger than that of frozen layer. The freeze-thaw front moves downward. So the soil water storage capacity increases and the soil water infiltration strengthens. And the lateral flow of slope surface also increases. Thus, the soil water content in the active layer is higher and the suprapermafrost water level is in an upward trend.

At the same time, influenced by the slope topography, the thickness of the active layer on the upper slope is greater than that on the lower slope. And the freeze-thaw front on the upper slope is gentler than that on the lower slope. The change amplitude of soil temperature on the upper slope is smaller than that on the lower slope. As a result, during the freeze-thaw period, the change of soil moisture and suprapermafrost water level on the upper slope is relatively gentle compared with the lower slope. In addition, due to the influence of slope gravity, soil texture and vegetation cover, the soil on the upper slope mainly receives the recharge of atmospheric precipitation. So the source is relatively simple and the generating probability of slope runoff is higher than that on the lower slope. In addition to the recharge of atmospheric precipitation, the soil on the lower slope will also accept the supply of uphill soil water or overland runoff. There are also supplies of rivers and lakes. So the water filling capacity and water holding characteristics in active layer on the lower slope are stronger than that on the upper slope. Therefore, on the whole, the soil water content of the upper slope is lower than that of the lower slope. And the suprapermafrost water level on the lower slope is relatively stable.

4.2. *Vertical migration characteristics of soil hydrological process in active layer*

Fig. 9 shows the simulation results of variation of soil water storage and bottom leakage flux in the active layer. The simulation time is one freeze-thaw cycle (September 28, 2015 to September 26, 2016). It can be seen from the figure that the water storage capacity of frozen soil is relatively high in the rapid freezing stage and the thawing stage. And the

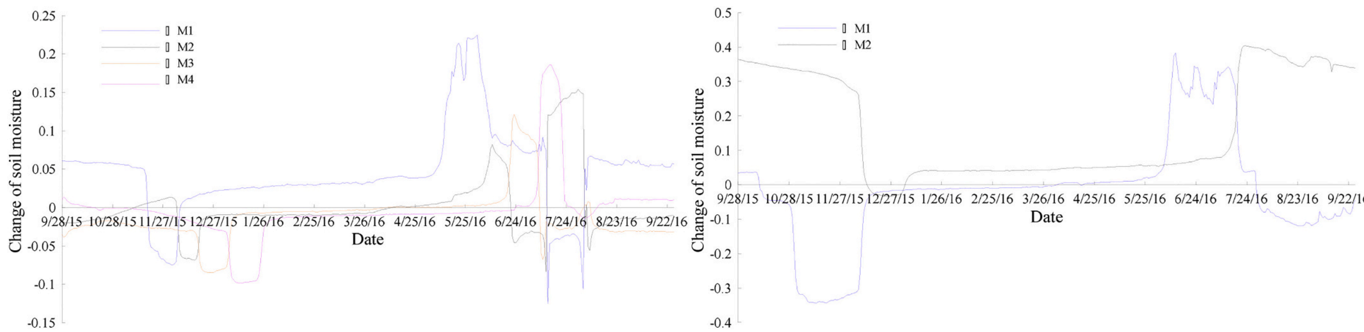


Fig. 10. Change results of soil moisture between layers in the active layer.

flux of seepage at the bottom is also strong in the same period. It means that the soil moisture in the active layer mainly migrates downward in the rapid freezing stage and the thawing stage. In the rapid freezing stage, influenced by the bottom-up freeze of the soil, the soil moisture will migrate to the freeze-thaw front and infiltrate downward due to the temperature gradient. In the thawing stage, the soil begins to thaw from top to bottom due to the rising temperature. It will also lead to the up-bottom infiltration of soil moisture due to be driven by the increased rainfall. Moreover, it can be seen from the figure that the soil moisture in the active layer has a downward migration trend after a freeze-thaw cycle (Zhao et al., 2000). Once the soil begins to freeze, the soil moisture will migrate to the freeze-thaw front. The slower the soil freezes, the greater the soil moisture increases at the freeze-thaw front. Because the bottom-up freeze process of the active layer is a slow process, it will result in the increase of soil water content near the permafrost table after a freeze-thaw cycle. This is the main reason for the formation of underground ice near the permafrost table.

The soil will undergo the bidirectional freeze process in the later period at rapid freezing stage. During this period, the soil temperature in the middle part of the active layer is high, while the temperature in the upper and lower parts is low. It will lead to that the soil moisture will migrate to the freeze-thaw front due to the temperature gradient. So in addition to infiltration from top to bottom, the soil moisture also infiltrate upward. In the stable freezing stage, the soil completely freezes due to the lower temperature. The water storage of the frozen soil in the active layer is basically stable. So the bottom seepage flux is also stable. Fig. 5 shows that the soil temperature at the upper part of the active layer is low and the lower part is high in this stage. And the temperature gradient gradually increases. Therefore, driven by the temperature gradient, the unfrozen water in the active layer moves from bottom to top. However, due to the extremely low soil temperature, the content of unfrozen water are limited, which makes its migration volume less. Fig. 10 shows the change results of soil moisture between layers in the active layer. It can be seen from the Fig. 10 that although the soil is completely frozen during the freezing stage, there are still slight changes of soil moisture at surface layer. This means that there is an upward migration of unfrozen water in this period.

5. Conclusions

This article investigated the soil hydrological process in the active layer of permafrost regions. It compares with the relation among the atmospheric precipitation, soil moisture and suprapermafrost water table at the typical stage. And it also simulates the influence of freeze-thaw processes on soil hydrological process in the active layer by using the freeze-thaw module of HYDRUS-1D software. Based on the above-mentioned results, the following conclusions can be drawn.

1) The soil moisture and the suprapermafrost water-level are divided into four stages based on the freeze-thaw process. Rainfall infiltration is the main driving force of soil hydrological processes in the active layer, and the freeze-thaw front of the active layer are the main limiting factors. Due to the influence of freeze-thaw process, the precipitation in the freeze period decreases. The soil water-storage-capacity will decrease because of the soil freezing. And the soil water infiltration stops and the slope lateral flow also decrease. So the soil moisture and the suprapermafrost water-level are in a downward trend. In the thawing period, the conclusion is the opposite.
2) The active layer thickness (ALT) is greater on the upslope than that on the downslope due to the influence of terrain slope. It leads to that the change of the freeze-thaw front on the upslope is more gently than that on the downslope. And the change variation of the soil moisture and the suprapermafrost water-level on the upslope is also more gently than that on the downslope. So the soil moisture content on the upslope is also more low than that on the downslope. And the suprapermafrost water-level permafrost on the downslope is relatively stable.
3) Temperature is the key factor that affects soil hydrologic process of the active layer in permafrost regions. There is the coupling relationship between soil temperature and soil moisture at different depths during the freeze-thaw process. Soil temperature and soil moisture showed a significant exponential linear correlation at different depths. Moreover, the soil temperatures and the suprapermafrost water levels at different depths show extremely significant level under the slope scale. The relationship between soil temperature and suprapermafrost water level shows Boltzmann function relations by fitting analysis of non-linear least square method.
4) Soil moisture in the active layer mainly migrates downward in the rapid freezing stage and the thawing stage. It has a downward migration trend after a freeze-thaw cycle. Because the bottom-up freeze process of the active layer is a slow process, it will result in the increase of soil water content near the permafrost table after a freeze-thaw cycle. This is the main reason for the formation of underground ice near the permafrost table. Moreover, driven by the temperature gradient, the unfrozen water in the active layer moves from bottom to top during the freezing stage.

Although a great deal of analysis has been done on the soil hydrological process in the active layer of permafrost regions, this study is limited to the period of the field observation; especially, the time series of monitoring data of rainfall, soil moisture and suprapermafrost water level is relatively short. Thus, to some extent, this has restricted the study revealing the change of soil water movement in the active layer of permafrost regions. So it requires more field-monitoring data in the future to verify the validity of the conclusions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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