Innovative water resources management – understanding and balancing interactions between humankind and nature

Impacts of the thawing-freezing process on runoff generation in the Sources Area of the Yellow River on the northeastern Qinghai-Tibet Plateau

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Abstract. In cold regions, precipitation, air temperature and snow cover significantly influence soil water, heat transfer, the freezing-thawing processes of the active soil layer, and runoff generation. Hydrological regimes of the world's major rivers in cold regions have changed remarkably since the 1960s, but the mechanisms underlying the changes have not yet been fully understood. Using the basic physical processes for water and heat balances and transfers in snow covered soil, a water-heat coupling model for snow cover and its underlying soil layers was established. We found that freezing-thawing processes can affect the thickness of the active layer, storage capacity for liquid water, and subsequent surface runoffs. Based on calculations of thawing-freezing processes, we investigated hydrological processes at Qumalai. The results show that the water-heat coupling model can be used in this region to provide an understanding of the local movement of hydrological regimes.

1 Introduction

Recently, the earth system has been influenced by permafrost and glacier evolvement. The area of China's seasonally frozen soil region is $5.137 \times 10^6 \, \text{km}^2$, with an additional $2.068 \times 10^6 \, \text{km}^2$ as permafrost. This accounts for 75 % of China's total land area (Xu and Deng, 1991). Investigation of permafrost hydrology is important for local ecosystem security and human life. The extensive collection of field measurement data during the last decades has increased considerably, including the available information on hydro-meteorological processes in cold regions, but most of these data are too fragmentary.

Frozen soil plays an important role in the hydrology of cold regions (Harris et al., 2009). Many studies on frozen soil have been conducted. The SHAW model incorporates land surface processes to describe the snow-melting effect and the freezing-thawing process in a one-dimensional study (Flerchinger and Saxton, 1989). The most important part of this kind of model is the connection between coupled mechanisms. Snow cover greatly affects the heat and water transfer

to the underlying soil. Thus, soil water-heat movements and snow cover conditions have important theoretical value (Jorgenson et al., 2001; Harris et al., 2001; Heginbottom, 2002; Romanovsky and Osterkamp, 2001).

The coupled, dynamic model developed in this paper, using snow cover and frozen soil together, sets the connection between snow cover and soil and demonstrates an association between snow cover and soil.

2 Methods

The snow-soil coupled model established in this paper comprises a snow cover: water and heat movement model and a frozen soil: water-heat coupled movement model.

2.1 Snow cover model

On the basis of conservation of energy (Xu and Li, 2003), the net heat flux of snow cover is equal to the intersystem heat increase over the same interval. The snow exchanges energy with the atmosphere above and ground below. The net energy

flux of the snowpack can be expressed as

$$Q_{\text{net}} = Q_r + Q_s + Q_l + Q_p + Q_g \tag{1}$$

where Q_{net} is net input energy for snowpack (J m^{-2}); Q_r is the net radiation flux (W m^{-2}); Q_s is flux of sensible heat (W m^{-2}); Q_l is flux of latent heat (W m^{-2}); Q_p is heat flux supplied by precipitation (W m^{-2}); Q_g is ground heat flux (W m^{-2}) always being neglected.

Based on the water balance, daily snow melt was estimated using the net energy of the snow cover.

The snow melt can be divided into three phases: warming, ripening and output (Dingman, 1994).

$$W_{\text{liq}} = W_{\text{liq}} + (P_r E + \Delta W) \tag{2}$$

$$W_s = W_s + (P_s S \Delta W) \tag{3}$$

where W_{liq} is liquid water content (m); W_s is snow water equivalent (m); ΔW is the energy for water transfer; P_s is snowfall (m); S is sublimation (m); E is evaporation (m); C_i is heat capacity of snow ($\text{J kg}^{-1\,\circ-1}$); λ_f is latent heat of fusion (kJ kg^{-1}).

When W_{liq} is larger than the holding capacity of the snow cover, the outflow from the snow cover is described as

$$W_{\text{out}} = W_{\text{liq}} - W_{\text{liq\_max}} \tag{4}$$

where $W_{\text{liq\_max}}$ is the holding capacity of the snow cover (m) and W_{out} is the outflow from the snow cover (m).

## 2.2 The frozen soil water-heat coupled movement model

We hypothesized the following assumptions could be applied to our model, including the influence of soil water vapor migration and heat flow transfer can be ignored; the soil is considered vertical and non–plastic soil; vertical heat and moisture flux; and Darcy's law applies to moisture movement in both saturated and unsaturated conditions (Shoop and Bigl, 1996). Based on these assumptions, water and heat movement in seasonally frozen soil can be treated as a one-dimensional problem.

Water movement in freezing and thawing soil can be expressed as Richard's equation and a one-dimensional heat transport equation for a freezing or thawing column of soil.

$$C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial Z}\left(\lambda \frac{\partial T}{\partial Z}\right) + L_f \rho_i \frac{\partial \theta_i}{\partial t} \tag{5}$$

$$\frac{\partial \theta_l}{\partial t} = \frac{\partial}{\partial Z}\left(D(\theta_l)\frac{\partial \theta_l}{\partial Z} - K(\theta_l)\right) - \frac{\rho_i}{\rho_l}\frac{\partial \theta_i}{\partial t} \tag{6}$$

where $D(\theta_l)$ is the diffusivity of soil ($\text{m}^2\,\text{s}^{-1}$); $K(\theta_l)$ is unsaturated hydraulic conductivity of soil (m s^{-1}); ρ_s is density of ice (kg m^{-3}); ρ_l is density of liquid water (kg m^{-3}); θ_l is
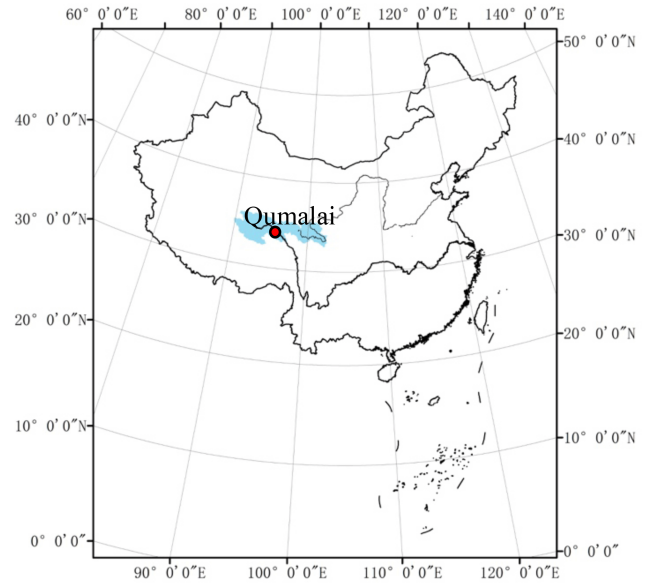
Figure 1. Distribution of observation site in the Three–River Source Region.

volumetric liquid water content (%); θ_s volumetric ice content (%); C_s is volumetric heat capacity of soil ($\text{J m}^{-3\,\circ-1}$); λ is thermal conductivity of soil ($\text{W m}^{-1\,\circ-1}$); L_f is latent heat of fusion (J kg^{-1}); T is soil temperature ($^\circ$); Z is depth (m); t is time (s).

2.3 Coupled model

Based on the water balance, the water content θ_{l_top} in the top layer of soil relied on the outflow from snow pack W_{out}, and evaporation from soil surface E_{soil}, the liquid content in top soil layer was given by

$$\theta_{l\_\text{top}} = \beta(W_{\text{out}} - E_{\text{soil}}) \tag{7}$$

where β is the constant coefficient.

3 Study site

The observation site selected for this study, Qumalai (34.13° N, 95.78° E), is located in the middle of the Three-River Source Region. The average elevation of Qumalai is 4500 m (Fig. 1). Controlled by the high altitude and pressure, the climate in Qumalai includes strong radiation, long light duration and seasonal variations for warm (four or five) months and cold (seven or eight) months. The mean annual air temperature is $-3.3°$. The mean annual precipitation is 380–470 mm. (Yin et al., 2010).

The atmospheric data used in this study includes hourly precipitation, air temperature, relative humidity, wind velocity, hours or daylight and atmospheric pressure. Daily snow thickness, soil freezing depths, soil temperature at depth of
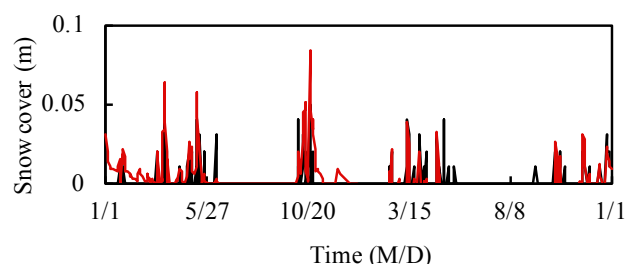
Figure 2. Comparison between simulated (red solid line) and measured (black solid line) results for the thickness of snow cover from 2005 to 2006.

Figure 3. With the observed soil surface temperature at the corresponding times, the comparison between measured (red dashed line) and simulated (blue dashed line) freezing depth of soil from October 2005 to June 2006.

15 cm and soil water content at the depth of 50 cm were monitored from 2005 to 2006.

Permafrost and seasonal frozen soil is widely distributed throughout the study area. Because of the presence of frozen soil, water retention in the soil can be enhanced for both rain and snow melt compared to soils in non-frozen or temperate regions. The permafrost dynamics greatly influence the hydrologic processes (McGuire, 2002; Walker et al., 2003).

4   Results

4.1   Snow depth

Observation of air temperature, snow surface temperature, humidity, rainfall, wind velocity, atmospheric pressure and hours of daylight provided a good dataset for driving the snow cover model. Comparisons between simulated and measured results for snow depth in 2005–2006 are shown in Fig. 2.

According to Fig. 2, the snow depth trends were the same for both the simulated results and the measured values. At Qumalai, snow accumulation was measured from late October through the middle of May the following year, when the melting process finished. Between mid-March and early November, the snow depth reached a maximum.

4.2   Freezing depth

The daily mean freezing depth was used in the following analysis. Figure 3 shows the depth of frozen soil from October 2005 to June 2006. The simulation of the frozen soil trend for the whole period was consistent with measurements.

The daily mean soil temperature grew progressively colder in October, and the surface soil began to freeze at the same time. Over time, the soil froze deeper, and after 141 days (11 March), it was frozen to 95 cm.

The majority of the site began to thaw in April, when temperatures grew warmer. The shallow layer of soil began thawing on 15 March. By early April, the layer below 140 cm also began to thaw, though the layers between 70 and 140 cm
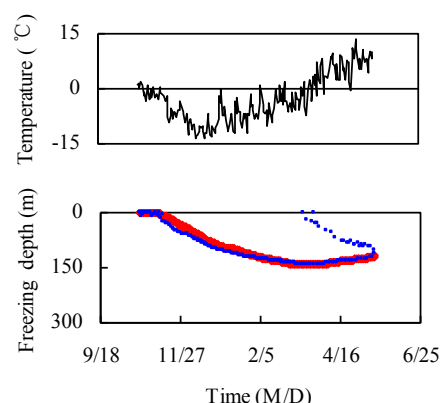
depth remained frozen. The remaining frozen soil thawed from both the top and bottom depths.

4.3   Soil temperature

Figure 4 shows the simulated and measured daily average temperatures for every day of 2005–2006. According to Fig. 4, both the simulated and measured soil temperatures show the same trend. The soil temperature warmed from late March into late October, which corresponds to when the soil thawed (Fig. 3).

To detect the numerical model efficiency, efficiency coefficients (EC) and root mean squared errors (RMSE) were used. RMSE for simulated daily soil temperatures of 2005–2006 ranged from 1.82 to 1.9°, and EC was 0.94. There was no distinct difference for the surface soil. This means that there was no system error for the model used at these sites, and the simulated temperature for surface soil was coincident with the measured value.

4.4   Soil water content

Soil liquid water content was measured at 50 cm from April to October 2005 at Qumalai. The comparisons between simulated and measured results are shown in Fig. 5.

The simulated liquid water content decreased in early May, when there was heavy evaporation and no precipitation. As the evaporation decreased, the liquid water content increased, while precipitation created an increase in soil moisture.

From the simulation results, we found that during the thawing period, the soil liquid water content was significantly affected by the surface conditions, including precipitation and evaporation.
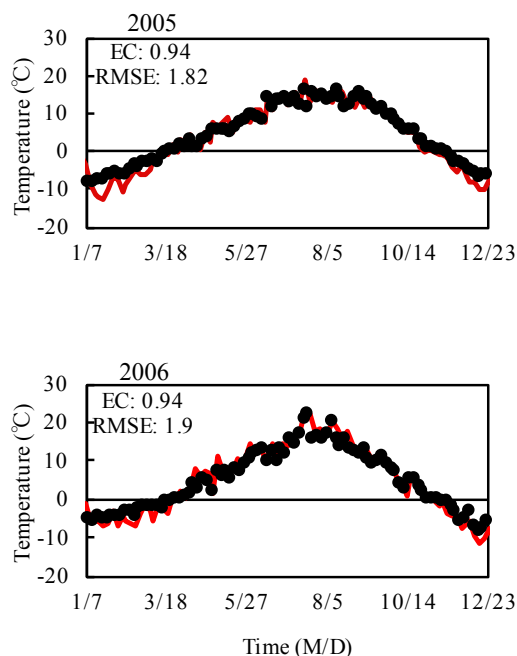
Figure 4. Comparison between simulated (red solid line) and measured (black dashed line) results for soil temperature at 15 cm depth in 2005–2006.
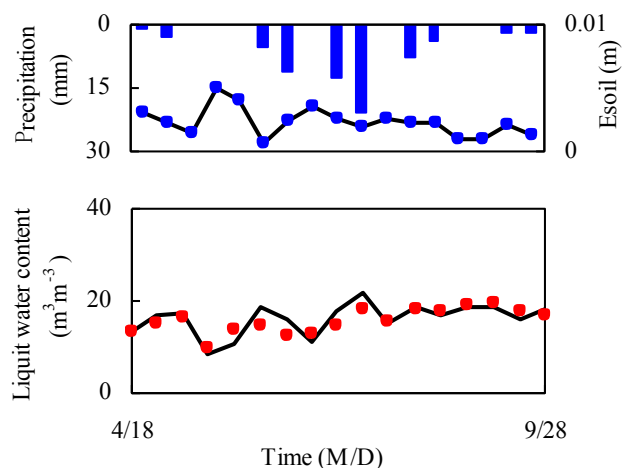

Figure 5. With the observed precipitation (blue bar) and simulated evaporation (black solid line with blue circle) at the corresponding time, comparison between simulated (black solid line) and measured (red dotted line) results for soil liquid water content at 50 cm depth in 2005.

4.5 Runoff

4.5.1 In soil thawing period

In most parts of the Three-River Source Region, the liquid water storage capacity gradually increased as the soil water phase changed from ice to liquid. The thawing process
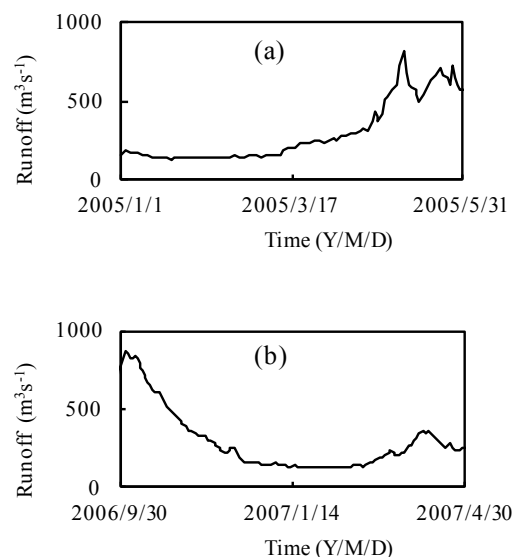
Figure 6. Runoff in the Yellow-River Source Region from 2005 to 2007. The study was carried out during the thawing (March to April) and freezing (October to March) periods.

caused the unsaturated soil status and snowmelt filtration. Runoff from the Yellow-River Source Region did not vary very much until late April, when the soil was completely thawed (Fig. 6a).

4.5.2 In soil freezing period

Runoff fluctuated between 124 and 240 $m^3 s^{-1}$, resulting from increased air temperature, evaporation and snowmelt. Runoff increased suddenly in mid-December 2006 (Fig. 6b) because of the high air temperature and deep frost depth. Based on the above analysis, the main factors affecting runoff during the frozen soil period are air temperature, evaporation and frozen soil, which stops further penetration of liquid water causing it to runoff.

During the later period of frozen soil, especially from late February to mid-March 2007, the runoff increased. This was due to the frozen soil and increasing precipitation and air temperature.

5 Conclusions

Snow cover has significant effects on water and heat in freezing and thawing soil. According to the main physical processes of water and heat transfer in snow cover and soil, a cold region snow-soil coupled model was established. Using measured data for seasonal snowmelt, water and heat status, frozen depth, liquid water content and soil temperature were simulated numerically. The simulation results were compared with measured values at corresponding times and locations to verify the reliability and precision of the model.

With the thawing and freezing of soil, runoff varied greatly. This means seasonal variations in the thawing-freezing process of the soil's active layer played a significant role in the seasonal runoff shift in the Three-River Source Region.

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