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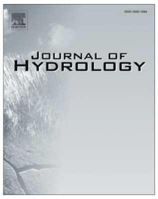

Simulation and prediction of suprapermafrost groundwater level variation in response to climate change using a neural network model

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SUMMARY

Suprapermafrost groundwater has an important role in the hydrologic cycle of the permafrost region. However, due to the notably harsh environmental conditions, there is little field monitoring data of groundwater systems, which has limited our understanding of permafrost groundwater dynamics. There is still no effective mathematical method and theory to be used for modeling and forecasting the variation in the permafrost groundwater. Two ANN models, one with three input variables (previous groundwater level, temperature and precipitation) and another with two input variables (temperature and precipitation only), were developed to simulate and predict the site-specific suprapermafrost groundwater level on the slope scale. The results indicate that the three input variable ANN model has superior real-time site-specific prediction capability and produces excellent accuracy performance in the simulation and forecasting of the variation in the suprapermafrost groundwater level. However, if there are no field observations of the suprapermafrost groundwater level, the ANN model developed using only the two input variables of the accessible climate data also has good accuracy and high validity in simulating and forecasting the suprapermafrost groundwater level variation to overcome the data limitations and parameter uncertainty. Under scenarios of the temperature increasing by 0.5 or 1.0 °C per 10 years, the suprapermafrost groundwater level is predicted to increase by 1.2–1.4% or 2.5–2.6% per year with precipitation increases of 10–20%, respectively. There were spatial variations in the responses of the suprapermafrost groundwater level to climate change on the slope scale. The variation ratio and the amplitude of the suprapermafrost groundwater level downslope are larger than those on the upper slope under climate warming. The obvious vulnerability and spatial variability of the suprapermafrost groundwater to climate change will impose intensive effects on the water cycle and alpine ecosystems in the permafrost region.

1. Introduction

Worldwide hydrological processes have been significantly affected by climate change. In permafrost regions, climate change and permafrost degradation have resulted in changes to the original rainfall–runoff relationship and runoff generation mechanism (Bense et al., 2009; Woo, 2012). A few studies have documented that changes in the groundwater systems contributed to the surface runoff increase and seasonal variations in Eurasian river parameters in the arctic regions (Peterson et al., 2002; Ye et al., 2009). In contrast, the permafrost degradation in the Qinghai-Tibet Plateau (QTP) has resulted in a runoff decrease (Shen et al., 2009; Wang et al., 2007). However, little is known about the interactions between permafrost changes, groundwater dynamics and surface runoff variation (Woo, 2012; Shiklomanov et al., 2013; Chang et al., 2015). Due to the very harsh environmental conditions, there is very little field monitoring data of groundwater systems, which has limited our understanding of the permafrost groundwater dynamics. The groundwater systems in permafrost areas significantly differ from those in non-frozen areas. Frozen layers, as a special regional aquiclude or aquitard layer, block or weaken the hydraulic connections between the surface water and groundwater, which make the groundwater systems very complex (Zhou et al., 2002; Quinton and Marsh, 1999; Woo, 2012; Cheng and Jin, 2013). Therefore, we still have no effective mathematical method or theory for use on the hydrogeological processes of permafrost groundwater (McKenzie et al., 2007; Bense et al., 2009; Woo, 2012).

With permafrost being a medium of limited permeability, groundwater is normally found in thawed zones. Active groundwater circulation can occur above, within, or beneath the permafrost,

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known respectively as suprapermafrost, intrapermafrost, and subpermafrost groundwater (Zhou et al., 2002; Woo, 2012). Suprapermafrost groundwater occurs mostly in the active layer. As this layer is subject to seasonal freezing and thawing, the active soil freezing–thawing processes play a decisive role in the recharge, movement, spatial distribution, and cycle of suprapermafrost groundwater in cold areas (Quinton and Marsh, 1999; Woo, 2012; Chang et al., 2015). The circulation of the suprapermafrost groundwater is important to the hydrological cycle in the permafrost region because it is strongly linked to the processes of infiltration, evaporation, redistribution of water in the soil, and exfiltration in support of runoff (Callegary et al., 2013). Only the suprapermafrost groundwater supplies water to the base flow for the continuous permafrost area (Woo, 2012; Ligotin et al., 2010). Therefore, understanding the dynamics and variation of the suprapermafrost groundwater under climate change is crucial in revealing the hydrological cycle processes of cold regions.

Mathematical modeling is generally used as a powerful tool to improve our understanding of groundwater systems. In non-permafrost regions, physically based numerical models have been used in recent years for the simulation and analysis of groundwater systems and have been applied to problems ranging from aquifer safe yield analysis to groundwater remediation and quality issues. However, these modeling techniques are very data-intensive, labor-intensive and expensive. The hydrogeological theory and models that have widely been used in non-permafrost regions, such as Darcy's flow law based differential equation systems of groundwater dynamics, are not suitable for permafrost groundwater flows that are controlled by thermodynamics (Rushton, 2003; Bense et al., 2009; Ge et al., 2011). Furthermore, field observation data of groundwater systems are very sparse in permafrost regions. In the permafrost region of QTP, for example, there were no field groundwater monitoring sites before 2008 (Cheng and Jin, 2013; Chang et al., 2015). Under data-scarce conditions, the use of physical-based models is highly restricted. Therefore, in such cases, empirical models serve as an attractive alternative, as they can provide useful results using less data, are less laborious and are more cost-effective. Artificial neural network (ANN) models are one such type of model, which can serve as universal approximators and are very much suited to dynamic nonlinear system modeling (ASCE, 2000a).

The applications of the ANN technique in hydrology range from real-time modeling to event-based modeling. It has been used for rainfall–runoff modeling and precipitation forecasting as well as for the modeling of stream flows, evapotranspiration and water quality (ASCE, 2000a,b; Garcia and Shigdi, 2006). In particular, ANN models have been successfully used in the prediction of groundwater level changes (Daliakopoulos et al., 2005; Dillip et al., 2010; Heesung et al., 2011). However, most research areas are arid or semi-arid areas without permafrost; very little research has been conducted on groundwater systems in permafrost regions using artificial neural network models. Due to the cold climate and harsh conditions in the region, obtaining the measured data is relatively difficult. Using an ANN forecasting model could provide a way to reveal the suprapermafrost groundwater level fluctuations, which will help us to better understand the influence of suprapermafrost groundwater on the hydrological cycle in permafrost regions.

The Qinghai-Tibet Plateau in western China, a source area for several rivers in Asia such as the Yellow River and the Yangtze River, embraces a variety of hydrologic processes. Water cycling plays an unequivocal role in buffering or intensifying the climate impact on water resources and ecosystems (Wang et al., 2012). The warming climate has attracted researchers' attention to shrinking glaciers, permafrost degradation, and the deterioration of ecosystems on the Plateau (Cheng and Wu, 2007; Yang et al., 2007; Wang et al., 2011). For insight into the impacts of climate change and permafrost degradation on the regional water cycle, it is imperative to understand the suprapermafrost groundwater dynamics in QTP under these conditions. Consequently, using extensive field monitoring data from the center of the QTP permafrost region in this research, we want to (1) construct a suprapermafrost groundwater level model by using an ANN framework and examine the validity of the model and (2) investigate the impacts of air temperature and precipitation variation on the suprapermafrost groundwater dynamics and its spatial differences along a hill slope.

2. Materials and methods

2.1. Site description and data collection

The study area is located in the Zuomaoxikong watershed of the Fenghuo Mountains. The Zuomaoxikong watershed is an important anabranch of the Beilu River in the source area of the Yangtze River on the Qinghai-Tibet Plateau. The observation sites of the suprapermafrost groundwater were located in a typical alpine meadow area on the left bank of the Zuomaoxikong River (Fig. 1), where the permafrost is well developed. The elevation ranges from 4680 to 5360 m a.s.l., and it belongs to the arid plateau climate region. The annual average temperature is −5.2 °C, and the annual average precipitation is 290.9 mm, but the annual average evapotranspiration is as much as 1316.9 mm, and the annual relative atmospheric humidity is 57%. The depth of the permafrost layer is approximately 50–120 m, with the active layer's depth varying from 0.8 to 2.5 m. The main type of vegetation is alpine meadow, and the dominant vegetation community consists of *Kobresiapygmaea*, *K. humilis*, and *K. capilifolia*.

In a typical alpine meadow (site B in Fig. 1), a slope groundwater flow field that was cut by the river (the underground ice exposed at the river edge, which has an obvious exchange relationship between the underground water and the surface river) was chosen to build suprapermafrost groundwater observation plots at an elevation of 4766 m. In the observation field, two observation holes were constructed at a depth of 160 cm, of which one was located on the upper section of the slope and the other on the lower section, with a distance of 100 m between them (Fig. 1). HOBO U20-001-04 water level data loggers (ONSET Co., USA) were used to monitor the suprapermafrost groundwater level. This built-in pressure type groundwater level sensor with a fully enclosed titanium alloy shell is suitable for use in cold, harsh environments, with the measurement accuracy and resolution being less than 0.014 kPa and 0.14 cm. The groundwater level was observed twice every day, and the average value of all observations every day was taken as the suprapermafrost groundwater level depth. As shown in Fig. 1, two portable micro-meteorological stations (HOBO Weather Station, ONSET Co., USA) were established near the experimental fields to measure the air temperature, precipitation, wind velocity and direction, and total radiation. All the data were collected from July 2009 to December 2012.

2.2. Artificial neural network methods

An ANN is a large parallelly distributed information processing system that has certain performance characteristics resembling the biological neural networks of the human brain (Haykin, 1999). A neural network is characterized by its architecture that represents the pattern of connection between nodes, its method of determining the connection weights and the activation function. Unlike physically based numerical models, ANNs do not require explicit characterization and quantification of the physical properties and