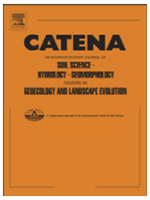
Catena 129 (2015) 63–75

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena



Soil moisture dynamics of typical ecosystems in response to precipitation: A monitoring-based analysis of hydrological service in the Qilian Mountains

Feixiang Sun [a,b,c], Yihe Lü [a,*], Jianglei Wang [a,b,d], Jian Hu [a,b], Bojie Fu [a]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Policy Research Center for Environment and Economy, Ministry of Environmental Protection of the People's Republic of China, Beijing 100029, China
[d] Tsinghua Holdings Human Settlements Environment Institute, Beijing 100083, China

ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form 26 February 2015
Accepted 3 March 2015
Available online 13 March 2015

Keywords:
Hydrological service
Soil moisture
Ecosystem
Elevation gradient
Temporal variability

ABSTRACT

Hydrological service by soil under mountain ecosystems is a hot topic in current ecological research. We monitored the precipitation and soil moisture dynamics and measured the soil hydrological parameters of grassland and forest ecosystems along an elevation gradient in the Dayekou catchment of the central Qilian Mountains in northwestern China. Soil moisture dynamics in response to rainfall events exhibit different characteristics with different ecosystems and at different elevations. The soil conditions (including soil texture, soil structure, and soil hydrological parameters), the local meteorological condition, and the physiological characteristics of the vegetation can help explain eco-hydrological differences. The total rainfall increased with an increase in elevation across the rainy season. Soil moisture content increased with an increase in altitude and differs with land cover on average values. Grassland and forest at low elevations have 50% and 41.7% of the soil moisture content level under shrubland at high elevations, and Qinghai spruce forest soil has the greatest "green water (the water used mainly by the ecosystem itself)" capacity. Fluctuation in soil moisture diminishes with increased depth, yet the trend is not obvious under shrubland at high elevations. The sensitivity of soil moisture response to rainfall differed depending on land cover and soil depth. Soil moisture under alpine shrubland is far more sensitive to single rainfall events, whereas other land-cover types display only typical responses in periods of frequent rainfall events (continued-rainfall scale). The study of soil moisture dynamics contributes to research on hydrological service in mountain ecosystems, and is helpful in promoting knowledge innovation regarding the relationship between water and ecosystems.

1. Introduction

Water resources are limiting factors for economic development and environmental health in many regions. In dryland ecosystems, water is the primary medium of connectivity, as it controls physical and biological processes across scales (Austin et al., 2004; Miller et al., 2012; Turnbull et al., 2012; L. Wang et al., 2012; Wilcox et al., 2012). Hydrological service in mountain ecosystems has always been a central research concern in ecosystem service studies. In arid and semi-arid regions, water regulation/retention by mountain ecosystems is regarded as the typical subject of hydrological service (Liu et al., 2009; Zhang et al., 2011). Many experiments and observations have been done on hydrological processes and mechanisms in addition to ecosystem service assessments at different scales and in different regions. Hydrological research at catchment and small scales are usually based on ecosystem characteristics, in situ precipitation, evapotranspiration, infiltration, and runoff (C. Wang et al., 2013; S. Wang et al., 2013); yet continuous observations of soil moisture dynamics of different ecosystems are still need to be strengthened (Li et al., 2014). Knowledge of soil moisture is critical for developing an understanding of numerous hydrological processes in soil hydrology, meteorology, and ecology research (Brocca et al., 2010; Green and Erskine, 2004; He et al., 2012). Soil moisture is regarded as the basis of quantitative research on hydrological dynamics and ecological patterns/processes (Rodriguez-Iturbel, 2000), participating as crony in the terrestrial hydrological cycle across the "lithosphere–biosphere–atmosphere–hydrosphere" and affecting the growth and succession of vegetation. According to previous studies, land cover has a great influence on the water regulation capacities of mountain ecosystems (Guo et al., 2000; Sun et al., 2014; Venkatesh et al., 2011), yet soil moisture can clearly reflect differences in regulation capacities via dynamic responses to precipitation, evapotranspiration,

---

* Corresponding author.
E-mail addresses: guihuafeixiang@163.com (F. Sun), lyh@rcees.ac.cn (Y. Lü), jianglei.wang@qq.com (J. Wang), yb_hjian20122@163.com (J. Hu), bfu@rcees.ac.cn (B. Fu).

http://dx.doi.org/10.1016/j.catena.2015.03.001
0341-8162/

and infiltration. The relationship between vegetation patterns and soil moisture dynamics has been used to assess the rationality of revegetation in the Loess Plateau of China, which has scarce water resources; and in a comparison of five vegetation types, pine woodland is found to induce the largest water loss on surface runoff, followed by sloping cropland, alfalfa, semi-natural grassland, and shrubland (Chen et al., 2007, 2010).

In previous studies of the Qilian Mountains, most of the research is concentrated on mechanisms of water regulation, including canopy interception, the water absorption by litter, and the water infiltration rate of soil under different landcovers (Jin et al., 2001; Tian, 2011; Wang, 2006). Liu et al. (2008) studied the differences in temporal variability of soil moisture among grassland, shrubland, and forest habitats by means of field observations near the forest boundary in the Qilian Mountains and found that vegetation type can make a difference in the dynamic responses of soil moisture. In analyzing soil moisture and rainfall size during the growing season from 2003 to 2008 in the Qilian Mountains, He et al. (2012) found soil moisture responding sensitively in surface layers, and the sensitivity dropping with depth increasing. Large rainfall events (>20 mm) play a key role in soil water storage in grassland and meadow ecosystems in the Qilian Mountains (He et al., 2012). Soil moisture plays a key role in the water-transfer of mountain ecosystems. In the Qilian Mountains, the meteorological and geographical conditions vary from east to west, giving rise to distribution differences in the vegetation belt in southern and northern slopes. However, comparisons between areas of high and low altitudes related to eco-hydrological service are scarce, a circumstance that serves as a bottleneck in advancing the development of hydrological research in mountainous areas.

This paper aims to reveal the responsive characteristics of soil moisture dynamics of grassland, shrubland and forest ecosystems at different altitudes; to discuss the interactions between vegetation and soil moisture content; to assess the contribution of grassland/shrubland/forest ecosystems to hydrological service in mountain areas; and to discuss possible changes in hydrological service with future land-cover scenarios under climate change and new management policies. This study may contribute to recognizing water regulation service and assessing hydrological service of mountain ecosystems.

2. Materials and methods

2.1. Study area

The Qilian Mountains (94°52′–103°09′E; 36°26′–40°01′N), located in the northeast of the Qinghai province and on the west edge of the Gansu province, are composed of a series of mountains and valleys in arid and semi-arid northwestern China and serve as the origin of several inland rivers (including the Heihe, Shiyang, and Shule Rivers, among others). Of these, the Buha River is the largest water resource of the famous Qinghai Lake in the Qinghai–Tibet plateau. By virtue of mountain glaciers and precipitation, the Qilian Mountains are important ecological shelters in northwestern China and give rise to the Hexi Corridor — the famous Silk Road. The Qilian Mountains have a typical continental climate, with annual precipitation ranging from 150 mm in the foothills to 800 mm in the high mountains and mainly concentrated from June to September. The annual average temperature ranges from 6 °C to −5 °C with increasing elevation. The mountains peaks mostly have an elevation of above 4000 m and are covered with snow all year round. The ecosystem in the Qilian Mountains is mainly comprised of the following four types: Qinghai spruce forest, Qilian juniper forest, shrubland, and grassland. The water storage capacity of forests in the Qilian Mountains amounts to approximately 552 million m^3 (Che et al., 1992). However, the forest cover of the Qilian Mountains decreased from 1978 to 1990 (Wang et al., 2014); then, from 1990 to 2007, the forest cover increased rapidly, facilitated by a series of protection and restoration measures (Y.K. Wang et al., 2012). Forests are important for flood control, runoff regulation, and soil erosion control, and thus contribute to hydrological service at catchment scale.

A cold semi-arid catchment named Dayekou (82.73 km^2) was chosen as a typical representative study area (Fig. 1). The average annual temperature in the area is approximately 0.5 °C (extreme temperatures range from 28.0 °C to −36.0 °C since temperature was first recorded), with July temperatures ranging from 10.0 °C to 14.0 °C (Gao, 2003). Annual precipitation of the Dayekou catchment ranges from 300 mm in low-altitude hilly areas to 600 mm in high-altitude remote mountain areas; over 60% of the precipitation is concentrated in the period from June to September. The year 2013 was an ordinary year (from 2002 to 2011, the minimum annual rainfall occurred in 2004 with 289.7 mm, and the maximum annual rainfall took place in 2007 with 550.9 mm), with an annual rainfall of 380.4 mm and 85.9% of the rainfall concentrated in June–September (according to meteorological observations made at an elevation of 2550 m). The mean annual relative humidity is 60%, and annual pan evaporation is approximately 1200 mm. The main ecosystem in this catchment is mainly comprised of Qinghai spruce forest (*Picea crassifolia*, including moss–spruce forest, shrub–spruce forest, and grass–spruce forest), Qilian juniper forest (*Sabina przewalskii*), Alpine shrubland (*Potentilla fruticosa L.*, *Salix gilashanica C.*, *Caragana jubata Pall.*, and *Spiraea alpina Pall.*), and sub-alpine grassland (*Polygonum viviparum*, *Carex*, *Stipa capillata*, *Artemisia selengensis*, and *Iris lactea*). This catchment presents a clear bottom-up vertical vegetation configuration: mountain meadow/grassland, mountain forest, alpine shrub and meadow belt, and alpine sub-ice sparse vegetation. The upper forest lines vary from 3300 to 3400 m. Mountain meadows are missing in areas in which the river valley is steep and narrow. Vegetation spatial variation is similar to that presented in Fig. 2. The main forest type of Qinghai Spruce is distributed on the shady slopes, with a canopy density of 0.6 on average.

2.2. Experimental setting and data collection

The soil hydrological parameters (including the natural soil moisture content and the field water capacity) were measured. As forests can provide various ecosystem services, including habitat provision, climate regulation, carbon storage, and water supplies (Foley et al., 2005), Qinghai spruce forest and alpine shrubland have become priorities in our research. Four groups of soil moisture and temperature dynamic monitoring systems (three groups of H21 and one group of U30 soil moisture and temp logger systems with five S-SMC-M005 soil moisture and five S-TMB-M006 temperature-smart sensors in each group, Decagon Devices Inc., Pullman, WA) were placed in the Qinghai spruce forest separately at elevations of 2700, 2900, 3100, and 3300 m to measure soil moisture dynamics at depths of 10, 20, 40, 60, and 80 cm in May of the year 2013 before the rainy season. Data were collected by the HOBO weather station logger every 15 min; three groups of the same monitoring systems (H21) were introduced in the shrubland at elevations of 2900, 3300, and 3500 m, respectively; one group of H21 and one group of U30 systems were placed in the grassland at elevations of 2800 and 2900 m, respectively. The measuring accuracy of H21 and U30 systems are the same, with the only differences in their power supply (Table 1). As precipitation in high-altitude mountain areas varies greatly depending on elevation, we set up seven groups of rainfall-monitoring systems separately at 2570 m in grassland, 2700 m within and outside of forest, 2900 m in grassland and forest, 3300 m in forest, and 3500 m under shrubs. The year 2013 was an ordinary year for rainfall in recent decades. Since soil moisture is closely related to rainfall, soil moisture data for the year 2013 was chosen for the analysis of an ordinary year status in this paper.

2.3. Analytical method

The soil bulk density, organic carbon content, soil texture (sand, silt, and clay) and field water capacity were measured, and the soil porosity