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Changes in groundwater level dynamics after low-impact forest harvesting in steep, small watersheds

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SUMMARY

Groundwater in steep watersheds has complicated dynamics because hydrological processes are strongly affected by topography. To clarify the influence of harvesting on groundwater levels in hillslope forests, the pre- and post-harvest relationships between rainfall and groundwater levels were examined focusing on the frequency and elevation of observed groundwater levels. The dynamics of groundwater levels changed in two ways. First, the watering-up frequency, defined as the ratio of non-zero groundwater frequency to total observations increased in the entire watershed, except in wells in which the pre-harvest watering-up frequency was sufficiently high as to prevent further increase. Second, increased watering-up ratios, defined as the ratio of groundwater level to soil depth in each class of groundwater level sorted in descending order similar to the discharge–duration curve, were detected in the higher class of groundwater level for wells located in the upper riparian zone. These increased watering-up ratios were interpreted as the expansion of saturated areas observed mainly during heavy rainfall events. The reduced interception rate after harvesting resulted in increased soil moisture, which led to increases in watering-up frequencies and ratios. In addition, changes in the physical properties of surface soil may also lead to increased maximum groundwater levels because of decreasing hydraulic conductivity for lateral flow in the upper soil layer. This study suggests that the groundwater regime in hillslope forests differs spatially according to the topographic conditions, and the spatiality changes depending on the growth stage of vegetation.

Introduction

Groundwater in forested watersheds has important effects on vegetation, regional water regimes (Sklash and Farvolden, 1979), and stream solute loading processes (Dahm et al., 1998). Forest disturbances such as harvesting, site preparation, and construction of forest roads change water discharge (Bosch and Hewlett, 1982; Brown et al., 2005), quality (Aust and Blinn, 2004), and groundwater. The relationship between forest harvesting and groundwater/surfacewater levels has been examined intensively in wetland forests (Riekerk, 1989; Aust et al., 1997; Sun et al., 2000, 2001; Xu et al., 2002). Reduced transpiration and interception loss following harvesting increase the water level (Riekerk, 1989; Sun et al., 2000; Xu et al., 2002), whereas reduction of post-harvest groundwater level results from soil surface evaporation and transpiration during regrowth of vegetation. During vegetation recovery, evapotranspiration can exceed pre-harvest levels (Aust et al., 1997; Bliss and Comerford, 2002). As for hillslope forests, Johnson et al. (2007) reported a temporary post-harvest increase in groundwater levels during rainfall events, whereas Mannerkoski et al. (2005) did not detect differences before and after harvesting. However, few studies have examined the relationship between harvesting and groundwater levels in hillslope forests, which are the result of complicated hydrological processes.

Because vertical matrix hydraulic conductivities for undisturbed forest soils are generally higher than the maximum rainfall intensity (Kosugi, 1997), most of the rainfall in hillslope forests infiltrates the soil. Then lateral groundwater flow runs down with saturation above the bedrock forming a temporary groundwater surface (Tsukamoto and Ohta, 1988; Tani, 1997; Uchida et al., 2004). The behavior of lateral groundwater flow is dominated by the topography of the ground surface and the bedrock, and rainfall intensity, resulting in nonuniform groundwater levels. Variation by location can occur even in adjacent areas of the same hillslope

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(Montgomery et al., 1997; Hutchinson and Moore, 2000). Lateral groundwater and local infiltration flow descending from a hillslope causes the groundwater table to rise around riparian saturated areas as described in the variable source area theory (Tsukamoto, 1963; Hewlett and Hibbert, 1967; Ragan, 1968). Kubota et al. (1987) reported that saturated areas near streams temporarily expanded during rainfall events and the area of expansion was correlated with the amount of rainfall. It has also been reported that return flow from the bedrock layer strongly affects saturated areas in the soil (Montgomery et al., 1997; Uchida et al., 2002). In nonrainstorm periods, on the other hand, the water tables, primarily in riparian zones, maintain base flow. Thus, groundwater in hillslopes is seldom observed except during rainfall events. Even when it does accumulate, groundwater levels do not necessarily increase synchronously in hillslopes and riparian zones (Seibert et al., 2003; Sidle et al., 1995; Uchida et al., 2004). These fluctuations in the short period and spatial variability in groundwater levels in hillslopes areas make it difficult to conduct a simple analysis of groundwater levels coupled with the time series of cumulative rainfall, which is an effective method to evaluate water table dynamics (Fenelon, 2000; Ferdowsian et al., 2001; Weber and Stewart, 2004).

The influence of harvesting on groundwater in hillslope forests cannot be sufficiently understood solely by monitoring the water table with observation wells, which would require a large number of wells (Montgomery et al., 1997; Hutchinson and Moore, 2000; Johnson et al., 2007); an analysis of the above-mentioned temporal and spatial variation in groundwater dynamics is also required. Because there are no groundwater surfaces in hillslopes during nonrainstorm periods, the frequency at which groundwater appears in wells is more useful. For example, Dubé et al. (1995) used the watering-up frequency to indicate the percent of time that water tables were above the soil depth. Comparisons between rainfall intensity and maximum groundwater levels (Johnson et al., 2007) can also provide important information. On the other hand, because soil depths on hillslopes differ widely with location (Tromp-van Meerveld and McDonnell, 2006; Maeda et al., 2006), relativizing groundwater level by well depth (Johnson et al., 2007) is also effective when comparing groundwater levels among wells. Such comparisons should include statistical analyses such as comparing correlation coefficients and standard deviations among wells (Seibert et al., 2003).

When assessing the influence of harvesting, the extent and magnitude of disturbance through harvesting is important. Harvesting itself affects discharge by changing evapotranspiration (Bosch and Hewlett, 1982; Brown et al., 2005). However, forest management practices that accompany harvesting, such as the construction of forest roads and skid trails, skidder activity, and plowing, may also cause substantial soil disturbance that alters infiltration rates (Malmer and Grip, 1990; Aust and Lea, 1992; Ziegler et al., 2006) and accelerates surface erosion (Francis and Taylor, 1989; Edeso et al., 1999; Wallbrink et al., 2002). Taking this into consideration, it is important to first reveal the influence of harvesting alone on groundwater levels by eliminating the effects of disturbance induced by other activities.

To clarify the influence of harvesting on groundwater in a hillslope forest, we compared the groundwater dynamics of two hillslope watersheds in a paired watershed experiment in which harvesting was conducted in one watershed while minimizing other disturbances. Before harvesting, we installed wells in both watersheds to monitor groundwater levels continuously, and examined the characteristics of groundwater behavior in relation to topography for 5 and 4 years before and after harvesting, respectively. To clarify the effects of harvesting on groundwater levels in hillslope forests, we compared the pre- and post-harvest relationships between rainfall and the presence (frequency) and height of groundwater levels.

Site description

The Fukuroyamasawa Experimental Watershed (35°12′N, 140°06′E, elevation 124–227 m) is located in the University Forest of the University of Tokyo, Chiba Prefecture, Japan. Geologically, the area consists of marine deposits from the Neocene period covered with brown forest soil. The mean annual rainfall from 1994 to 2003 was 2216 mm, and the mean annual temperature from 1998 to 2000 was 14.2 °C. It rarely snows and most precipitation is rainfall. Fig. 1 shows the topography of the study area. There are two adjacent, paired, steep watersheds, namely watersheds A and B, with areas of 0.80 and 1.09 ha, respectively. The hillslope gradients are more than 30° in the upper parts of both watersheds, and the channel gradients are 5–8°, resulting in an average gradient of 25.5° in watershed A and 23.5° in watershed B. The average soil depth is 2.87 m in watershed A and 2.22 m in watershed B (Shiraki et al., 1999). During rainfall, there are streams near the lower to middle part of the gulley line indicated in Fig. 1, but these almost always dry up during non-rainfall periods, except around weirs. Weirs have been constructed in both watersheds, and their water levels have been measured since 1993. *Cryptomeria japonica* and some *Chamaecyparis obtusa*, common plantation trees in Japan (Komatsu et al., 2007), were planted at a density of ca. 4400/ha in both watersheds in 1929. Major thinning has took place once prior to 1954. In 1991, stand densities and mean tree heights were 1061/ha and 20.9 m in watershed A, and 856/ha and 21.2 m in watershed B, respectively (Shiraki et al., 1999).

Watershed B was clear-cut in spring 1999 (January–March). To minimize soil disturbance, logging from watershed B was done using skylines, and most branches and leaves were piled by hand and left in approximately 40 locations in the watershed after harvesting. These litter piles had dry weights of roughly 4.7×10^4 kg (Hashimoto and Suzuki, 2004). There are no forest roads or skid trails in the watersheds. In summer 1999, the first summer after harvesting, annual herbaceous plants had not yet fully covered watershed B. In February 2000, the Fukuroyamasawa watershed was completely fenced with wire netting to exclude deer, and young trees were planted in watershed B. By summer 2000, the watershed had a dense growth of trees and annual herbaceous plants. Weed and brush removal was conducted once a year between 2001 and 2003.

Maita et al. (2005) reported that annual water yields in watershed B increased by an average of 295.9 mm/year in the 3 years after harvesting (2000–2002). The increase in water yields was induced by both discharge in peak flows and base flow, although the base flow increased more significantly. Because the mean annual water yield in watershed B was 709.2 mm (1994–1998, excluding 1996 because of missing data), this increase accounted for a large portion of the water yield, corresponding to approximately 40% of the annual pre-harvest water yield. Hotta et al. (2007) reported that because of the efforts to avoid ground disturbance during harvesting, suspended sediment did not increase post-harvest.

Material and methods

Groundwater levels and soil moisture

The locations of wells and tensiometers are shown in Fig. 1. There were 14 wells in watershed A and 19 in watershed B. The wells were constructed by drilling to the bedrock with an auger, and placing a PVC pipe (6 cm diameter) with small holes punched