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Estimating the collapse of aggregated fine soil structure in a mountainous forested catchment☆

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ABSTRACT

This paper describes the relationship of forest soil dryness and antecedent rainfall with suspended sediment (SS) yield due to extreme rainfall events and how this relationship affects the survival of forest plants. Several phenomena contribute to this relationship: increasing evaporation (amount of water vapour discharged from soil) due to increasing air temperature, decreasing moisture content in the soil, the collapse of aggregates of fine soil particles, and the resulting effects on forest plants. To clarify the relationships among climate variation, the collapse of soil particle aggregates, and rainfall–runoff processes, a numerical model was developed to reproduce such aggregate collapse in detail. The validity of the numerical model was confirmed by its application to the granitic mountainous catchment of the Nagara River basin in Japan and by comparison with observational data. The simulation suggests that important problems, such as the collapse of forest plants in response to decreases in soil moisture content and antecedent rainfall, will arise if air temperature continues to increase.

1. Introduction

Documented hydrological effects of a warmer climate include soil dryness, decreased antecedent rainfall, melting of snow and ice in polar regions, desertification in continental interiors, sea-level rise, and locally intense rainfall (Mpelasoka et al., 2009; Sato et al., 2007; Wetherald, 2009; Bobrovitskaya et al., 2003). Recent studies have identified a tendency of global warming to affect forested basins more than other basins (Allen et al., 2010; Schiermeier, 2009; Shinoda et al., 2004). Enhanced warming in granitic mountainous forested basins causes soil desiccation because moisture evaporation from the soil increases. In surface soil layers in forests (A or B layers), fine soil particles such as silt or colloidal soil components maintain the strength of soil clods, which is influenced by the effects of subsurface moisture and other soil properties; however, the strength of soil aggregates can be lost and the soil can tend towards dispersion when climatological or hydrological conditions change. In previous studies, soil hydrological properties including infiltration, runoff, and sediment concentration have been measured, and the percentage of water-stable microaggregates in the soil has been calculated as an indicator of soil degradation. These studies found that, in addition to climatic variations, soil properties are highly affected by extensive land use of the area, intensive grazing, such as by goats, and small wildfires (e.g., Boix et al., 1995; Chesnokov et al., 1997; Dunne and Black, 1970; Govorun et al., 1994).

Forest soil includes components ranging from large particles (approximately 1.0 cm in diameter) such as gravel to fine particles such as silt and colloids. When soil clods are maintained, even when the aggregated soil collapses, they do not immediately collapse or get transported over the soil surface or into river channels because of a shielding effect whereby the fine particles are

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protected by larger particles such as gravel. When forest soil is adversely affected by climatological conditions, the clods can collapse, and the soil structure can be easily damaged by water from rainfall. The related fine soil from collapsed aggregated material can move with water on forest slopes because the shielding effect of large particles has been destroyed (An et al., 2010). Previous studies of runoff from sandy and gravelly soils have generally focused on erosion by raindrops or erosion of bare land (Cai and Barry, 1996). These studies of the erosion of earth surfaces generally assume an absence of vegetation, and thus applicable natural study sites are limited. In contrast, most river basins in Japan, as well as basins of major rivers of the world (e.g., Mississippi and Yellow rivers), include some forests (Boix et al., 1995). The importance of flocculation of silty sediments to sediment transfer in a stream channel was demonstrated by Wolanski and Gibbs (1995).

Soil structure is defined as the arrangement of particles and associated pores in soil across the size range from nanometres to centimetres. Biological influences can be demonstrated in the formation and stabilisation of aggregates, but it is also necessary to distinguish clearly between those forces or agencies that create aggregations of particles and those that stabilise or degrade such aggregations. When a calcareous clay soil was dispersed ultrasonically, organic carbon was concentrated in the finer fractions in mildly leached soil, whereas in calcareous clay, organic carbon was concentrated in the silt fraction (Ahmed and Oades, 1984; Oades, 1993; Fattet et al., 2011; Randall et al., 1974). The speed of this recovery determines the effectiveness of erosive rainfall events. Fine soil structure is determined by how individual soil granules bind together and aggregate, which determines the arrangement of soil pores between them. Fine soil structure has a major influence on the movement of water and air, biological activity, root growth, and the emergence of seedlings. A wide range of soil-management practices is used to preserve and improve soil structure. These include increasing soil content by placing agricultural land in crop rotation, reducing or eliminating tillage and cultivation in cropping and pasture activities during periods of excessive dryness or wetness when soils may tend to shatter or smear, and ensuring sufficient ground cover to protect soil from raindrop impacts (Imeson et al., 1995).

Models focussing on granitic mountainous catchments have been developed to estimate soil loss and its associated on- and off-site effects. Slope-scale soil erosion was first described by Ellison (1947) and numerically modelled by Wischmeier and Smith (1959). Recent erosion models have emphasised physical processes (Jetten et al., 2003; Rompaey et al., 2005; Moffet et al., 2007) and spatially realistic conditions. Empirically based models are simple to use but do not realistically portray natural processes; process-based (physically based) models are better able to incorporate natural processes, but they require substantial computing time (Renschler and Flanagan, 2002; Vente and Poesen, 2005; Croke and Nethery, 2006). The equations and laws of hydrology have been developed from research in small experimental flumes or plots. When these equations are applied to larger watersheds, however, they commonly introduce discrepancies in the results due to unknown factors that did not exist in the plots (Brezonik et al., 2001; Einstein, 1950; Kalinske, 1947; Beven, 1979). Another important issue is that the scale of data and the selection of a model from numerous available models strongly influences the results (Renschler et al., 2000). The heterogeneity of the real world is easily overlooked or eliminated in a large-scale model (Turner, 1989). Determining the modelling scale, data, and size of sub-watersheds or hydrologic units in models has a considerable effect on model results. The possible loss of information should be thoroughly understood and the model selected based on the purpose of the study. Fine soil particles in forest soils are important to agricultural water reserves. If large amounts of fine particles in a forest soil disperse and run off, the effective porosity of the remaining soil increases, and the moisture content of the forest soil can decrease, potentially leading to challenges to the survival of forest plants. Under such circumstances, it is necessary to construct a dynamic model of moisture, sand, and gravel that is applicable to forested basins.

This study modelled the collapse of aggregates of fine soil particles in the A or B layer of forest soils using interparticle stress and the true adhesive force generated by the effect of soil-particle sedimentation. The model was then combined with a dynamic model of moisture and sediment on a catchment scale, from which was constructed an integrated dynamic model of moisture, sand, and gravel that is applicable to forested basins (Mouri et al., 2011a,b, 2012a, 2013a,b,c). This model clarifies the long-term relationships among warmer climate, forest-soil dryness, antecedent rainfall, the collapse of fine soil particle aggregates, and their effects on forest plants.

2. Description of study site and initial calculation

The Nagara River basin (1985 km^2) is located on the western border of the Nobi Plain in Holocene sediments of Honshu Island, Japan. The Nagara River is joined by the Yoshida, Itadori, Mugi, and Itonuki rivers and then flows west into the Ise Inland Sea. The highest altitude in the basin is 1709 m and average annual rainfall is approximately 1915 mm. Approximately 85% of the population (1,777,000 people) is served by the sewer system. Table 1 provides general information on the Nagara River, which has a main watercourse length of 166 km. The river consists of three segments, determined by the channel gradient: the gradient in the downstream part is 1/400, the midstream part is 1/300, and the upstream part is 1/100. The river's abundant waters are used to irrigate an area of 80 km^2, mainly from small tributaries and waterways. A land-use map was generated from Landsat Thematic Mapper images (21 October 1997; 30 March 1998) using a clustering method (ISODATA). Mountainous, urban, and cultivated areas account for 73.3%, 6.5%, and 20.2% of the land area, respectively (Fig. 1). The dominant surface geological features is weathered granite, silt and clay covered by forest (approximately 75%), and the depth of the soil layer on the mountain slope is ~1.0 m. The river bed is veneered by coarse sediment particles (Fig. 2).

3. Methods

3.1. Distributed hydrological sub-model

A rainfall–runoff sub-model based on the kinematic wave model (Chow et al., 1959; Sunada and Hasekawa, 1994; Mouri and Oki, 2010; Mouri et al., 2010, 2011c, 2012b; Shiiba et al., 1999;

Table 1
General information on the Nagara River.

Item	Description
Location	Central Honshu, Japan (N: 34°04′–35°59′, E: 136°36′–137°04′)
Area and length of main stream	1985 km^2, 166 km
Origin and highest point	Mt. Dainichi (1709 m)
Outlet	Ise Bay, Pacific Ocean
Main geological features	Granite, andesite, ryolite, gneiss
Major lakes	None
Mean annual precipitation	1915.3 mm (1979–2000) at Gifu
Mean annual runoff	116.5 m^3/s (1954–2001) at Chusetsu
Land use	Mountainous area (73.3%), Urban area (6.5%), Cultivated area (20.2%)
Population	915,100 (1995)

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