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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)

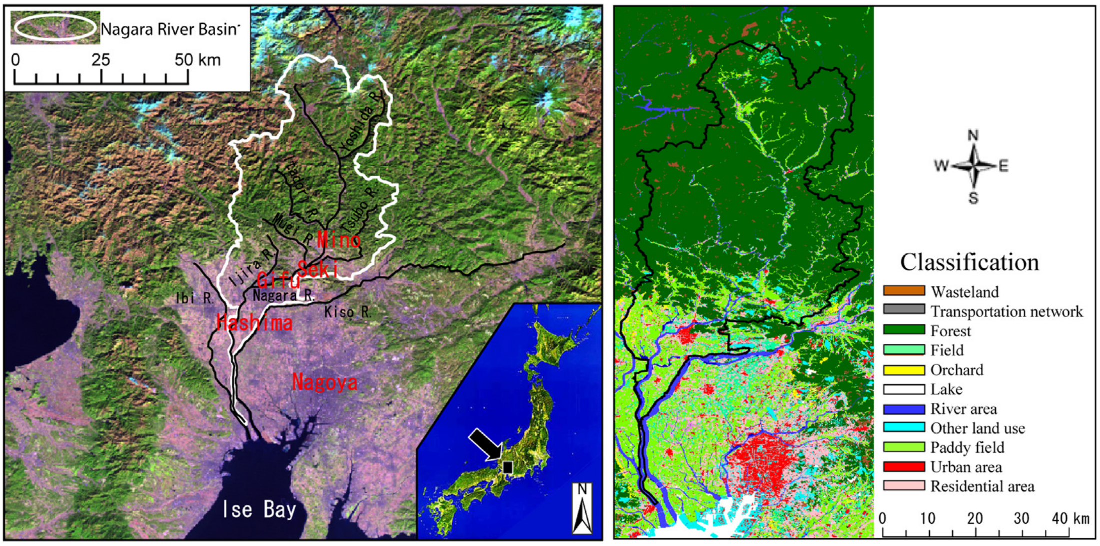

Fig. 1. Location of the Nagara River basin and distribution of land uses in the region. The distribution of land uses was estimated from LANDSAT/TM data using ISODATA clustering.

Takasao and Shiiba, 1995; Takahashi et al., 1987; Mulungu et al., 2005; Mouri et al., 2011b) was applied to each slope element in the digital elevation model (DEM) of the Nagara River basin. Using the kinematic wave model, the downstream distribution of water in the surface layer can be used to calculate shallow groundwater levels when predicting fusion conditions for fine soil particles.

The governing equation of the one-dimensional hydrodynamic model can be written in simplified form as

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = r. \tag{1}$$

Equation (1) is a continuity equation with no lateral inflow or outflow, where q is the flow volume per unit width on a slope, h is the cross-sectional area of a stream, r is rainfall intensity, x is a spatial coordinate, and t is a temporal coordinate.

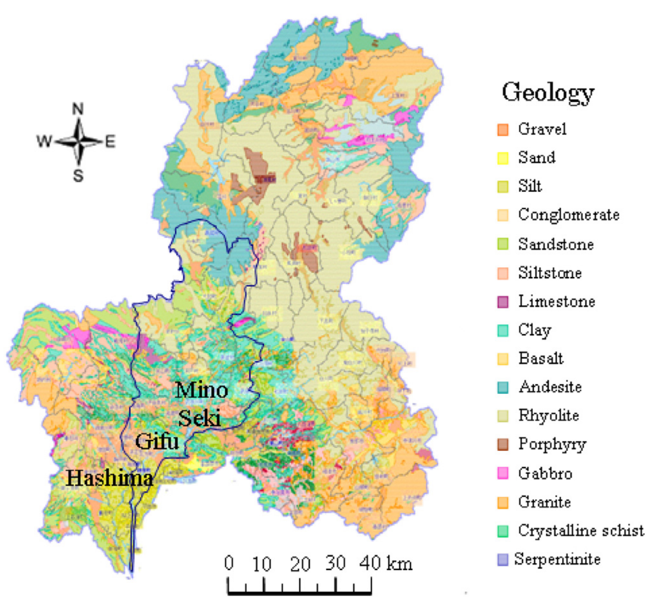

Fig. 2. Map showing the spatial distribution of geology throughout the Nagara River basin. Data are from the Gifu Prefectural Government, the Ministry of Land, Infrastructure and Transport (MLIT), and Digital National Information (DNI).

The equation of motion is

$$q = \begin{cases} \alpha h, & h \le d, \\ \alpha (h-d)^m + \alpha h, & h > d, \end{cases} \tag{2}$$

where m is Manning's coefficient, and α is calculated as

$$\alpha = k \sin \theta / \gamma, \tag{3}$$

where k, θ, and γ represent the effective porosity. The depth d of the A layer in the downstream direction is given as

$$d = \gamma D, \tag{4}$$

where D is the depth of the surface soil layer.

3.2. Sub-model for collapse of soil particle aggregates

The collapse of fine soil particle aggregates is expressed using the relationship between moisture in the soil and the intermolecular bonding force, along with the true adhesive force as a function of overburden pressure. An interparticle bonding force exists between fine soil particles as a result of surface tension. The surface tension T_s acting on a fine soil particle is expressed in terms of air pressure as

$$2T_s = 2u_a \left\{ \left(r + \frac{L}{2} \right) \cdot \cos \theta - r \right\}. \tag{5}$$

Here, u_a denotes air pressure, r is rain density ($r = d$), θ is the angle determined by the meniscus at the contact part of the soil particle ($\theta = 30°$), and L is the diameter of the soil particle. The force at the contact point F is expressed in terms of water pressure u_w as

$$F = 2u_w \left\{ \left(r + \frac{L}{2} \right) \cdot \cos \theta - r \right\}. \tag{6}$$

The interparticle bonding force σ', with consideration given to a true adhesive force (analogous to a covalent bond) generated by the effect of sedimentation, is expressed as

$$\sigma' = c + 2(u_a - u_w)\{(r + L/2) \cdot \cos \theta - r\} + 2T_s. \tag{7}$$

Therefore, the fusion condition for fine soil particles is defined using the relationship of the bonding force between particles with the shear force as

$$F_t = \frac{\sigma'}{\tau} \le 1. \tag{8}$$

The migration of fine particles from the forest slope F_t is described by the relationship between the interparticle bonding force σ' and the shear force of a soil particle τ as

$$F_t = \sigma_t/\tau = \frac{\alpha[c + 2(u_a - u_w)\{(r + L/2)\cdot\cos\theta - r\} + 2T_s]}{[\{\gamma_{sat}\cdot h' + \gamma_t(D - h')\}\sin\theta\cdot\cos\theta]} = \frac{2\sqrt{2}\cdot T_s/d}{\{\gamma_{sat}\cdot h' + \gamma_t(D - h')\}\sin\theta\cdot\cos\theta}, \tag{9}$$

where γ_t denotes the wet unit weight of the soil, h' is the subsurface groundwater level in the soil layer, and d is the apparent depth of the soil (=γD, where γ is the effective porosity and D is the depth of the soil). Major factors and parameters with explanations and units are summarised in Table 2. If the groundwater level rises above the surface of the soil particles, the interparticle bonding force and the surface tension acting on the particles decrease, the shear force exceeds the bonding force, and the fine soil particles are mobilised in suspension. When the water level becomes lower than the surface of the soil particles, dispersion of the small soil particles stops. When the soil is saturated with water, the soil's porosity and hydraulic conductivity k, which is dependent on soil moisture and normally becomes constant and maximum at saturation, change as certain particles are removed. The amount of change in the hydraulic conductivity can be obtained using the relationship between the effective porosity and the hydraulic conductivity of the initial setting.

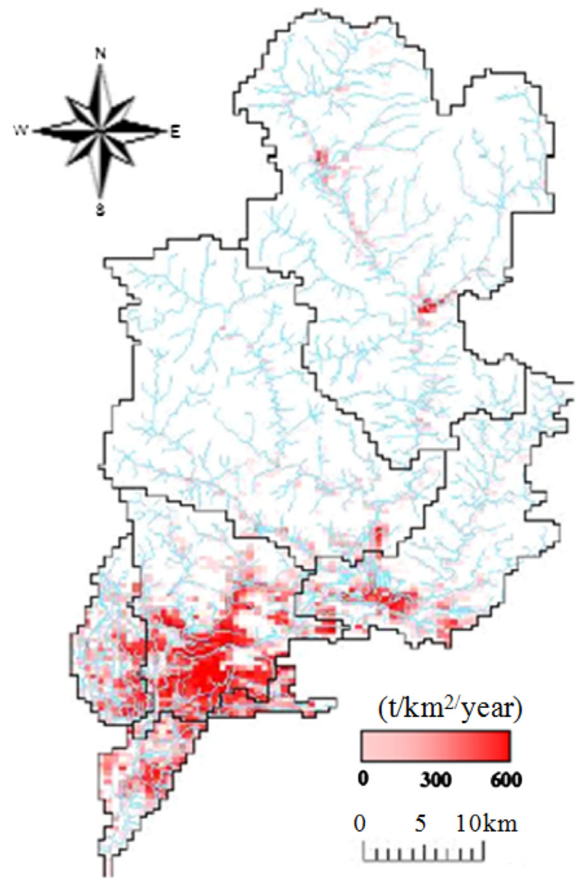

Fig. 3. Map showing the spatial distribution of suspended sediment in 2000. Data are from the Ministry of Land, Infrastructure and Transport (MLIT).

4. Model application and results

Fig. 3 shows the spatial distribution of suspended fine soil particles for the Nagara River basin. Dispersion amounts are large in the southeastern and eastern parts of the cultivated area. This means that the conditions for dispersion of fine soil particles are not uniquely tied to ground surface destruction. Fig. 4 illustrates a reasonable agreement between simulated and observed river discharge. Fig. 5 shows the relationship between the SS yield from surface and subsurface layers and river discharge obtained by continuous calculation over the year 2000, which included the Tokai disaster. On 7 September 2000, a stagnant rain front occurred near Japan's main island of Honshu. Warm conditions associated with the east side of Typhoon 14 migrated towards this front for 11–12 days, during which the front's activity increased, resulting in record rainfall in Aichi, Mie, and Gifu Prefectures of the Tokai district. Starting on the evening of 11 September, rainfall increased over 2 days, amounting to as much as 600 mm in Tokai. In the city of Nagoya, 428 mm of rain fell on 11 September, twice the average precipitation for September, and the total precipitation for the 2 days was 567 mm. In the city of Tokai, Aichi Prefecture, between 114 and 492 mm of rain was recorded in the 1-h period beginning at 7:00 P.M. on 11 September. Widespread flooding and attendant damage occurred in Nagoya. The majority of mass-flow-related damage, including the collapse of aggregated soil, in 2000 resulted from the Tokai heavy rainfall disaster. Destruction of the surface layer was limited to times of extreme events (discharge $\geq$ 100 m^3/s). However, discharge of fine soil particles also occurred during times of light rainfall during the base-flow period (discharge $<$ 100 m^3/s). Comparison of the calculated total annual amount of fine soil particles (approximately 26,000 $\times$ 10^3 m^3) with observational data for the Nagara River (approximately 25,000 $\times$ 10^3 m^3 measured SS) yielded a 4% error in volume. Fig. 6 shows the relationship between the amount of dispersion of fine soil particles and the amount of SS yield

Table 2
Descriptions of the typical parameters used for calibration.

Symbol	Name	Numerical range	Units
h	Cross-sectional area of a stream	0.01–10,000.00	m^2
h'	Groundwater level in the surface-layer sediment	0.01–5.00	m
q	Flow volume per unit width on a slope	0.01–1000.00	m^3/s
k	Coefficient of water permeability	10^{-9} to 1.00	cm/s
m	Manning rule coefficient	1.67	–
t	Temporal coordinate	0.00–31,356,000.00	s
x	Spatial coordinate	0.00–15,000.00	m
r	Rainfall density	0.00–1000.00	mm/h
θ	Slope gradient	0.01–1.00	–
γ	Effective lacuna percentage	0.40–0.60	–
γ_{sat}	Saturated unit weight of the sediment	1.50–2.00	t/m^3
γ_t	Wet unit weight of the sediment	1.50–2.00	t/m^3
γ_w	Unit weight of water	1.00	t/m^3
D	Thickness of layer A	0.01–1.00	m
d	Depth of the A layer in the downstream direction	0.01–1.00	m
c	Viscosity force of a particle	0.01–10.00	kgf/m^2
σ_t	Perpendicular stress	0.01–10.00	kgf/m^2
σ'	Effective perpendicular stress	0.01–10.00	kgf/m^2
τ	Shear force	0.01–10.00	kgf/m^2

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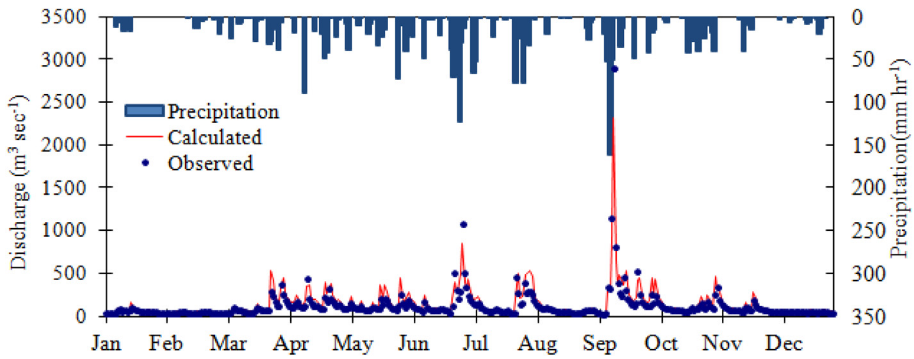

Fig. 4. River discharge simulation results throughout the Nagara River basin including the Tokai event of 7–11 September 2000. The red line shows the calculated river discharge. The blue dots show observed river discharge. The bars show precipitation. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency.

classified according to level. Fig. 7 shows the simulated temporal variation in SS concentration in four selected rivers from 1978 to 2002 and demonstrates that the model captures most of the variations in SS concentration.

5. Discussion

Fine particles in surface soils of forests consist of so-called soil aggregates, in which soil particles form clusters. In addition to the effect of the aggregate structure, the strength of the surface soil is increased by pressure and gravity as it accumulates (Gregory, 1997; Gladman et al., 2010). However, when the soil dries due to increased temperature, the pore pressure (moisture) is lost and the structure of the soil aggregate is easily destroyed by water supplied as rainfall. Forest soil consists of particles of various diameters, and fine soil particles do not run off easily if the aggregate structure is maintained (Rimal and Lal, 2009). Once the soil aggregate has collapsed, the shielding effect is lost, and the fine soil particles can be mobilised (Bagarello et al., 2006). Fine soil structure and the arrangement of soil pores are determined by how individual soil granules clump or bind together and aggregate. Fine soil structure has a major influence on the movement of water and air, biological activity, root growth, and seedling emergence. A wide range of 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 the soil from raindrop impacts.

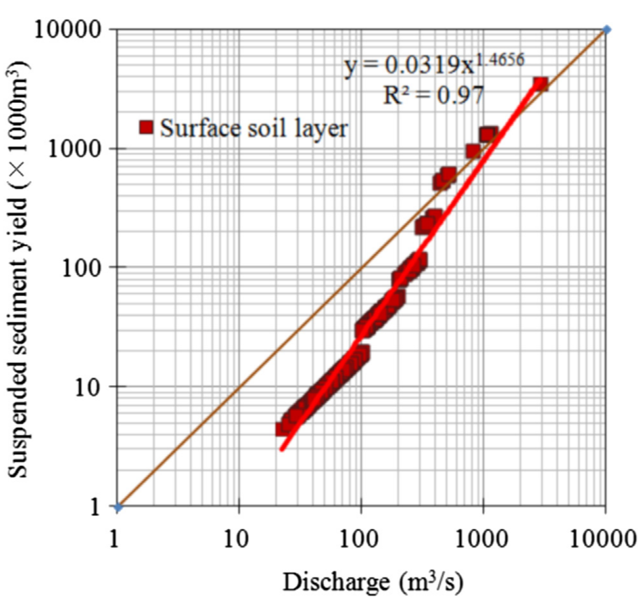

Fig. 5. Simulation results of the relationship between suspended sediment yield and river discharge throughout the Nagara River basin including the Tokai event of 7–11 September 2000. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency, following Mouri et al. (2011a,b, 2013a).

Phenomena related to surface erosion on slopes include shallow landslides (surface failure), bank failures, landslides, large-scale failures, and bare-land erosion. The most commonly documented of these are shallow landslides that occur due to intense rainfall, other landslides, and large-scale erosion. Researchers have constructed a dynamic model of moisture, sand, and gravel by integrating mass movement and surface erosion and have confirmed the reproducibility of the data in terms of the amounts of sand and gravel supplied to rivers and the temporal duration of the supply (Beguería, 2006; Chang and Slaymaker, 2002; Hovius et al., 2000). Such studies have provided results that are useful in the context of disaster prevention.

To understand the environmental impacts of sand and gravel mobility, the soil particle size of focus must be reassessed. Most environmental problems relating to sand and gravel are, in fact, caused by fine soil particles (Dearing and Jones, 2003; Dise et al., 1998; Fenn et al., 2003; Galloway et al., 2003; Goodale et al., 2000; Gundersen et al., 1998; Hotta et al., 2007; Pistocchi, 2008). The volume of fine soil particles contained in river water per unit time is generally proportional to the square of the flow rate, which has been documented for numerous sites (JSCE, 1999). The supply of fine soil particles has been assessed in terms of surface erosion systems such as sidewall erosion and boulder flow (Bouchnak et al., 2009; Oh and Jung, 2005; Orwin and Smart, 2005; Whitford et al., 2010). This would suggest that fine particles are supplied mainly during large-scale floods. It is axiomatic, however, that river water contains fine soil particles even during fine weather and during medium- and small-scale floods during base flow periods. Furthermore, surface flow generally does not occur on forest slopes during times of no rain or times of medium- or small-scale floods (Dun et al., 2009; Neary et al., 2009). Therefore, forest soils are assumed to be a major source of fine soil particles during extreme floods and base flow.

Among the components of aggregate structures of forest soil, fine soil particles such as silt and colloids are important elements of the water-cultivation function of forests. When aggregate structures of forest soil disintegrate, and large volumes of fine soil

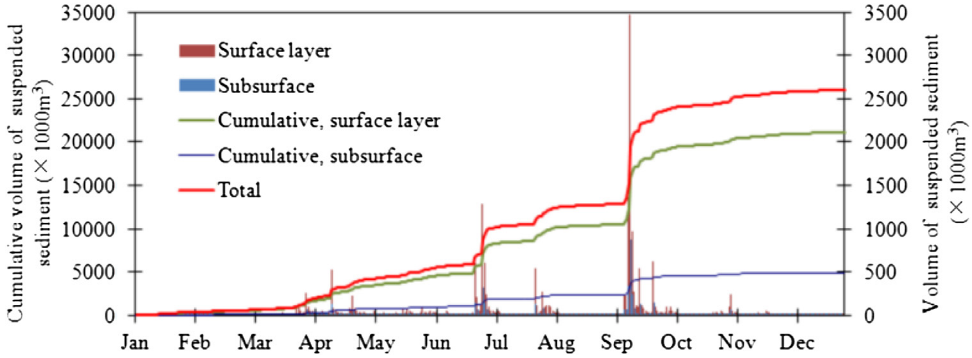

Fig. 6. Simulation results of time series of suspended sediment and layer destruction classified into the surface layer and subsurface layer throughout the Nagara River basin and including the Tokai event of 7–11 September 2000. The green line shows the calculated suspended sediment yield from the surface layer. The blue line shows the calculated suspended sediment yield from the subsurface layer. The red line shows the total amount. Data are from the Ministry of Land, Infrastructure and Transport (MLIT) and the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency.

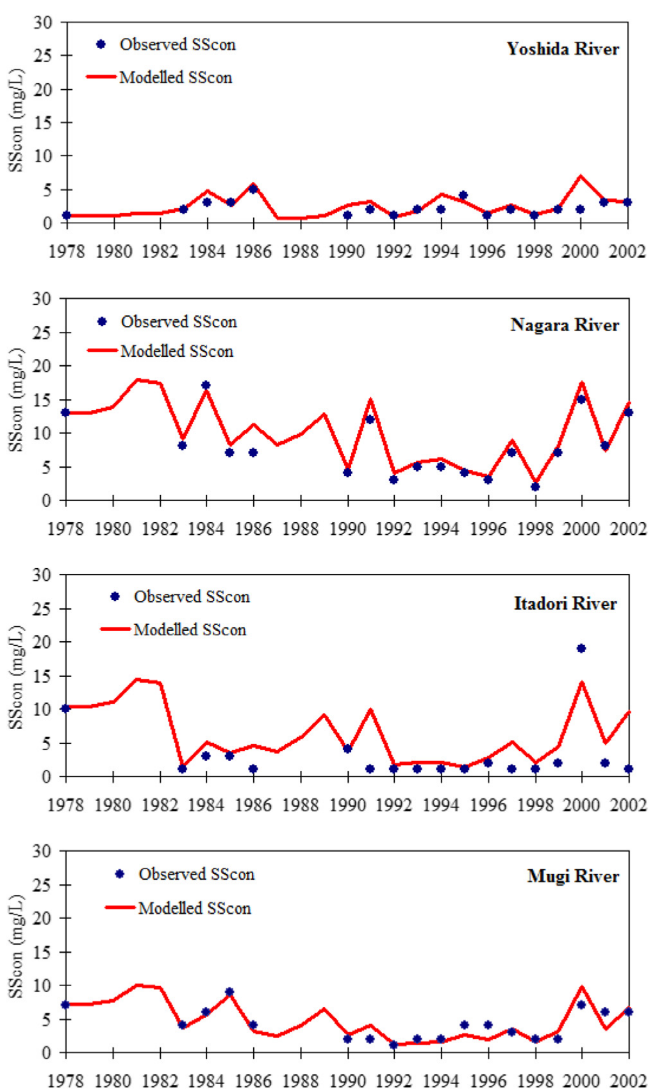

Fig. 7. Annual validation of SS concentration (SScon) based on soil aggregate collapse at four selected sites along the granitic mountainous slope (1978–2002; $R^2 = 0.76$). Data are partially from the Chubu Regional Bureau of the Ministry of Land, Infrastructure and Transport (MLIT) and the Japan Meteorological Agency, Japan.

particles run off, the water-cultivation function of the forest deteriorates, which may affect the survival of plants (Buytaert et al., 2007; Zheng et al., 2008). Furthermore, because the influence of the interparticle bonding force due to moisture is large for fine soil particles, the strength of such an aggregate decreases as moisture is removed (An et al., 2010; James and Roulet, 2009). The aforementioned studies show that increased evaporation caused by elevated temperatures associated with warmer climate causes moisture loss from soil, which leads to a decrease in the strength of soil aggregates and easier collapse into fine soil particles. As a result, the effective porosity of the soil increases, and the moisture content of the soil decreases, forming a vicious cycle.

The collapse of fine particle aggregates and increased suspended sediment runoff volumes are directly related to global environmental problems, such as deterioration of forest conditions and reduced survivability of forest plants. These phenomena are also important for the prevention of sediment-related natural disasters (Mouri et al., 2013b,c; Schiermeier, 2009).

The correlation between the suspended sediment yield and discharge or precipitation was very high, $R^2 = 0.97$, and the correlation function increased exponentially (Fig. 5). The increasing or decreasing ratio of SS yield was larger than that for discharge by approximately 3–23%. Surface landslides occurred mostly during heavy rainfall events. On the other hand, the results indicate that collapse of soil aggregation occurred mainly during heavy rainfall events and during times of low precipitation (Fig. 6). Additionally, the simulated suspended sediment was modelled with an accuracy of approximately 4% annually (Fig. 7). The relationship between soil moisture and erosion could depend on climate variation among different events. Over a period of months or a year, erosion will be related to the actual number of rainfall events that occur along the transects and to the state of aggregation or erodibility status of the soil. Over a period of 15–30 years, erosion will depend on the stability and resilience of the soil and vegetation.

6. Conclusions

This study modelled the drying of forest soils such as by decreases in antecedent rainfall under a warmer climate condition and the resulting runoff of fine soil particles in sandy, gravelly sediment. By expressing the dispersion (runoff) of fine particles due to destruction of soil aggregates, including an interparticle bonding force and an adhesive force generated by the effects of sedimentation, the conditions for aggregate collapse were identified, and a model was formulated based on the relationship between the collapse of fine soil particle aggregates and increased porosity. It can be shown that increased evaporation related to elevated temperatures causes moisture loss from soil, which leads to a decrease in the strength of aggregates in the soil and the collapse of fine soil particle aggregates. As a result, the effective porosity of the soil increases, and the moisture content of the soil decreases, forming a vicious cycle. The dispersion of fine particles and increased sediment runoff volumes that could result from a warmer climate are directly related to global environmental problems, such as deterioration of forest conditions and reduced survivability of forest plants. These phenomena are also important for the prevention of sediment-related natural disasters.

Discrepancies between simulated SS concentrations and observational data for selected locations can be explained by uncertainties in the distribution of precipitation, the river flow rate, geographical features, and the geology. However, this study of the spatial and temporal distribution of suspended sediment may contribute to the development of policies, research targets, technologies, and education necessary to explain the trend of increasing SS delivered to river estuaries. The model developed here incorporates climate and land-use data and may be used to study how these factors affect hydrology for catchment management.

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