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Characteristics of suspended sediment and river discharge during the beginning of snowmelt in volcanically active mountainous environments

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ABSTRACT

To better understand instream suspended sediment delivery and transformation processes, we conducted field measurements and laboratory experiments to study the natural function of spatial and temporal variation, sediment particles, stable isotopes, particle size, and aspect ratio from tributary to mainstream flows of the Sukhaya Elizovskaya River catchment at the beginning of and during snowmelt. The Sukhaya Elizovskaya River is located in the Kamchatka Peninsula of Russia and is surrounded by active volcanic territory. The study area has a range of hydrological features that determine the extreme amounts of washed sediments. Sediment transported to the river channels in volcanic mountainous terrain is believed to be strongly influenced by climate conditions, particularly when heavy precipitation and warmer climate trigger mudflows in association with the melting snow. The high porosity of the channel bottom material also leads to interactions with the surface water, causing temporal variability in the daily fluctuations in water and sediment flow. Field measurements revealed that suspended sediment behaviour and fluxes decreased along the mainstream Sukhaya Elizovskaya River from inflows from a tributary catchment located in the volcanic mountain range. In laboratory experiments, water samples collected from tributaries were mixed with those from the mainstream flow of the Sukhaya Elizovskaya River to examine the cause of debris flow and characteristics of suspended sediment in the mainstream. These findings and the geological conditions of the tributary catchments studied led us to conclude that halloysite minerals likely comprise the majority of suspended sediments and play a significant role in phosphate adsorption. The experimental results were upscaled and verified using field measurements. Our results indicate that the characteristics of suspended sediment and river discharge in the Sukhaya Elizovskaya River can be attributed primarily to the beginning of snowmelt in volcanic tributaries of the lahar valley, suggesting a significant hydrological contribution of volcanic catchments to instream suspended sediment transport. Daily fluctuations in discharge caused by snowmelt with debris flow were observed in this measurement period, in which suspended sediment concentration is ~10 mg/l during nonflooding periods and ~1400 mg/l when flooding occurs. The oxygen and hydrogen isotope measurements, when compared with Japan, indicated that the Kamchatka region water is relatively lightweight, incorporating the effects of topography; and the water from the beginning of the snowmelt is relatively lightweight when compared with water from the end of the snowmelt. The trend line of isotopes from the beginning of the snowmelt was defined by a slope of 6.88 ($n = 12$; $r^2 = 0.97$), significantly less than that of isotopes from the snowmelt (8.72). The sediment particles collected during the snowmelt were round in shape caused by the extreme flows and high discharge. The shape of the sediment particles collected at the beginning of the snowmelt, assumed to be fresh samples from the hillslope, was sharper caused by the relatively small discharge by moderate snowmelt. Finally, the relationship between river discharge and suspended sediment concentration was indicated. The results are compared with mountainous rivers of Japan and Malaysia. A new diagram is proposed to describe the relationship between suspended sediment concentration and river discharge.

1. Introduction

Water resulting from precipitation on land, represented mainly by rain water, follows several paths before reaching oceans or seas or before being recycled back to the atmosphere. Sediment transport depends on a number of factors, the most important of which are the

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amount of available water, precipitation (both average and peak), discharge (volume and velocity), topographical and environmental features of the terrain, basin geology, magnitude of human impact, and amount of sediment or load that the river or stream can carry (Richmond et al., 2003; Delpla et al., 2009; Alexander et al., 2010; Syvitski, 2011; Mouri et al., 2013a,b,c, 2014). In a volcanic environment, many of the drivers of sediment discharge (loss of surface materials by erosional forces) are significantly enhanced compared with other mountainous areas (Jing and Chen, 1983; Poesen and Hooke, 1997; Teramoto et al., 2005). Volcanically influenced sedimentary settings are complex systems that reflect the addition of volcanic ejecta and their subsequent transport and deposition over a wide range of mountainous environments (Fisher and Smith, 1991; McPhie et al., 1993; Mascarenhas-Pereira et al., 2006; Manville et al., 2009).

1.1. Water streams in volcanic territory and the sediment loads

In volcanic areas, especially on volcanic slopes, various types of water streams are created. Lahars follow the paths of river valleys. A lahar is a mudflow resulting from the interaction between loose volcanic rocks and water on the slopes of the volcanoes caused by snow and ice melt during eruptions and the breakthrough of crater lakes. These are mass wasting events that are triggered by a fluvial event. During these events, the snowmelt starts when the subsurface is still frozen, triggering overland flow and landslides. Runoff helps determine the nature of lahars and the sediment yield of the river (Neall, 1976; Deike and Jones, 1980; Decaulne and Saemundsson, 2006; Fiorucci et al., 2011; Iida et al., 2012). Permanent and temporary rivers (tributaries of the lahar valley) are water streams that originate on the slopes of the volcano but that are of a type that also occur in other types of mountains. The river beds are created by channel processes that do not differ from those of mountain rivers found in nonvolcanic areas (Mascarenhas-Pereira et al., 2006; Petry et al., 2007; Ermakova, 2009; Veldkamp et al., 2012).

Water drainage in the rivers of volcanic territories can be described as episodic (Cilento, 1937). There are two key reasons for this. First, the unconsolidated volcanic rocks that form the slope of the volcano have high water permeability. The groundwater level within active volcano territories is located very close to the surface, facilitating the extremely fast flow of water into the underlying layers. The infiltration rate of the river flow is determined by the features of the valley structure (Oguchi et al., 2001; Mouri et al., 2013a,b). The second reason for sporadic water drainage from rivers in volcanic areas is associated with the intermittent nature of their supply from precipitation, seasonal melting of snowfields, and catastrophic melting of ice and snow during volcanic eruptions. Most of the year, especially in winter, many of these rivers have no water. However, a dry river has full flow during spring snowmelt and during catastrophic melting of ice and snow during eruptions, which results in most of the cumulative erosion experienced by the slope terrain. Thus, the dry or full-flow state depends on daily fluctuations and seasonal conditions, as well as the permeability of the terrain, contributing to pulsating flow conditions during heavy flows.

The diurnal flow regime is completely determined by the melting of glaciers and snowfields and is transformed by the infiltration of the runoff. In the period of increasing water flow, the rivers are actively being filtered into thick fluvial sediments and gradually filling the underflow path. The latter decreases infiltration and thus determines the increase in surface runoff. Aquifer filtering also contributes to the intraday cyclical flow (Mouri et al., 2011c,d, 2013d; Kuksina and Chalov, 2012).

The saturated sediment water flow of the rivers flowing from the volcano is characterised by a mass-wave movement such as debris flow, which is associated with the features of the water flow in the channel. Mechanical changes in the mainstream such as the collapse of the foot of a glacier, the creation and eruption of temporary dams, and the river bed deformation allow water to seep into the loose volcanic strata; the output of this water downstream leads to abrupt changes in the water flow downstream and upstream. This kind of pulsating flow also occurs in glacial rivers, which exhibit similar short-term fluctuations (Ballantyne and McCann, 1980).

The sediment load of rivers in volcanic regions forms under a variety of geomorphologic and hydrological conditions (O'Connor et al., 2003; Noyesa et al., 2009) such as heavy rainfall, leakage from crater lakes, melting snowfields and glaciers, or volcanic eruption. The total volume of the sediment load usually forms under the influence of strong fluctuations in water content, resulting in diurnal variations and even intrahourly changes in water and sediment conditions, which can significantly exceed intraannual fluctuations (Martin and Meybeck, 1979; Chalov, 2012; Mouri et al., 2012).

During the period of high snowmelt in the spring, the rivers in the volcanic territories of Kamchatka are full flowing, actively contributing to cumulative erosive changes in the terrain. The greatest material transport occurs during volcanic eruptions (Kuksina and Chalov, 2012). The sediment of the rivers consists of dry boulder gravel and sand material and is characterised by lens bedding (Kuksina and Chalov, 2012).

1.2. Channel processes

Changes in the type of rivers cutting the slopes and foothill areas of active volcanoes are associated with different types of river valleys (Petry et al., 2007; Hamann et al., 2010; Verbist et al., 2010; Chalov et al., 2013). Seasonal fluctuations in the water and sediment flow determine the variability in the channel network. The susceptibility to eruption and the maximum flow of sediment in the middle of the rivers in volcanic areas ('dry' river beds) define a specific mode of vertical variation. When the surface filtration flow predominantly consists of thick sedimentation, materials tend to accumulate on the surface. Under these conditions, changing or diverting the flow of surface runoff in the absence of additional sources of solid material is difficult; thus, in this case, the erosion is quite significant (Lawler et al., 1992; Oguchi et al., 2001; Kuksina and Chalov, 2012).

The speed of the entrenchment of dry rivers into soft volcanic sediments is evidenced by the fact that the Sukhaya Khapitsa River whose valley in the upper and middle stream was filled to the edges with sediments of the ignimbrites and agglomeration stream of the 1956 eruption of Bezymyanny volcano had already cut through this stratum by 1962 and continued to entrench into the underlying glacial deposits (Kraevaya, 1964). Thus, the maximum depth of its entrenchment over 6 years was ~35 m. Downstream, the entrenchment depth decreases with further widening of the bed. The cross section of the valleys of dry rivers from the head to the mouth undergoes significant changes. In the river head, as a rule, valleys have a V-shaped cross section. In the middle reach, owing to intensive underwashing of the soft stratum building up the edges, the valley assumes the shape of a canyon, which testifies to the increasing role of lateral erosion. In the lower reach, the valley profile flattens out.

The deformation of river beds in volcanic areas has a specific character caused by the extremely uneven water flow. Water sources originate on the volcano slopes, but flow within different types of mountain channels according to river mechanics, which are not different from those of braided rivers of nonvolcanic areas. Structures of focal branching of volcanic rivers are random and are completely modified by each flood. Thus, from the daily fluctuations in the water flow, separate flows can be measured every 10 min (Yukiyoshi et al., 2005; Ermakova, 2009; Mouri et al., 2011b, 2013c,e,f).

2. Study area description

2.1. Brief description of the study area

The Kamchatka Peninsula is located in northeast Russia and is the second largest peninsula in Russia (total area: 370,000 km^2; length: 1500 km). The peninsula is connected to the mainland by the narrow Kamchatka isthmus of the Parapolsky dale. Kamchatka is a young