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River responses to the 2010 major eruption of the Merapi volcano, central Java, Indonesia

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ABSTRACT

This study examines the fluvial readjustment of a Javanese river impacted by the major eruption of the Merapi volcano (Indonesia) in October and November 2010. The basin of the Opak River, located on the southern flank of the Merapi, was subject to substantial sediment input related to massive pyroclastic deposits that were remobilized by numerous lahars during the year after the eruption. Two study sites were equipped in order to evaluate the morphodynamic evolution of the riverbed of the Opak River. Topographic surveys, bedload particle marking, and suspended sediment sampling revealed an important sediment mobilization during efficient flash floods. Surprisingly, no bed aggradation related to the progradation of a sediment wave was observed. Two years after the eruptive event, marked bed incision was observed. The Opak River readjustment differs from that of other fluvial systems affected by massive eruptions in two ways. Firstly, local population extracted the sand and blocks injected by the eruption as they represent a valuable economic resource. Secondly, several dams trapped the major part of the sediment load remobilized by lahars.

1. Introduction

Since the 1980 eruption of Mount Saint Helens in the USA, numerous studies have focused on river adjustments after major explosive volcanic events (Gran and Montgomery, 2005). They mostly concern hydrological effects and the geomorphological dynamics of valley bottoms (Gran and Montgomery, 2005; Major and Mark, 2006; Tanarro et al., 2010; Gran, 2012; Gran et al., 2011, 2015; Pierson et al., 2011; Pierson and Major, 2014; Umazano et al., 2014; Zheng et al., 2014). They show how very large quantities of sediment brought through tephra fall, pyroclastic flows, or debris avalanches contribute to modifying the river system and sometimes even radically changing the drainage network.

The eruptions of the 1980 Mount Saint Helens (USA), 1991 Pinatubo (The Philippines), and 2008/2009 Chaitén (Chile), produced tephra volumes as high as 2.5, 5 to 6 and 1 to 4 km^3 respectively of extruded material. As a consequence, hillslopes and valley bottoms were buried by several meters of poorly sorted material over tens to hundreds of square kilometers (Major and Mark, 2006; Gran, 2012; Umazano et al., 2014). Pierson and Major (2014) in their synthesis on the hydromorphological effects of eruptions on drainage basins suggest two main series of consequences of this sudden and massive supply of sediment. The first one concerns runoff production and flood discharges; and the second, erosion mechanisms, sediment sources, and sediment transport.

The hydrological disturbances correspond to a *flashier* response to storms because of a decrease in soil infiltration capacity owing to tephra deposits and a loss of vegetation (Gran and Montgomery, 2005; Pierson and Major, 2014; Umazano et al., 2014). Major and Mark (2006) – who studied the hydrological evolution of streams impacted by the Mount St Helens eruption – showed that flow peaks had larger magnitudes and generally rose more rapidly. They indicated that this increase in magnitude lasts between 5 and 10 years after the eruption and that it is not only owing to hillslope runoff but also to changes in channel hydraulics (reduction of flow resistance because of channel smoothening and straightening and to an increase of the sediment transport rate).

The second major change concerns the channel geometry and the sediment transport rate. The main result of these large eruptions is a major increase in sediment yield directly after the volcanic crisis and for decades after its end. Sediment transport rates may reach levels amongst the highest in the world observed for hydrosystems, approaching 10 m^3/ha/mm of rain (Manville et al., 2009). Lavigne (2004) calculated erosion rates of 1.5 to 2.7 × 10^5 m^3/km^2/y in two

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catchments on the Merapi and Semeru volcanoes. Sediment comes from two sources: (i) on hillslopes, abundant, fine, noncohesive sediments are subject to intense erosion through the development of rill networks; and (ii) in the river network, valley filling with pyroclastic materials or debris avalanche deposits are mobilized mainly by large mass movements such as lahars but also through vertical and lateral erosion during the high flow season (Lavigne and Thouret, 2000, 2002).

Post-eruptive lahar sediment concentration may be 10 to 20 times higher than the sediment concentration of pre-eruptive floods and up to 100 times higher than that found in undisturbed volcanic catchments (Pierson and Major, 2014). Particularly in tropical regions, lahars are the main processes involved in reworking volcanoclastic material, as tens of them take place during the months following the eruption and they may occur for decades afterward.

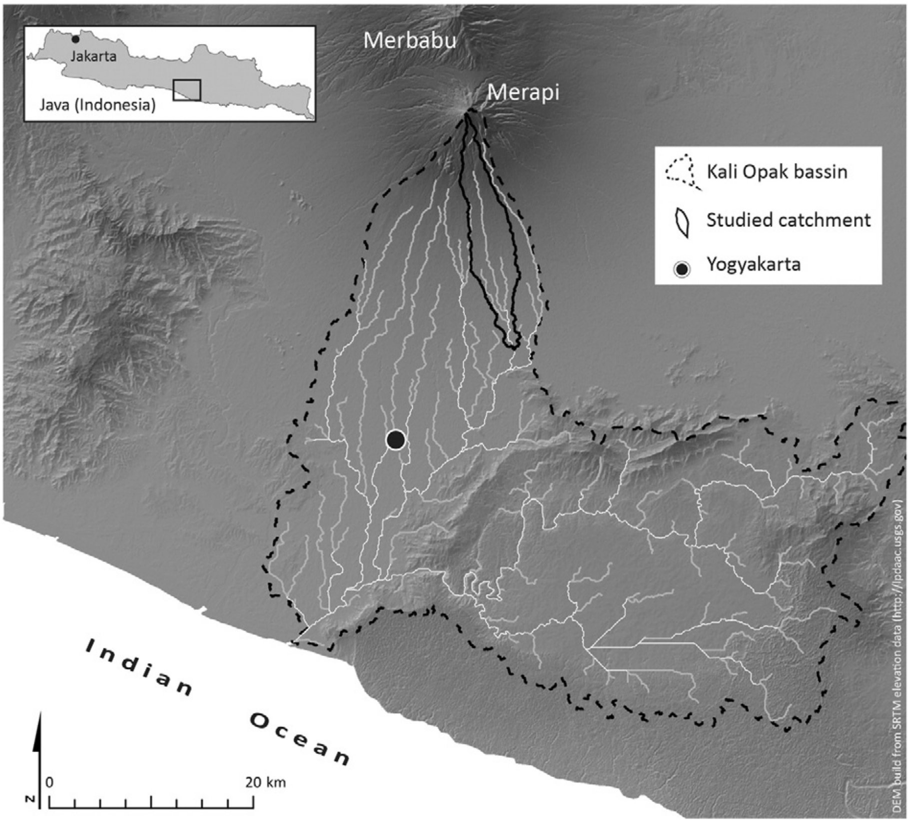
Once remobilized, the sediment inputs propagate downstream as a sediment wave modifying the channel geometry of the river. At the basin scale and considering a longer time span, Pierson et al. (2011) describe the migration of this sediment wave as a cycle with channel aggradation and then degradation. The elevation of the channel bed is coupled with widening, the development of mobile and braiding beds, and a fining and smoothening of the beds. The degrading phase corresponds to the reincision of the channel in the lahar and flood deposits. It leads to the return of a single-thread channel with progressive bed armoring and channel stability but also to the development of bank erosion and lateral migration (Pierson and Major, 2014). Riverbed stability and narrowing is accompanied by riparian vegetation growth (Gran et al., 2015). The duration and magnitude of this cyclical perturbation is described as very variable depending on the magnitude of the eruption, the climatic environment, and the local conditions.

Considering the extreme nature of the volcanic events studied in the literature, the parameters that control the post-eruption evolution of the river system are generally described only as natural and that the role played by human activities seems negligible. This study investigates the morphologic adjustment of rivers following the 2010 October–November Merapi (central Java, Indonesia) eruption, in particular with regard to the role played by local populations. The Merapi is indeed a very active but densely populated volcano that experienced its largest eruption in >100 years in autumn 2010 (Surono et al., 2012; Cronin et al., 2013; Jousset et al., 2013; Pallister et al., 2013). The populations of the Merapi are highly dependent on the volcano. Rice and others crops rely on the very fertile properties of the volcanic soils and on a dense and complex irrigating system directly connected to the river network (Lavigne et al., 2015). Moreover, sandy volcanic material is widely exploited for the construction sector locally and for exportation. This close interaction between the population and the very active volcanic environment induces tremendous hazards but may also contribute to deeply modify the post-eruptive adjustments of the system on which the population depends.

To follow the channel adjustments of the river to the 2010 eruption and the role played by human activities, two study sites were selected on the middle part of the Opak River. Those sites are located at the very end of the reach affected by the strongest lahars. Between September 2011 and March 2015, the morphometric evolution of the stream, the hydrological regime, and the sediment transport were surveyed. Our objectives were to evaluate the impact of a major eruptive event on the sediment reload of the middle part of a very anthropized river system and to better understand the role played by floods in the propagation of the sediment wave produced by hypercontracted flows and lahars in the upper part of the course.

2. Study area

The Merapi is a volcano located in central Java (Indonesia) known for its frequent activity (Fig. 1). Its eruptions occur every 4 years on average with an interval ranging from 2 to 15 years. Merapi eruptions are



DEM build from SRTM elevation data (http://lpdaac.usgs.gov)

Fig. 1. Location of the Merapi volcano and the Opak River basin, Java, Indonesia.