



Assessing the effects of consecutive sediment-control dams using a numerical hydraulic experiment to model river-bed variation

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ABSTRACT

In the Kotaki River Valley, Japan, the Fossa Magna has produced a large-scale collapse and landslide zone. Debris flows occur annually in the Kotaki River, which has headstreams in the Hakuba range (altitude: 2267 m) located in Niigata Prefecture. Sediment-related disasters occur over extensive areas from headwater to downstream cities and in a variety of forms. This will produce large quantities of upstream sand in the future, which may cause flooding through the deposition of sediment near downstream junctures. In such a river, it is necessary to control sediment runoff from the upper stream and prevent extreme changes in the height of the downstream riverbed. To protect people and properties from sediment-related disasters, consecutive sediment-control dams are erected. These dams are built into the upstream areas of mountain streams to accumulate sediment, suppressing its production and flow. On the Kotaki River, in areas of the river where the MTL is exposed, the potentially large quantity of sediment discharge during floods was reduced by installing three sets of slit barriers to prevent landslides while allowing the passage of fish. This dam system was modelled after extant slit barriers of this nature. Previous investigations of temporal changes in sediment-regulating function and sediment outflow in river sections with continuous slit barriers have incorporated many unknown factors. We performed a numerical simulation of a section of the Kotaki River containing slit barriers to prevent landslides and examined the characteristics affecting sediment-regulating functions.

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1. Introduction

The Japanese term “sabo” was recognised at the International Hydrological Science Convention in Brussels, Belgium, in 1951 and has since become widely known worldwide. Japan has a long experience with sediment-related disasters and has developed various preventive measures. A “sabo” dam structure protects the downstream terrain from the effects of riverbed erosion, hillside landslide and a large amount of sediment flow. As early as the Nara period (in the 8th century A.D.), laws were enacted to restrict logging for the protection of mountain hillslopes and streams. The principles of sediment management in mountainous catchments were further developed in the Edo period (from 1603 to 1868), when individual feudal clans implemented many sabo works. However, despite these measures, sediment-related disasters have continued to occur, hindering ship transportation and causing floods. It is our responsibility to restore nature by improving devastated

mountain areas and their river systems. Through such efforts, we can create a new era of sabo works, one that builds on the long history of sabo knowledge and is both environmentally and human friendly. Effective sediment control can aid in conserving water and sediment and in preventing natural disasters throughout an entire drainage basin.

Japan first became involved in international technological cooperation and exchange of sediment-related disaster prevention techniques when experts were sent to Costa Rica in 1967 by the Ministry of Land Infrastructure and Transport (MLIT). Since then, Japan has continued to engage in technological cooperation and exchange with a number of countries.

Large-scale sediment disasters triggered by rainfall can destroy infrastructure and threaten human lives and livelihoods. In Japan's Kotaki River basin, sediment is the most volumetrically important contaminant. The sediment flux can be generally characterised by comparing the sediment produced in mountainous regions with its movement and deposition in river channels. Most of the sediment supplied from mountainous regions is transported from upper to lower river reaches during rainfall events. To better understand and control sediment movement in river

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basins, proper evaluation of rainfall-runoff and sediment-yield processes is necessary.

Ground sills are a commonly used method of controlling sediment. In Taiwan, this method is widely used in upstream areas in combination with series of check dams to stabilise streambeds against sediment scouring and to help control streambed gradients. High-gradient streams often exhibit a naturally formed step-pool architecture that likely represents the self-adjustment of the stream toward higher bed stability (Guangwei, 2011; Lenzi, 2002; Lin et al., 2008). In longitudinal profile, the river-channel morphology of a reach with ground sills is similar to that of a channel with step-pool and pool-riffle sequences. Mo's (1987) field observation of the upstream region of the Jhuo-Shuei River, Taiwan, found that step pools are bed-armouring morphological channel features that help to reduce the water power that causes sediment transportation, making the channel more stable.

Montgomery and Buffington (1997), in their classification of streams, explained the tendency of supply-limited rivers to form a step-pool geometry. Whittaker and Jarggi (1982) also noted that unstable riverbeds formed step pools readily when flow discharge was significant and sediment size ranged widely.

Quantitative analyses have focused primarily on the amount of soil erosion resulting from human activities. Such analyses have used the amount (Li, 1989; Li and Wei, 2011) and natural background value (Wu, 1994) of soil erosion and natural (Chen, 1988; Jing and Chen, 1983) and artificial (Tang et al., 1991) accelerated erosion to quantify the impact of human activities on environmental change in soil-erosion regions. Quantitative approaches to the analysis of human influence have included mainly geological and morphological assessments, land-use/cover-change methods, and considerations of climate fluctuation and soil and water conservation (Mouri et al., 2012a; Wang et al., 2003). These methods have had important theoretical value and practical significance in the ecological assessment of environmental evolution and anthropogenic mechanisms of water and soil loss in the Loess Plateau of China. However, they can produce different or even contradictory conclusions due to limitations in the ranges of application (Wang et al., 2003). Check dams are important engineering measures to conserve soil and water in hilly and gully regions. Many check dams have been used in the Loess Plateau because they are highly effective in comprehensively controlling soil and water loss (Fang et al., 1998; Hu et al., 2002; Jiao et al., 2003; Li, 2003). Additionally, the process of sediment deposition behind a check dam can directly indicate sediment yields in the controlled area of the dam. From the perspective of system theory, the controlled area of a check dam can be regarded as a basin system; this theoretical perspective facilitates the quantitative analysis of water and soil loss resulting from human influence. Based on system theory, an observability–controllability model of periphery (COMP) has allowed the analysis of anthropogenically influenced soil erosion in the controlled area of the Shipanmao check dam located in the hilly and gully region of the Loess Plateau. In comparison with traditional

analyses, the COMP approach provided quantitative results that can be used to effectively guide changes in trends of human-influence intensity and direct watershed water and soil conservation in the Loess Plateau.

To date, few studies have evaluated the effectiveness of check dams in controlling gully and soil erosion. Marston and Dolan (1999) concluded that engineering structures installed to control sediment export in an arid watershed in Wyoming, United States, were not always effective or even necessary. In a study of the effectiveness of loose-rock check dams for gully control in northern Ethiopia, Nyssen et al. (2004) found that 39% of the dams surveyed were destroyed within the first 2 years. The collapse of these dams was associated strongly with runoff energy, expressed as the product of drainage area and slope gradient. The upstream geomorphological effects of dams differ from downstream effects. Upstream channel aggradation is gradual due to the increase in base level (e.g., Petts and Thoms, 1986). As a consequence, dams fill rapidly with sediment, especially in semiarid environments with high sediment yields (Poesen and Hooke, 1997). Downstream effects are more complex. Changes in discharge and sediment load can alter the cross-sectional shape, channel form, slope gradient, and grain size of the bed material (Brandt, 2000). The erosional capacity of 'clear' water can increase following sediment deposition behind a dam. Investigation of the effects of dam construction on fluvial processes in ephemeral channels is complicated by the absence of such processes most of the time. The morphological regime of ephemeral channels is unsteady because responses to irregular, torrential rainfall are rapid and cause extreme morphological dynamics; channels that are dry for several months may suddenly carry high discharges and sediment loads (Conesa Garcia, 1995). In such environments, large floods that transform channels and produce large sediment movements have return periods of 2–6 years (Conesa Garcia, 1995). These high-magnitude, low-frequency floods appear to govern channel development (Knighton and Nanson, 1997).

The objectives of this study were to evaluate the effectiveness of check dams for gully control in the study area, to identify the morphological effects of check dams in ephemeral streams based on field observations, and to analyse the impacts of check-dam installation on erosion–deposition dynamics.

The evolution of the bed deposits, including erosion and deposition, was predicted from the bed–load relationship derived from Ashida and Michiue's (1972) formula, which incorporates the mixing layer and grain size distribution. The convection–diffusion equation gives the suspended-load volume, as set out by Ashida and Michiue (1972), as well as the diffusion equations. The unsteady flow, a mixture of tranquil and jet flow, can be calculated using the MacCormack constrained interpolation profile (CIP) or flux-difference splitting (FDS) methods (Yabe, 1996; Zhang et al., 2003). In this study, diminished nonuniform flow was considered to have reached a stable state for the following reasons. The rate of stream-bed change was low relative to the flow rate. Therefore, artificial viscosity could be established such that variations in the

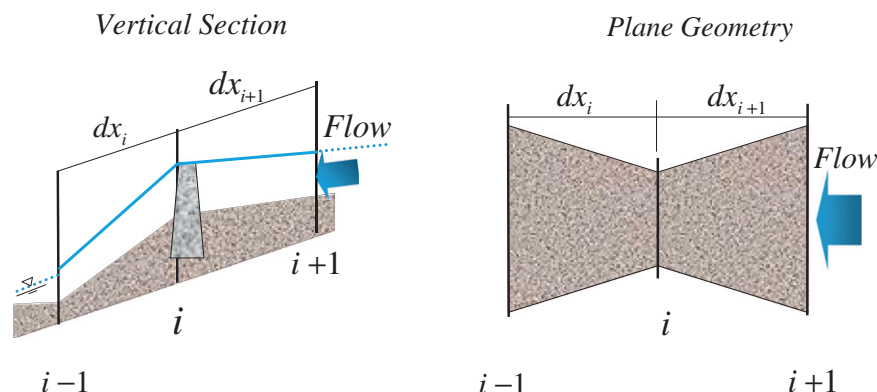


Fig. 1. Calculation method 1 near the dam structure.

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