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Effect of tree thinning and skidding trails on hydrological connectivity in two Japanese forest catchments

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ABSTRACT

Land use composition and patterns influence the hydrological response in mountainous and forest catchments. In plantation forest, management operations (FMO) modify the spatial and temporal dynamics of overland flow processes. However, we found a gap in the literature focussed on modelling hydrological connectivity (HC) in plantation forest under different FMO. In this study, we simulated HC in two steep paired forest subcatchments (K2 and K3, 33.2 ha), composed of Japanese cypress (*Chamaecyparis obtusa* Endl.) and Japanese cedar (*Cryptomeria japonica* D. Don) plantations (59% of the total area) against a tree thinning intensity of 50% at different time. Additionally, construction of new skidding trails and vegetation recovery was simulated on five thinning-based scenarios that covered a 40-month test period (July 2010 – October 2013). As a future scenario, six check-dams located in the main streams were proposed to reduce sediment and radionuclide delivery. An updated version of Borselli's index of runoff and sediment connectivity was run, using the D-infinity flow accumulation algorithm and exploiting three 0.5-m resolution digital elevation models. On the basis of the pre-FMO scenario, HC increased at catchment scale owing to tree thinning and the new skidding trails. This change was more noticeable within the area affected by the FMO, where HC increased by 11.4% and 10.5% in the cypress and cedar plantations in K2 respectively and by 8.8% in the cedar plantation in K3. At hillslope plot and stream scales, the evolution in the values of HC was less evident, except the increment (by 5.4%) observed in the streams at K2 after the FMO. Progressive vegetation recovery after the FMO triggered a slight reduction of connectivity in all compartments of both subcatchments. Forest roads and especially skidding trails presented the highest values of HC, appearing as the most efficient features connecting the different vegetation patches with the stream network. The spatial and temporal evolution of HC over the five past scenarios correlated well with the observed changes in runoff yield, as well as with the available values of rainfall interception and throughfall before, during, and after the FMO. The simulation of the proposed scenario recommends the construction of check-dams as effective landscape features to somewhat reduce HC and thus to decrease the sediment and radionuclide delivery rates from the two subcatchments.

1. Introduction

At catchment scale, land cover factors, land use changes, rainfall parameters, and soil properties determine the magnitude of overland flow processes across different compartments (López-Vicente et al., 2008). In mountainous forest areas, land use composition and spatial patterns are among the dominant first-order factors controlling the hydrologic response at the subcatchment scale (Shi et al., 2014). Besides this fact, a slight increase in the overall fractional vegetation cover, estimated as the C-RUSLE factor, in headwater catchments is likely to have a large effect on sediment production and delivery (Molina et al., 2008). The replacement of natural vegetation by plantation forest modifies the precipitation–runoff relationships and streamflow records (Little et al., 2009). In spite of good vegetation growth and coverage, the different types (species) of plantation forest trigger considerable differences in rainfall interception, throughfall, stemflow, and eventually runoff and sediment yields (Cao et al., 2008).

Hydrological connectivity (HC) has emerged in the latest decade as

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a significant conceptual framework for understanding the transfer of surface water and sediment through landscapes (Poeppl et al., 2017). According to these authors, geomorphic response of fluvial systems to human disturbance is determined by system-specific boundary conditions, vegetation dynamics, and human-induced functional relationships between the different spatial dimensions of connectivity. For effective catchment management and intervention in hydrological systems, a process-based understanding of hydrological connectivity is required so that the use of a range of techniques and approaches are needed (Bracken et al., 2013). Models and indices were developed to simulate HC, such as the 'volume to breakthrough' of Bracken and Croke (2007), the 'network index' of Lane et al. (2009), the 'connectivity of runoff model' of Reaney et al. (2014) as well as by exploring sediment cascades using graph theory (Heckmann and Schwanghart, 2013). A few years ago, Borselli et al. (2008) developed the 'index of runoff and sediment connectivity' (IC) testing successfully this approach in a large catchment in central Italy against field observations. This qualitative index accounts for the combined effect of the upslope topographic and land use characteristics and the values of these parameters throughout the flow paths that a soil particle has to travel to arrive at the nearest defined stream or sink. Afterwards Cavalli et al. (2013) proposed some improvements on the original equation related to very steep slopes and Gay et al. (2016) for lowlands with high infiltration rates. The ability of this index has been proved in different fields and catchments, such as in Spain (López-Vicente et al., 2013, 2015, 2016) and in Australia (Vigiak et al., 2012). In Japan, Chartin et al. (2013) proved its capacity to map hydrosedimentary connectivity in a catchment contaminated with fallout radionuclides emitted after the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident.

Forest management operations (FMO) in plantation forest — such as landing, tree planting, forest road engineering, thinning, cutting, extraction (harvesting) and transport (skidding trails) — modify runoff and sediment yield and downstream environmental issues. For example, Onda et al. (2010) observed at catchment and plot scales that overland flow decreased about five to ten times with increasing values of understory vegetation density in managed and unmanaged plantations of Japanese cypress (*Chamaecyparis obtusa* Endl.) and Japanese cedar (*Cryptomeria japonica* D. Don), as well as in broadleaf forests. In steep terrain, such as most forested areas of central Japan, forest harvesting activities may increase the occurrence of mass movements, especially in younger forests (< 25 years after harvesting and replanting), thus altering the volume of sediment storage in the channel that links sediment supply from hillslopes with sediment yield downstream (Imaizumi and Sidle, 2012). Strip thinning changes the rainfall-runoff balance and peak flow responses (Dung et al., 2011; Sun et al., 2015a). However, Dung et al. (2015) found different hydrological responses among nested catchments caused by changes of hydrological connectivity via overland flow generated by newly installed and reactivated skidding trails. Skidding trails and forest roads can play roles of sediment source and pathway for runoff and sediment, from forest floor to stream channel (Mizugaki et al., 2008). The effect of landscape pattern changes on hydrological processes has been studied by many authors and disciplines in the world. Lin et al. (2014) studied correlations between daily stream flow and changes of landscape indices, including connectivity, in a forestland area in southeastern China under high human pressure. Marchamalo et al. (2016) found that man-made linear features such as terrace embankments and tracks have a major influence on sediment connectivity in small catchments differing in topographic and land use characteristics. However, information and methods to approach these issues on modelling HC in plantation forest managed with different FMO is insufficient.

Forest areas are very important and common in Japan. > 70% of the Japanese archipelago is covered by forest, of which 60% is evergreen coniferous forest (Onda et al., 2010). Japanese cedar and cypress plantations are two of the dominant evergreen coniferous trees that cover most infertile upper slopes. On March 2011, several hydrogen explosions affected three of the six nuclear reactors of the FDNPP, which triggered the release of a vast amount of radionuclides into the environment and contaminated forests in the Fukushima Prefecture and in a minor way in the Miyagi, Tochigi, Gunma, and Ibaraki prefectures (Kato et al., 2017). Evrard et al. (2013) studied the evolution of radioactive dose rates in fresh sediment deposits near the FDNPP and evaluated the potential mobility of contaminated sediments between hillslopes and the rivers with Borselli's index. In other landscapes, previous studies demonstrated that the radionuclide spatial patterns at catchment scale are strongly correlated with physiographic features such as gradient, orientation, and vegetation cover of the slopes, as well as with overland flow and surface water processes (Navas et al., 2011, 2013). However, specific studies on hydrological connectivity in plantation forests affected by the FDNPP accident and managed with tree thinning are limited.

In this study, we hypothesize that tree thinning and construction of new skidding trails modify the spatial patterns and magnitudes of HC at hillslope, catchment, and stream scales as well as in the different compartments of the landscape. To prove this statement, we simulated HC in two Japanese paired forest subcatchments devoted to plantation forest under different scenarios of FMO, including vegetation recovery after the operations, and proposed a future water conservation scenario. Namely, the objectives are to (i) simulate HC at five thinning-based scenarios following a time line (July 2010–October 2013) with an updated version of Borselli's index at high spatial resolution (0.5 m of cell size) and using the D-Infinity algorithm; (ii) analyse the spatial patterns and temporal changes of HC within the area affected by the FMO as well as at plot, subcatchment, and stream scales; (iii) validate the simulated values of HC with available data of runoff and stream yield obtained at three hillslope plots and six gauging stations; and (iv) propose a future scenario with six new check-dams located in the main streams to reduce the highest values of HC and thus of sediment and radionuclide delivery. This study contributes to the understanding of the spatially distributed behaviour of hydrological connectivity in a plantation forest affected by tree thinning, skidding trails, and vegetation recovery. Finally, the proposed scenario may help in managing polluted soils caused by the FDNPP accident in Japanese headwater catchments.

2. Materials and methods

2.1. Study area

The study area is composed of two adjacent subcatchments (SubC), so-called K2 (19.6 ha) and K3 (13.6 ha), located on Mt. Karasawa near Sano City (Tochigi Prefecture) in central Japan. The area is located at 172 km southwest of the FDNPP and managed by the Tokyo University of Agriculture and Technology (Fig. 1A). Subcatchment K3 is a tributary of K2, which is located in the left bank of the Tone River Basin. The hydrological boundaries of both subcatchments were defined upward from the joining point of both outlets (36° 22′ 03″ N; 139° 36′ 02″ E; 76 m asl) (Fig. 1B). Landscape is steep with average slope steepness of 66% and 65% in K2 and K3 respectively, and the highest peak is located in K2 at 286 m asl. The plantation forest is made by Japanese cedar and Japanese cypress and was planted in 1971 and 1972 (Kato et al., 2012). These trees have a mean diameter at breast height (DBH) of 19.1 ± 3.9 cm, a mean stand height of 16.0 m, and a mean canopy cover fraction of 0.974. The original stand density and basal area were of 2198 stems ha^{-1} and 50.4 m^2 ha^{-1} respectively (Sun et al., 2014a). However, these plantations received no management practice and were abandoned since planting until 2011 when tree thinning started (Sun et al., 2014b). The understory vegetation is sparse in most places and dense in others, mainly including fern species (*Gleichenia japonica*), shrubs (*Cleyera japonica*, *Ardisia japonica*, *Rhododendron kaempferi*, and *Eurya japonica*) and herbs and grasses (*Carex lanceolate* and *Trachelospermum asiaticum*). The native and broad-leaf trees are *Quercus serrata*