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.

Keywords: hydrological connectivity; plantation forest; tree thinning; skidding trail

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 a significant conceptual framework for understanding the transfer of surface water and sediment through landscapes (Poepl 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 have 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. More than 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* and *Pinus densiflora* (Prof. Takashi Kamijo, personal communication; Fig. 1C).

Climate is humid temperate with an average annual precipitation of 1416 mm (period 2010-2014) measured in an open rain gauge in the study area. The mean annual temperature was 14.2°C (data obtained at Yamakoshi, the nearest national weather station). The region has two dominant storm periods: the Baiu season from late June to mid-July, and the typhoon season from late August through October. Precipitation from May to October (6 months) accounted for 78% of the total annual precipitation during the study period. The soil is an orthic brown Cambisol with silt loam texture. A 1.0-cm thin humus layer covers the mineral soil, with an
average bulk density of 1.2 g cm$^{-3}$. The total deposition of FDNPP-derived $^{137}$Cs at this study site was estimated to be < 10,000 Bq m$^{-2}$ based on the results of an airborne monitoring survey by MEXT (http://radioactivity.mext.go.jp/en/), and thus monitoring of radiocesium discharge rates and runoff delivery is necessary (Kato et al., 2012).

2.2. Modelling of hydrological connectivity (HC)

We used part of the modifications made by Cavalli et al. (2013) of the index of runoff and sediment connectivity (IC) proposed by Borselli et al. (2008). The IC model accounts for the characteristics of the drainage area ($D_{up}$, upslope module) and the flow path length that a particle has to travel to arrive at the nearest sink ($D_{dn}$, downslope module). The $D_{dn}$ factor considers the probability that runoff and sediment arrives at a sink along a flow line, whereas the $D_{up}$ factor summarizes the potential for downward routing of the overland flow produced upslope and expands the same analysis to an area:

\[
IC_K = \log_{10} \left( \frac{D_{up,K}}{D_{dn,K}} \right) = \log_{10} \left( \frac{\overline{W} \cdot \overline{S} \cdot \sqrt{A_K}}{\sum_{i=K,dn} d_i \cdot W_i \cdot S_i} \right) 
\]

where $A$ is the upslope-contributing area (m$^2$), $\overline{W}$ is the average weighing factor of $A$ (dimensionless), $\overline{S}$ is the average slope gradient of $A$ (m m$^{-1}$), $d_i$ is the length of the $i$th cell along the downslope path (m), $W_i$ is the weight of the $i$th cell (dimensionless), and $S_i$ is the slope gradient of the $i$th cell (m m$^{-1}$). Values of slope steepness < 0.005 must be replaced by the value $S_i = 0.005$, and those > 1 must be set to a maximum value of 1. The subscript $K$ indicates that each cell $i$ has its own IC-value.

This index is defined in the range of $[-\infty, +\infty]$, and connectivity increases when IC grows towards $+\infty$. The role of the linear landscape elements (LLE: vegetation strips, forest roads, trails and skidding trails, etc.) is added by modifying the map of flow direction: a mask with
two values, 0 for the LLE and 1 for the remaining area. In the original version of the model as well as in other studies, the $W$ weighing factor is equal to the C-RUSLE factor. We also chose this factor, instead of using other landscape factors, such as the surface roughness (Cavalli et al., 2013) or the infiltration rates (Gay et al., 2016), in order to simulate the different FMO. The $W$ map for each scenario was generated by using five different maps of the C-RUSLE factor.

The weighted flow path length and the $W$, $S$, and $A$ factors were calculated with the D-infinity flow accumulation algorithm (Tarboton, 1997) that is available in the software SAGA© 2.1.2 64 bit, instead of using the D8 single-flow algorithm of the original version. This approach is recommended by the European SedAlp research group of sediment transport in mountainous basins (Cavalli et al., 2015) as well as in the TauDEM 5.2 suite tools for the extraction and analysis of hydrologic information from topography (Tarboton, 2013). According to these authors, the D-infinity method captures the real flow paths, especially on hillslopes where divergent flow predominates; and it has advantages over the multiple flow direction (MD) method that introduces unrealistic overdispersion. Another reason that leads to the choice of the D-infinity approach is related to the DEM resolution. If the cell size is smaller than the width of the channels, the use of the D8 algorithm would limit high-drainage areas (i.e., the channel network) to sequences of single cells, thus underestimating channel widths. In contrast, the D-infinity algorithm better approximates channel width by partitioning flow over the entire cross section. Therefore, the D-infinity algorithm produces representative spatial patterns of HC through the basins (Martínez-Murillo and López-Vicente, 2017). Finally, the IC model includes the ‘stream’ layer (value 0 for the streams and 1 for the remaining area) that is associated with the presence of permanent streams (see Appendix A in Borselli et al., 2008). Values of HC are linked to the streams and the outlet of each subcatchment.

2.3. Forest management operations and scenarios
Six management-based scenarios were simulated in the two subcatchments and, considering the time line of monitored vegetation changes: five thinning-based, between 2010 and 2013, and one future scenario (Table 1; Fig. 2A). These changes included tree thinning and construction of new skidding trails at different times, the incipient but quick understory vegetation growth in the areas affected by tree thinning, and the ongoing understory recovery in the most recent scenarios. In the first scenario (Sc1), we simulated HC under the conditions prior to the implementation of the forest management operations (FMO). Scenario Sc1 corresponded to the period July 2010 – June 2011 (1 year), where the stand density of the 40-year-old cypress forest was 2500 ha\(^{-1}\), whereas that of the 41-year-old cedar forest was 1300 ha\(^{-1}\). In the second scenario (Sc2), between July and December 2011 (6 months), strip thinning was done in K2 affecting 1.8, 6.1, and 1.7 ha of the cypress, cedar, and mixed cypress and cedar plantations respectively (Table 2); and new skidding trails were constructed. Strip thinning was administered by felling two tree lines in an alternative pattern (Fig. 2B). All thinning operations were conducted by forest workers using no heavy machinery, except for chainsaws, to minimize the soil disturbance. All twigs, branches, and timber from thinned trees were removed from the stand. In total, 50% of the stems were felled, corresponding to 48% of the basal area. The number of trees in the hillslope plots decreased from 27 to 13. The stand density decreased from 2198 to 1099 trees ha\(^{-1}\). The basal area was reduced from 50.4 to 26.2 m\(^2\) ha\(^{-1}\). The canopy density diminished from 0.974 to 0.758. The change in mean diameter at breast height (DBH) was relatively small, decreasing from 19.1 to 18.9 cm (more details in Sun et al., 2014c).

The third scenario (Sc3) lasted 12 months (January–December 2012) and simulated the initial recovery of the understory vegetation in the area affected by tree thinning during Sc2. In the fourth scenario (Sc4), between January and April 2013 (4 months), selective thinning was done in K3 affecting 2.1 ha of the cedar plantation (Fig. 2B). Scenario Sc4 included the ongoing vegetation recovery in the areas affected by tree thinning during Sc2. The fifth scenario (Sc5)
lasted 6 months (May–October 2013) and the incipient and continuing recovery (lower values of the C-RUSLE factor) of the understory vegetation affected by tree thinning in K3 and K2 respectively was simulated.

Finally, we proposed a future scenario (ScF) with six check-dams (CD) located in the main streams of the two SubC (see Fig. 1B), with the aim of reducing the values of HC at catchment scale. We except to promote a decrease of the radionuclide delivery rates in the study area from the observed cumulative deposition of radiocesium onto the forest floor (Teramage et al., 2014). The effectiveness of CD to reduce annual sediment yield has been proved worldwide, such as in tributary catchments of the Yellow River in China (Wei et al., 2017). We used the following criteria to select the position of the six CDs: (i) in those sections of the streams where the value of HC is above the 90th percentile from the total values of HC; (ii) close to the current trails to facilitate their potential construction; and (iii) located along the streams and separated between them. In order to evaluate the effectiveness of the CD to reduce HC, the C-RUSLE map used in ScF was the same as that of Sc5, except in the small areas upward of the location of the CDs that were considered as sedimentation areas within the channels, following the approach of Quiñonero-Rubio et al. (2016). As the hillslopes of the study area are very steep and the valley bottom is narrow, we considered that each sedimentation area was only 3 m², 1 m width by 3 m length, parallel to the stream, with a low weighting value (C = 0.001) using professional judgment. The stream layer was also modified in the sedimentation area to simulate the effect of the CD on the (dis)continuity of the overland flow pathways.

2.4. Field observations and model parameterization

The two subcatchments have been extensively described elsewhere (Kato et al., 2012; Sun et al., 2014a, b and c, 2015a and b; Dung et al., 2015), and a summary is provided below. Two hillslope plots were installed in the cypress plantation of the K2 SubC, named KS22 and KS24,
and one plot in the cedar plantation, named KS31 (Fig. 1B). The three forest plots had a rectangular shape, 10 m length parallel to the maximum slope, and 4 m width. Each plot covered 40 m$^2$, and the plastic board surrounding the plot was 0.3 m height. The three plots were located in steep slopes, with slope steepness between 30 and 40° (Fig. 3A). Gross precipitation was measured during the 40-month study period by an automatic weather station (Davis Instruments 7852 M, Hayward, CA, USA), including a rain gauge, on an open field close to the forest road (Fig. 3B). The data was stored every 5 min with a data logger (SQ1250; Grant Instruments Ltd., Cambridgeshire, UK; more details in Sun et al., 2014a). The detailed maps of the different land uses before (Fig. 3A) and after (Fig. 3C) the FMO were generated with the assistance of three orthophotos taken in March 2011, November 2012, and March 2013 and using the software QGIS©-64 2.14.0-Essen.

The six gauging stations were installed along the main streams following a nested configuration (Figs. 1B and 3D). Four gauging stations (denominated KV2-1, KV2-2, KV2-3, and KV2-4) were installed in K2, and two gauging stations (KV3-1 and KV3-2) in K3. Discharge was measured using a combination of Parshall flumes and box-type V-notch weirs. Data was recorded at 5-min intervals, and daily values calculated afterward (more details in Dung et al., 2015). As FMO caused topographic changes because of the construction of new skidding trails in the hillslopes, three airborne surveys were conducted in order to acquire an accurate DEM of the study area at each scenario. Three clouds of points were obtained in March 2011, November 2012, and March 2013 by penetrated laser (last return for ground measurements) that were used to generate the LiDAR-derived DEMs. These maps and all simulations were performed at 0.5 x 0.5 m of grid cell size. Before running the IC model, the continuity of the flow path lines throughout the hillslopes and in the streams was ensured by removing the local depressions of the three DEMs with the algorithm of Planchon and Darboux (2001; available in SAGA©-64 2.1.2). We considered a minimum slope gradient of 0.01° that can be associated with microtopography and thus to unrealistic sinks or DEM artifices. Then, the boundaries of
the K2 and K3 catchments were automatically calculated upward from the intersection point of both outlets with the software ArcGIS© 10.3. Because of the existing differences in topography between the three DEMs, these boundaries were calculated for each DEM to ensure an accurate simulation of HC. These differences can be explained by the small pixel size, the low differences of elevation along the divides, and the observed changes in the upslope-contributing area of the forest road during the three airborne surveys. The stream layers were also calculated for the three DEMs, and the threshold values of upslope area that define the beginning of the streams were selected after field observation of the streams in the headwaters of K2 and K3. The values of the C-RUSLE factor for the sparsely vegetated areas (skidding trails: 0.2652), the broad-leaf forest (0.0013), and the transitional woodland-shrub (0.0219) were obtained from Panagos et al. (2015). For the unpaved forest road (0.5027) and the bare soil (0.4500), we used the values proposed by López-Vicente and Navas (2009) and Capolongo et al. (2008) respectively. For the cedar (0.0058) and cypress (0.0085) plantations, we used the values proposed by Miller et al. (2003) for coniferous forests. Weighted values of the C-RUSLE factor were calculated for the remaining and mixed land uses, considering a progressive increase in the values with increasing vegetation recovery after the first thinning activities in the cedar (0.0112) and cypress (0.0130) plantations.

3. Results and discussion

3.1. Simulated hydrological connectivity

The duration and dates of the simulated scenarios agreed with the observed evolution and changes of rainfall interception and throughfall, runoff, nutrient, streams and sediment yield before, during, and after the FMO in the K2 and K3 SubC. Sun et al. (2014c, 2015a and b) reported these changes from open hillslope plots; and Dung et al. (2015), Fukushima et al. (2015), and Nam et al. (2016) from data collected in gauging stations. The values and spatial...
patterns of HC clearly changed over the five thinning-based scenarios and throughout the study area (Fig. 4). On the basis of the pre-FMO scenario (Sc1), the overall values of HC increased owing to tree thinning and the new skidding trails, reaching the highest values of connectivity during Sc2 and Sc4 in K2 and K3 respectively (Table 3). The mean HC increased by 4.4% in K2 and by 1.0% in K3 and is related to Sc1. According to the affected area distribution by FMO, the value raised to 55% and 15% in K2 and K3 respectively. Within this area, the evolution of HC was more noticeable, and connectivity increased by 8.6% and 7.4% in the K2 (Sc2) and K3 (Sc4) respectively. Incipient recovery of the understory vegetation after the FMO caused a slight decrease of HC related to Sc2 and Sc4 in K2 and K3 respectively. The low reduction of HC in these areas was explained by the low decrease in the values of the C-RUSLE factor. Despite the good recovery of the understory vegetation, the understory canopy cover remained lower than before the tree thinning activities. Despite this trend, HC remained higher than before the FMO during Sc3 to Sc5 and during Sc5 in K2 and K3 respectively. These results agree with those reported by Marden et al. (2007) at the scale of forest management areas (compartments), where most slopewash was generated in the first post-harvest year, and specially within the first 7 months following harvesting and before site recolonization.

At plot and stream scales, evolution in the values of HC was less evident, except the increment of 5.4% of HC in the streams of K2 during Sc2. The lack of clear evidence in the evolution of HC at plot scale can be explained by the small size of the three plots in comparison with the total hillslope area and the spatial variability of the values of HC. The standard deviation of the values of HC in Sc1, Sc2 and Sc4 were much higher than the differences in the values of HC between these scenarios. This complexity in the evolution of the values of HC was also described by Moreno-De Las Heras et al. (2012) in banded landscapes in Australia, where small reductions in the fractional cover of vegetation caused by selective thinning of the vegetation patches near a particular threshold can cause a higher
impact on the landscape hydrological connectivity than spatially random disturbances. Hence, the spatial location of the FMO can affect the evolution of HC at catchment scale.

Concerning the different land uses, values of HC clearly increased in the cedar and cypress plantations affected by FMO, and in a minor way in the mixed cedar and cypress plantation (Table 2). Values of HC increased by 10.5% and 8.8% in the cedar plantation during Sc2 and Sc4 respectively because of the new FMO. In the cypress plantation, the FMO triggered an increment of 11.4% of HC in Sc2 and related to Sc1. Values of HC only increased by 2.3% in the mixed cedar and cypress plantation after tree thinning because of the spatial location of the two patches of this type of vegetation that are located near the divides and without direct connection with the streams. One year after the FMO, the three types of plantation forest presented a moderate decrease in the values of HC, between 1.5% and 3.1%, related to the scenario when FMO happened caused by the incipient vegetation recovery. Native broad-leaf vegetation, scrubland, and mixed forest presented minor changes in the values of HC, between -1 and 1%, that can be associated with the inherent spatial variability of the simulated values of HC and because the three different DEMs generated slightly different maps of overland flow pathways.

As expected, the mean values of HC in the forest road were higher in all scenarios than the average values of connectivity at catchment scale. However, evolution in the values of HC in this feature were high and changeable, ranging between -4.2% and 2.6% during Sc2 and Sc4 respectively and related to Sc1. This wide range of variation was higher than the other ranges obtained in the remaining land uses that were not affected by FMO. López-Vicente et al. (2016) also obtained high values of connectivity with high variability in the forest roads of an afforested mountainous catchment. These authors found that flow paths converged in some sections of the roads where runoff moved parallel to the shape of this linear element, whereas runoff flowed out of the roads in definite sections. Roads induced a modification of flow
direction compared with the natural landscape that may explain part of our results. The different subcatchment boundaries derived from the three DEMs triggered different upslope-contributing areas on the pixels of the forest road during the simulated scenarios and may explain part of this variability. The highest values of HC during the six scenarios appeared in the skidding trails and thus can be considered as the main connectivity between the runoff, sediment, and radionuclides from the different compartments of hillslopes and stream network. This land use presented higher values of HC than those obtained in the forest road because skidding trails crossed the hillslopes from divides to the bottom reaching the streams, whereas the forest roads remained in the middle part of the hillslope and far from the streams. These results agree with those obtained by Croke et al. (2005) in a forest catchment in southeastern Australia where the forest road network acted as channels for direct connectivity into the stream, whereas the majority of the hillslope was characterised by dispersive flow pathways and diffuse connectivity.

The effectiveness of the check-dams to reduce overall values of HC was evaluated in the ScF scenario (Table 3). Connectivity decreased in both SubC, at plot and stream scales, and in the area affected by the FMO. The greatest reductions appeared in the KS31 plot (-1.32%) and in the streams of K2 and K3, by -0.14% and -0.17% respectively. These results were in agreement with those reported by Martínez-Murillo and López-Vicente (2017) in wildfire-affected areas, where check-dams constructed after the fire played a remarkable but short time effective role in slowing down delivery processes and off-site effects. Accounting for the small area affected by the proposed check-dams, 0.005 and 0.007% of the total area of K2 and K3 respectively, the effectiveness of these structures reducing HC can be considered as satisfactory.

3.2. Validation of simulated scenarios
The values and spatial patterns of HC and their evolution over the past five management-based scenarios were validated by means of two procedures: (i) using available data from Sun et al. (2015a and b), Dung et al. (2015), Fukushima et al. (2015), and Nam et al. (2016) obtained in the same study area; and (ii) with unpublished data of runoff yield. We first used the observed changes in the values of rainfall interception and throughfall obtained in the hillslope plots. And second, we analysed the evolution in the values of stream yield from six gauging stations before, during, and after the FMO in the K2 and K3 subcatchments (Fig. 5).

During the 40-month test period (July 2010 – October 2013), 189 storm events were recorded with rainfall depth > 1 mm per event in 473 rainy days and distributed as follows: 59, 25, 57, 17, and 31 events during Sc1, Sc2, Sc3, Sc4 and Sc5 respectively.

The average discharge coefficients (total accumulated outflow / total accumulated rainfall) in the KV gauging stations of K2 were 24%, 60%, 51%, 20%, and 49% during Sc1, Sc2, Sc3, Sc4, and Sc5 respectively; whereas in the stations of K3 were 15%, 34%, 25%, 15%, and 38% during Sc1, Sc2, Sc3, Sc4, and Sc5 respectively (Table 4). These results showed a good match with the general evolution in the values of HC in the two subcatchments, although the increase of HC simulated in Sc4 appeared later in the observed values of stream yield. This delay can be explained by the short duration of the Sc4, four months, in comparison with the other scenarios that lasted between 6 and 12 months. In addition, the average rainfall depth during Sc4, 6.2 mm event⁻¹, was the lowest of the five thinning-based scenarios.

The different changes in outflow values between the six gauging stations was similarly observed by Dung et al. (2015) and were associated with changes in internal hydrological flow pathways caused by removal of timber and hydrological connectivity via overland flow generated by newly installed and reactivated skidding trails. As these authors described for peak flow response, we also found that HC values, spatial patterns, and changes are scale-dependent with respect to drainage areas, preferential HC routes, location of the different
vegetation patches, and FMO. Nam et al. (2016) also found significant increases in specific sediment yield in K2 in the post-thinning period mainly associated with clearcutting and soil-surface disturbance by skidding trails. At plot scale, Sun et al. (2015a and b) demonstrated that thinning altered the interception components, with a significant rise of the throughfall rates and a decrease in the canopy water storage.

3.3. Implications and further research

Further research will deal with the effect of small topographic changes on the values of upslope-contributing areas on the linear landscape elements, such as forest roads and skidding trails. The concept of the volume to breakthrough of Croke et al. (2005) will be used to model the potential delivery of runoff from dispersive pathways. This topic may be of interest to refine the predictions of sediment and radionuclide discharge rates at catchment scale. Finally, additional simulations of HC considering alternative locations for installing check-dams in other sections of the streams and of the main gullies of the hillslopes will be of interest to propose the best management scenario for overland flow processes in the study area.

4. Conclusions

Hydrological connectivity (HC) was successfully simulated over the six management-based scenarios, with the updated version of Borselli’s index, and thus the use of the D-Infinity algorithm seemed in order as an accurate choice for HC studies in forest catchments. On the basis of the pre-FMO (forest management operations) scenario, HC increased at catchment scale due to tree thinning and the new skidding trails, in both subcatchments although in a different degree. This change was more noticeable within the area affected by the FMO, where HC markedly increased in the cypress and in the cedar plantations in K2 and in the cedar...
plantation in K3. The increase of HC in the mixed cypress and cedar plantation was less important than in the other plantations affected by tree thinning owing to its spatial location that is farther from the streams.

At hillslope plot and stream scales, evolution in the values of HC was less evident, except the clear increment of connectivity in the streams of K2 after the FMO. As expected, progressive vegetation recovery after the FMO triggered a slight reduction of connectivity in all compartments of both subcatchments. Skidding trails appeared as the most efficient landscape feature connecting the different vegetation patches, affected and nonaffected by the FMO, with the stream network. Forest roads were among the main features with the highest values of HC, although small changes in topography triggered marked changes on the upslope-contributing area to this feature, and thus on the simulated values of connectivity. These results highlight surface connectivity patterns as practical indicators for monitoring landscape processes.

The values of HC, their spatial patterns, and temporal changes were scale-dependent with respect to the upslope drainage areas, the spatial location of the preferential HC routes, and of the different vegetation patches and FMO. This study provided useful information for understanding the effect of tree thinning and construction of new skidding trails on the spatially distributed values of hydrological connectivity at subcatchment and stream scales and within the areas affected by the FMO. Results of the simulation of the proposed scenario with six check-dams located in selected locations along the main streams recommend their construction as somewhat effective landscape features to reduce hydrological connectivity and thus sediment and radionuclide delivery outside the study area.

Acknowledgements
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References


Table 1

Main characteristics of the six management-based scenarios (Sc) of hydrological connectivity (HC) following a time line (SubC: subcatchment; FMO: forest management operations; TT & ST: tree thinning and skidding trails; PVR: progressive vegetation recovery)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dates</th>
<th>Duration (months)</th>
<th>Vegetation management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc1</td>
<td>July 2010 – June 2011</td>
<td>12</td>
<td>Before FMO</td>
</tr>
<tr>
<td>Sc2</td>
<td>July – December 2011</td>
<td>6</td>
<td>TT &amp; ST</td>
</tr>
<tr>
<td>Sc3</td>
<td>January – December 2012</td>
<td>12</td>
<td>Before FMO</td>
</tr>
<tr>
<td>Sc4</td>
<td>January – April 2013</td>
<td>4</td>
<td>PVR</td>
</tr>
<tr>
<td>Sc5</td>
<td>May – October 2013</td>
<td>6</td>
<td>PVR</td>
</tr>
<tr>
<td>ScF</td>
<td>Future</td>
<td>Future</td>
<td>3 check-dams</td>
</tr>
</tbody>
</table>

From 2198 to 1099 trees ha⁻¹ (Sun et al., 2014c).

Table 2

Area devoted to the different land uses, mean values of hydrological connectivity (HC), and temporal changes (δ; %) of these parameters during scenarios Sc1, Sc2, and Sc4, in the whole study area (FR: forest road; ST: skidding trails; Cd: cedar; Cy: cypress; TT0: recent tree thinning; TT1: old tree thinning; BL: broad-leaf; nd: no data); land uses and values related to the forest management operations appear in grey colour

<table>
<thead>
<tr>
<th>Land use</th>
<th>Sc1</th>
<th>Sc2</th>
<th>Sc4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area</td>
<td>HC</td>
<td>Area</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>mean</td>
<td>%</td>
</tr>
<tr>
<td>FR</td>
<td>1.8</td>
<td>-3.589</td>
<td>1.9</td>
</tr>
<tr>
<td>ST</td>
<td>0.7</td>
<td>-3.068</td>
<td>0.9</td>
</tr>
<tr>
<td>Cd</td>
<td>29.3</td>
<td>-6.013</td>
<td>18.2</td>
</tr>
<tr>
<td>Cd-TT0</td>
<td>nd</td>
<td>nd</td>
<td>10.7</td>
</tr>
<tr>
<td>Cd-TT1</td>
<td>nd</td>
<td>nd</td>
<td>10.7</td>
</tr>
<tr>
<td>Cy</td>
<td>21.4</td>
<td>-5.854</td>
<td>5.5</td>
</tr>
<tr>
<td>Cy-TT0</td>
<td>nd</td>
<td>nd</td>
<td>16.4</td>
</tr>
<tr>
<td>Cy-TT1</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Short Cy</td>
<td>0.2</td>
<td>-5.085</td>
<td>0.2</td>
</tr>
<tr>
<td>Cd&amp;Cy</td>
<td>7.9</td>
<td>-5.750</td>
<td>2.9</td>
</tr>
<tr>
<td>Cd&amp;Cy-TT0</td>
<td>nd</td>
<td>nd</td>
<td>5.0</td>
</tr>
<tr>
<td>Cd&amp;Cy-TT1</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Cd&amp;Cy&amp;BL</td>
<td>9.7</td>
<td>-6.258</td>
<td>9.4</td>
</tr>
<tr>
<td>Native BL</td>
<td>28.4</td>
<td>-7.226</td>
<td>28.2</td>
</tr>
<tr>
<td>Scrubland</td>
<td>0.6</td>
<td>-6.093</td>
<td>0.7</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.1</td>
<td>-4.617</td>
<td>0.1</td>
</tr>
</tbody>
</table>

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Table 3

Values of the C-RUSLE factor and hydrological connectivity (HC) at subcatchment (SubC), plot, and stream scales and in the area affected by the forest management operations (FMO), during the six scenarios (Sc); relative changes (δ, %) are also shown.

<table>
<thead>
<tr>
<th>Sc</th>
<th>SubC</th>
<th>C-RUSLE</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>mean</td>
<td>sd</td>
</tr>
<tr>
<td>Sc1</td>
<td>K2</td>
<td>0.0189&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-6.162&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>0.0114&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-6.381&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sc2</td>
<td>K2</td>
<td>0.0228</td>
<td>-5.892</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc1&lt;/sub&gt;</td>
<td>20.3</td>
<td>4.4</td>
<td>11.0</td>
</tr>
<tr>
<td>K3</td>
<td>0.0114</td>
<td>-6.342&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.049&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc1&lt;/sub&gt;</td>
<td>0.1</td>
<td>0.6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-2.6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sc3</td>
<td>K2</td>
<td>0.0201</td>
<td>-5.947</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>0.0115</td>
<td>-6.342&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sc4</td>
<td>K2</td>
<td>0.0208</td>
<td>-6.016</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc1&lt;/sub&gt;</td>
<td>9.7</td>
<td>2.4</td>
<td>10.4</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc2&lt;/sub&gt;</td>
<td>-8.8</td>
<td>-2.1</td>
<td>-2.6</td>
</tr>
<tr>
<td>K3</td>
<td>0.0121</td>
<td>-6.316&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.088&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc1&lt;/sub&gt;</td>
<td>6.4</td>
<td>1.0</td>
<td>7.4</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc2&lt;/sub&gt;</td>
<td>6.3</td>
<td>0.4</td>
<td>-3.7</td>
</tr>
<tr>
<td>Sc5</td>
<td>K2</td>
<td>0.0184</td>
<td>-6.074</td>
</tr>
<tr>
<td></td>
<td>K3</td>
<td>0.0117</td>
<td>-6.354&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>ScF</td>
<td>K2</td>
<td>0.0183</td>
<td>-6.075</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc5&lt;/sub&gt;</td>
<td>-0.5</td>
<td>-0.2</td>
<td>0.04</td>
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<tr>
<td>K3</td>
<td>0.0116</td>
<td>-6.356&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.068&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>δ&lt;sub&gt;sc5&lt;/sub&gt;</td>
<td>-1.1</td>
<td>-0.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

<sup>a</sup> Before the FMO.  <sup>b</sup> Mean value at the KS22 and KS24 plots.  <sup>c</sup> Mean value at the KS31 plot.
Table 4

Discharge coefficients (total accumulated outflow / total accumulated rainfall; %) in the six gauging stations (KV); Avrg: average value; R: rainfall depth (mm event⁻¹)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>KV2-1 %</th>
<th>KV2-2 %</th>
<th>KV2-3 %</th>
<th>KV2-4 %</th>
<th>KV2-Avrg %</th>
<th>KV3-1 %</th>
<th>KV3-2 %</th>
<th>KV3-Avrg %</th>
<th>R-Avrg mm event⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc1</td>
<td>27</td>
<td>24</td>
<td>20</td>
<td>26</td>
<td>24</td>
<td>18</td>
<td>13</td>
<td>15</td>
<td>8.9</td>
</tr>
<tr>
<td>Sc2</td>
<td>77</td>
<td>43</td>
<td>67</td>
<td>53</td>
<td>60</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>16.0</td>
</tr>
<tr>
<td>Sc3</td>
<td>54</td>
<td>41</td>
<td>53</td>
<td>56</td>
<td>51</td>
<td>26</td>
<td>25</td>
<td>25</td>
<td>9.1</td>
</tr>
<tr>
<td>Sc4</td>
<td>11</td>
<td>25</td>
<td>19</td>
<td>25</td>
<td>20</td>
<td>18</td>
<td>11</td>
<td>15</td>
<td>6.2</td>
</tr>
<tr>
<td>Sc5</td>
<td>48</td>
<td>45</td>
<td>47</td>
<td>56</td>
<td>49</td>
<td>36</td>
<td>40</td>
<td>38</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Fig. 1. Location of the study area in central Japan (A). Hillshade map of the study area showing the location of the slope and road plots, the stream gauging stations, the open rainfall collector, and the forest roads and skidding trails (B). General view of the plantation forest in the steep slopes four years after the tree thinning and understory vegetation cut operations (C).
Fig. 2. Maps of land uses in scenarios Sc1, Sc3, and Sc4 (A). Design of tree thinning practices in hillslope plots of the K2 and K3 subcatchments (B; modified from Sun et al., 2015a).
Fig. 3. General view of the KS22 plot just after tree thinning and understory vegetation cut operations (A), of the forest road (B), of the KS31 plot three years after tree thinning and understory vegetation cut operations (C), and of the KV31 stream gauging station (D).
Fig. 4. Maps of simulated hydrological connectivity (HC) during the five thinning-based scenarios and the future scenario showing the location of the six new check-dams as conservation measures.
Fig. 5. Daily runoff recorded in the hillslope plots of the K2 (a.K2) and K3 (a.K3) subcatchments, and in the six gauging stations (b.K2 and b.K3) during the 40-month test period (July 2010 – October 2013). Dates of the forest management operations (FMO) and duration of the five thinning-based scenarios are indicated.