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Analyses on Forest Road Damages over the Past 19 Years Using Rainfall Evaluation with Return Periods in Gunma Prefecture, Japan †

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Abstract: This study acquired governmental subsidized recovery costs from forest road damages over the past 19 years between 2001 and 2019 in Gunma prefecture. Then, this study analyzed correlation coefficients between return periods of rainfall intensity in relation with soil water index as well as three-layer water tanks and recovery costs. The study sites were four AMeDAS stations such as Kanna, Fujioka, Nishinomaki, and Tashiro which had relatively large governmental subsidized recovery costs in 2001, 2007, and 2019. As a result, it was implied that large forest road damages could occur due to deep rainwater penetration because correlation coefficients between water tanks and recovery costs per forest road length tended to increase according to the deeper tanks.

Keywords: soil water index; three-layer water tank model; forest road length; construction cost; recovery cost

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1. Introduction

For sustainable forest management and low-cost forestry operation, appropriate road networks, including forest roads for trucks and strip roads for forwarders, must be developed in Japan. However, there are difficult conditions for promoting road network development in terms of weather, geology, topography, and soil quality [1]. Japan belongs to the Asian monsoon zone and has a hot and rainy climate. Torrential rains occur due to the rainy season in June and the typhoon in Autumn. Geologically, it is located in the orogenic belt where the Pacific plate subducts toward the continental plate, and not only has a complicated topography, but also soil with unique properties derived from volcanic ejecta is widely distributed. In addition to these conditions, the road network development has not progressed sufficiently because efforts related to road network development became reluctant due to the slump in lumber prices and the fact that many forest stands have not reached the age of use for planted forests. For this reason, road construction technology should be established and disseminated according to the weather conditions, geology, topography, and soil quality in Japan to improve the working environment for the sustainable forest management and forestry industry.

Iuchi et al. [2] analyzed effect factors for the forest road disaster in Southern Kyushu, Japan. As a result of analyzing the influence of various factors on the amount of collapsed soil by quantification type I, it was found that the influence is higher in the order of geology, catchment area, slope shape, vertical slope, and slope direction. Iuchi et al. [3] also analyzed the cross-drainage ditch blockages in Shirasu area of southern Kyushu, which contains pyroclastic flow deposits from the Aira caldera. The road networks in the Shirasu area have about three times more cross drainage ditches per 500 m than those outside the

Shirasu area, but the average blockage rate was higher regardless of the number of years elapsed. In addition, the road networks in all areas were rapidly blocked from the second year after the installation of the cross-drainage ditch. After the 4th year of elapse, the average blockage rate tends to be close to 100% regardless of the area. As a result of factor analysis of the cross-drainage ditch blockage using quantification type I, it was found that the effect was in the order of the year after the installation, topographical gradient around the cross-drainage ditch, geology, and road surface classification. They pointed out that the maintenance period of the cross-drainage ditch is about 3 years after opening in the Shirasu area and about 5 years in other areas as a guide.

Muneoka et al. [4] clarified the erosive power of forest road-surface flow depending on flow velocity. Muneoka et al. [5] also suggested there is no correlation between the roadside drainage area and locations that are subjected to intercepted subsurface flow and that such flow should be care near valleys with not only large drainage areas but also small drainage areas. Then, Muneoka et al. [6] measured actual cross drain spacing and compared with an existing guideline. They indicated that appropriate cross drain spacing can differ by dozens of meters even among segments with the same slope. Furthermore, Muneoka et al. [7] estimated the expected value of the number of forest road collapses in a 1-km road segment caused by a rainfall event with various intensities. The estimated expected value was 10^{-3} orders of magnitude with a rainfall event where the maximum rainfall per 24 hours was between 100 mm and 150 mm, while the value was 10^{-1} orders of magnitude with a rainfall event between 300 mm and 350 mm. They implied that they could predict the number of forest road collapses in a given area over a certain period, taking into account the increase in density of forest roads and the frequency of intense rainfall events due to climate change.

In order to examine the forest road establishment, maintenance, and improvement of drainage facilities by anticipating changes in rainfall from future climate change and changes in the forest environment by the increased clear-cutting operations, Aruga et al. [8] analyzed the damage to forest road facilities that occurred in Kanuma and Nikko cities, Tochigi prefecture, Japan during the heavy rains in Kanto and Tohoku regions in September 2015 and the East Japan typhoon in October 2019, based on the precipitation and clear-cutting in the watershed area. In summary, at the survey sites, the drainage facility was confirmed to be blocked or damaged by the outflow of logging residue from clear cutting sites; this also increased the runoff rate of the sediments. Precipitation data from the nearest Automated Meteorological Data Acquisition System (AMeDAS) stations were analyzed as return periods of the annual maximum hourly and daily rainfall intensity, the soil water index, widely used for predicting the increased risk of sediment-related disasters due to rainfall in Japan, and each tank storage comprised an in-line 3-layer tank model with which the soil water index was calculated [9].

Shuin et al. [10] suggested that the timing of shallow landslide occurrence depended on the return period of the first-layer tank, and the timing of deep-seated landslides depended on the return period of the second- and third-layer tanks, even though it is a model representing an underground surface layer and therefore, it is not intended for deep underground situations that could lead to deep-seated landslides or large-scale landslides. The use of the Tank Model as well as soil water index can be useful in hydrological studies and, consequently, in natural disasters, water resources and basin managements. Vasconcellos et al. [11] determined the spatial behavior of the soil water index by applying a distributed version of the Tank Mode to the Araponga river basin in southern Brazil and to verify its reliability through the comparison to soil moisture estimated with the measured water-tension values and the water retention curve. The comparison between the spatially distributed values of the soil water index and soil moisture confirmed the high potential of the soil water index derived from the D-Tank Model to be applied for predictions related to hydrological and environmental sciences.

This study acquired governmental subsidized recovery costs from forest road damages over the past 19 years between 2001 and 2019 in Gunma prefecture, Japan. Then, this study analyzed correlation coefficients between return periods on soil water index as well as three-layer tank storages and recovery costs.

2. Materials and Methods

In Gunma prefecture, relatively large governmental subsidized recovery costs (EUR 1 = JPY 132.40 as of 24 June 2021) were incurred in 2001, 2007, and 2019 (Figure 1), among which the Kanna, Fujioka, Nishinomaki, and Tashiro AMeDAS stations located in the western part of the prefecture (Figure 2). Since the amounts of rainfall were heavy (Table 1) and the governmental subsidized recovery costs were high, this study analyzed these four stations. The Kanna AMeDAS station included Kanna town and Ueno village, the Fujioka AMeDAS station included Fujioka city, the Nishinomaki AMeDAS station included Tomioka city, Shimonita and Kanra towns, and the Nammoku village, and the Tashiro AMeDAS station included Naganohara town and Tsumagoi village.

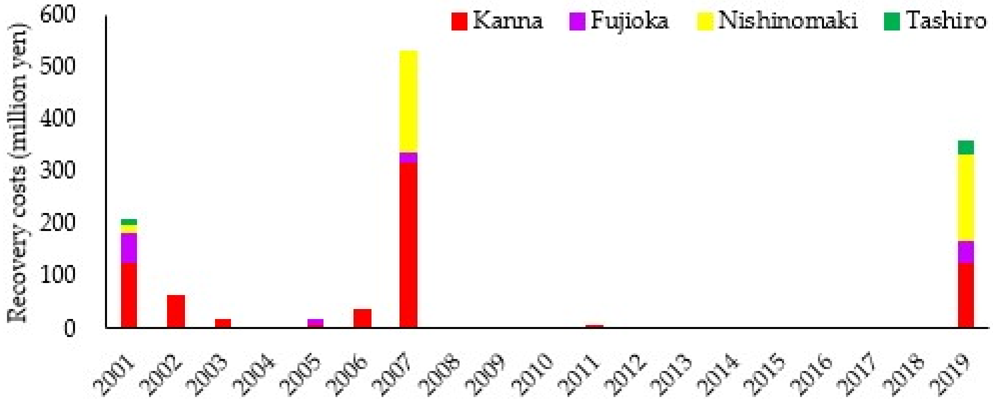

Figure 1. Governmental subsidized recover costs for Kanna, Fujioka, Nishinoki, and Tashiro AMeDAS stations in Gunma prefecture.

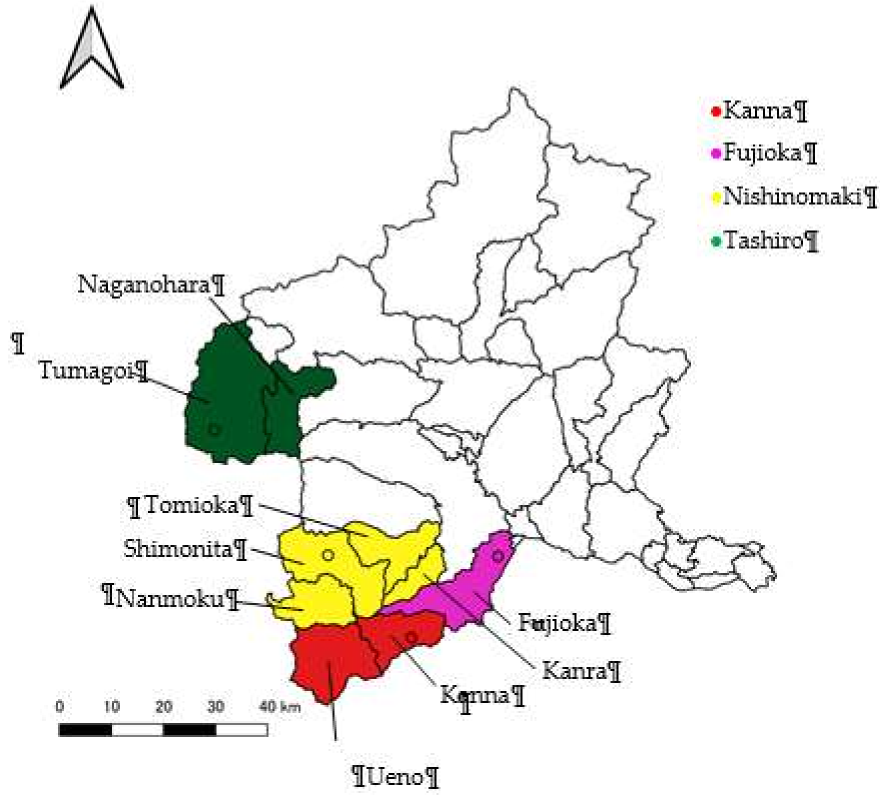

Figure 2. Kanna, Fujioka, Nishinoki, and Tashiro AMeDAS stations in Gunma prefecture.

Table 1. Cumulative rainfall (mm).

AMeDAS stations	2001	2007	2019
Kanna	407.0	504.0	465.0
Fujioka	167.0	211.0	368.5
Nishinomaki	394.0	428.0	496.5
Tashiro	299.0	344.0	442.5

This study analyzed correlation coefficients between return periods of rainfall intensity in relation with soil water index as well as each tank storage in an in-line 3-layer tank model with which the soil water index was calculated [9] and recovery costs per forest road length or construction cost between 2001 and 2019. The soil water index is used for predicting the increased risk of sediment-related disasters due to rainfall [9]. Sediment disasters (landslides and debris flows) that occur with heavy rains are closely related to not only the current rainfall but also the amount of water in the soil due to the rainfall so far. The soil water index is a numerical value representing the amount of rainfall accumulated in the soil as water content using a tank model. The soil water index is used as a criterion for heavy rain warnings (sediment disasters) and sediment disaster warnings announced by meteorological stations in each region of Japan. There are outflow holes on the sides of each of the three-layer tanks, indicating that water flows out into the surrounding soil, and infiltration outflow holes are present on the bottom, which indicate that water penetrates deeper. The amount of outflow from the outflow hole on the side of the first tank corresponds to the surface runoff, that from the second tank corresponds to the infiltration outflow on the surface layer, and that from the third tank corresponds to the outflow as groundwater. The inflow to the first tank corresponds to the precipitation, that to the second tank represents the infiltration outflow from the first tank, and that to the third tank is the infiltration outflow from the second tank. The soil water index is calculated as the sum of the amount of water (reservoir) remaining in each tank, which corresponds to the amount of water in the soil. The soil water index was calculated by conducting continuous calculations throughout the year using the 10-minute rainfall intensity, dividing the hourly rainfall data into six equal parts. For the calculation of the return period, the maximum value for each year between 1979 and 2019 was extracted and the Gumbel distribution was applied to these values [10].

3. Results and Discussions

Correlation coefficient between return period of third-layer water tank and recovery costs per forest road length was positive with the 5% significance for all data in these study sites (Table 2). Although the significance was not shown, the recovery costs per forest road length tends to have a stronger positive correlation as the tank becomes deeper. Furthermore, correlation coefficients between return periods of rainfall intensity in relation with soil water index as well as all three-layer water tanks and recovery costs per forest road length were also positive with the 1% or 5% significance in Kanna stations, especially that of the third-layer water tank was the strongest. Therefore, the deep infiltration of rainwater from the first-layer water tank (surface runoff), the second-layer water tank (the infiltration into the surface layer) to the third-layer water tank (the infiltration into the groundwater) may have caused a large-scale disaster.

At the Fujioka AMeDAS station, there is little change in the correlation coefficient regardless of the depth of the tank. Therefore, not only rainfall but also other factors such as geology, topography, and soil quality as well as the strength of the forest road structure, affected forest road damages. The third-layer water tank at the Nishinomaki AMeDAS station showed the highest correlation coefficient because 2 of the 3 samples took close values. The Tashiro AMeDAS station has not tested the correlation coefficient because the governmental subsidized recovery costs were one for 2001 and one for 2019, for a total of only two samples. The Tashiro AMeDAS station was not an area where forest road disasters occurred more frequently than the other three AMeDAS stations during this period.

Correlation coefficients between return periods of rainfall intensity in relation with soil water index as well as all three-layer water tanks and recovery costs per construction costs were similar to those for recovery costs per forest road length at the Kanna, Fujioka, Nishinomaki AMeDAS stations (Table 2). On the other hand, correlation coefficients between return period of rainfall intensity in relation with soil water index as well as first and second-layer water tank, and recovery costs per construction costs was positive with the 1% significance for all data in these study sites although the significance of correlation coefficient between return period of third-layer water tank and recovery costs per construction costs was not shown (Table 2). This would be due to including only construction costs, but not pavement and improvement costs during maintenance which strengthened forest road structure.

Table 2. Correlation coefficient between maximum annual return period and recovery cost per forest road length or construction cost.

AMeDAS	Total	Kanna	Fujioka	Nishinomaki
Sample	17	8	4	3
Per forest road length				
Soil water index	0.35	0.86**	0.31	0.65
First layer	0.23	0.93**	0.25	0.40
Second layer	0.27	0.75*	0.32	0.47
Third layer	0.58*	0.97**	0.29	0.99
Per construction cost				
Soil water index	0.70**	0.84**	0.11	0.63

First layer	0.85**	0.91**	0.05	0.38
Second layer	0.70**	0.72*	0.12	0.46
Third layer	0.46	0.97**	0.09	0.99

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$

4. Conclusions

This study acquired governmental subsidized recovery costs from forest road damages over the past 19 years between 2001 and 2019 in Gunma prefecture. Then, this study analyzed correlation coefficients between return periods of rainfall intensity in relation with soil water index as well as three-layer water tanks and recovery costs. As a result, it was implied that large forest road damages could occur due to deep rainwater penetration because correlation coefficients between water tanks and recovery costs per forest road length tended to increase according to the deeper tanks. Although the study sites were four AMeDAS stations such as Kanna, Fujioka, Nishinomaki, and Tashiro which had relatively large governmental subsidized recovery costs in 2001, 2007, and 2019 located in the western part of the prefecture, future study will include other part of the prefecture as well as other prefectures to extend analyses with more data if available.

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