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Changes in the Number of Natural Disaster on Japanese Railway Under Global Warming

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Abstract

This study evaluated the impact of increased heavy rainfall caused by global warming on natural disasters, train derailments caused by rainfall-induced disasters, and bridge washouts on Japanese railway from 1966 to 2023. The results are summarized as be follows: Heavy rainfall increased in this period. Natural disasters and train derailments caused by rainfall-induced disasters decreased before the 1980s and leveled off after the 1990s. The decrease in natural disasters is considered to the effect of the implementation of hard countermeasures, and the decrease in train derailments is considered to the effect of the improvement of train operation control methods against rainfall and the implementation of hard countermeasures. The fact that the number of natural disasters has leveled off without decreasing after the 1990s is considered to the result of the increase in heavy rainfall caused by global warming. Bridge washouts leveled off before the 1980s and increased after the1990s. The fact that the number of bridge washouts has leveled off despite the increase in heavy rainfall is considered to the effects of river improvement and the number of bridge washouts has increased after the 1990s is considered to the result of the increase in heavy rainfall caused by global warming.

Keywords: natural disasters, train derailments, bridge washouts, heavy rainfall, trend, global warming, Japanese railway.

1 Introduction

Japan consists of an archipelago located along the middle latitudes to the east of the Eurasian continent, with high levels of precipitation compared to many other parts of the world, due to the effect of typhoons and stationary fronts. Moreover, 70 percent of the land in Japan is mountainous with complex and fragile geological structure. Also, rivers in Japan are characterized short in length, flow quickly, and runoff quickly in the time of rainfall. For these reasons, every year many disasters caused by rainfall such as slope failure, debris flow and flooding have occurred, incurring damage on railways as well. Moreover, bridge washouts, which can be fatal to railways, often occur in Japan, recently bridge washouts have occurred every year.

In recent years, climate change such as a rise in temperature and an increase in the intensity and frequency of heavy rainfall is occurring due to an increase in the concentration of greenhouse gases due to human activities [1]. Such trends are expected to continue in the future [1]. Nemry and Demirel [2] and Palin et al [3] pointed out that with climate change, the railways will be affected by various factors, including increased buckling of tracks and sagging of overhead wires due to rising temperatures, increased slope failures and scouring of bridges due to increasing heavy rainfall, and increased flooding due to rising sea level. For example, in Europe, Palin et al. [4] indicated that in the United Kingdom, daily temperature conditions that cause track buckling and sagging of overhead wires can be expected in the 2040s. Sanchisa et al. [5] indicated that in Spain, the number of buckling of tracks due to rising temperatures will increase significantly at the end of the 21st century compared to recent years. In Japan, Uemura et al. [6] showed that if the disaster-prevention intensity remains the same as at present, the frequency of slope failures would be about 2.2 times higher in the end of the 21st century than at present in Tohoku region. Moreover, Uemura et al. [7],[8] showed that the frequency of suspended operations due to train operation control in times of heavy rainfall would be about 3.1 times higher in the Tohoku region and about 1.4 times higher in the Kantō region similarly. The train operation control is to implement suspended operations or reduced speed based on precipitation observed by rain gauges to ensure safe train operation in times of heavy rainfall.

Looking at the past, Suzuki [9] investigated the number of natural disasters and train derailments caused by rainfall-induced disasters on Japanese railway from 1966 to 2014 and showed that the number of natural disasters and train derailments was a decreasing trend. Suzuki and Uemura [10] indicated that the frequency of train operation control increased by about 15% per decade from 1976 to 2020 in the Tohoku and Kanto regions. Thus, on Japanese railways, over the long term, the number of natural disasters and train derailments caused by rainfall has shown a deceasing trend, while the frequency of train operation control has shown a increasing trend. For bridge washouts, no studies that have investigated past trend in bridge washouts have been found, bridge washouts have been recently occurred almost every year.

In this paper, we firstly conducted a statistical analysis of the number of natural disasters and train derailments caused by rainfall-induced disasters, expanding the period of coverage from Suzuki [9], as well as analysing the period of coverage separately. Secondly, we statistically analysed the trends in the number of bridge washouts. Finally, the relationship between the frequency of heavy rainfall and the number of natural disasters, train derailments and bridge washouts is discussed.

(a) Embankment collapse (b) Cut collapse

(c) Debris flow (d) Track flooding

Figure 1: Examples of natural disasters

2 Methods

2.1 Data

Data on the frequency of heavy rainfall with daily precipitation of 100 mm or more and hourly precipitation of 50 mm or more in Japan was obtained from the Japan Meteorological Agency (JMA) [11] The frequency of heavy rainfall in daily precipitation was extracted from data from 51 meteorological stations of JMA where precipitation observations have been continuous since 1901. The frequency of heavy rainfall in hourly precipitation was extracted from data from approximately 1,300 meteorological stations of Automated Meteorological Data Acquisition System (AMeDAS) of JMA.

Natural disasters include embankment collapse, cut collapse, sediment inflow, Debris flow, track flooding, rockfall and scouring etc., but the majority of natural disasters are considered to be rainfall-related. Figure 1 shows examples of natural disasters. Data on the number of natural disasters from 1966 to 2014 was obtained from Ota and Sugiyama [12] and Suzuki [9]. The number of natural disasters were the number of natural disasters that occurred at the Japanese National Railways (JNR) from 1966 to 1986 and the total number of natural disasters that occurred at the seven

(a) Train derailment on Tohoku Line in 1987

(b) Train derailment on Joetsu Line in 2020

Figure 2: Examples of train derailment caused by rainfall-induced disasters

(a) Bridge washout on Tadami Line in 2011

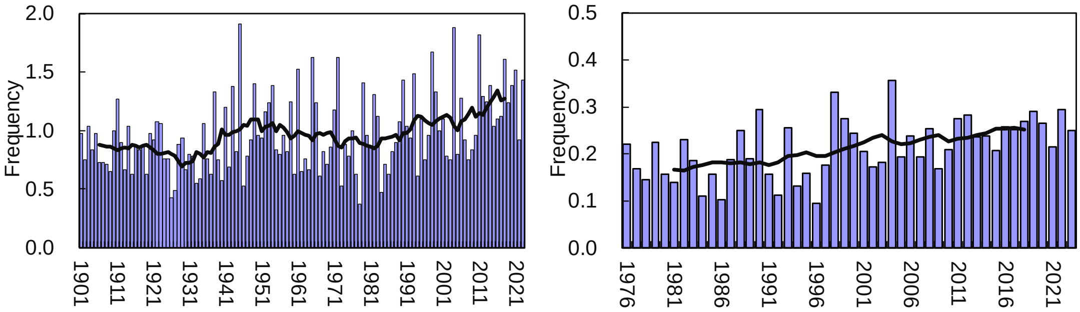
(b) Bridge washout on Banetsu-weast Line in 2022

Figure 3: Examples of bridge washouts

Japan Railway companies (JR) from 1987 to 2014. In Japan, the JNR was divided into seven companies and privatized in 1987. Natural disasters that occurred in the seven JR from 2015 to 2023 were extracted from the Journal of the Japan Railway Facilities Association [e.g., 13] in this study.

Figure 2 shows examples of train derailments caused by rainfall-induced disasters. Data on the number of train derailments caused by rainfall-induced disasters from 1966 to 2014 was obtained from Suzuki [9]. The number of train derailments were the number of train derailments that occurred at the JNR from 1966 to 1986 and the total number of natural disasters that occurred at the seven JR from 1987 to 2014. Train derailments that occurred in the seven JR from 2015 to 2023 were extracted from the reports of the Japan Transport Safety Board [e.g., 14] in this study.

Figure 3 shows examples of bridge washouts. Data on the number of bridge washouts from 1966 to 1986 was extracted from the reports of the JNR Facility Bureau [e.g., 15] for the frequency of heavy rainfall and the number of natural disasters, derailment accidents caused by rainfall-induced disasters, and bridge washouts. The Mann-Kendall test is one of the nonparametric tests and is a trend test method that



(a) Daily rainfall of 100 mm or more (b) Hourly rainfall of 50 mm or more

Figure 4: The time series of the frequency of heavy rainfall with daily rainfall of 100 mm or more and hourly rainfall of 50 mm or more and 11-year moving average

tests for trend based on the information of the sign of the differences between data in time series data.

3 Results

3.1 Analysis over the entire period

We tested the monotonic trends in the frequency of heavy rainfall and the number of natural disasters, derailment accidents caused by rainfall-induced disasters and bridge washouts over the entire target period using the Mann-Kendall test.

3.1.1 Heavy rainfall

Figure 4 shows the time series of the frequency of heavy rainfall with daily precipitation of 100 mm or more and hourly precipitation of 50 mm or more in Japan and their 11-year moving average. JMA [11] indicated shows that the frequency of heavy rainfall with daily precipitation of 100 mm or more from 1901 to 2023 and heavy rainfall with hourly precipitation of 50 mm or more from 1976 to 2023 are a significant increase trend at the significance level of 1%. Also, we tested the monotonic trends in the frequency of heavy rainfall with daily precipitation of 100 mm or more from 1966 to 2023 using the Mann-Kendall test. As a result, the frequency of heavy rainfall with daily precipitation from 1966 to 2023 are a significant increase trend at the significance level of 1%. Thus, the frequency of heavy rainfall is increasing in Japan due to climate change caused by global warming.

3.1.2 Natural disasters

Figure 5 shows the time series of the number of natural disasters from 1966 to 2023 in the JNR and the seven JR, and their 11-year moving average. Natural disasters occurred in the JNR era about 5,000 times per year in the 1970s and dropped to a few thousand times per year in the 1980s. Furthermore, it has dropped to a few hundred times per year since the 1990s in the JR era.

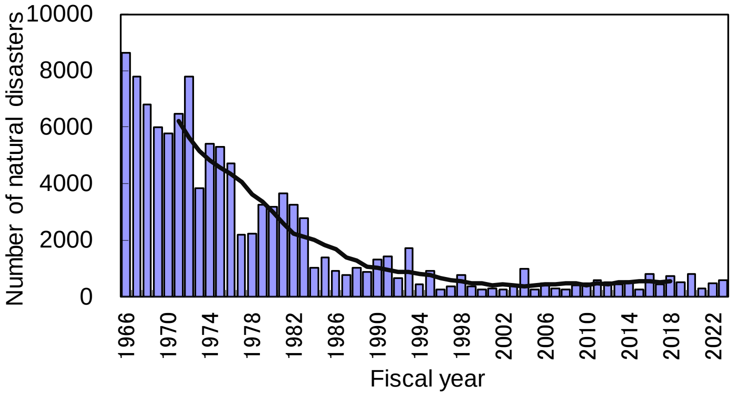


Figure 5: The time series of the the numbers natural disasters and 11-year moving average

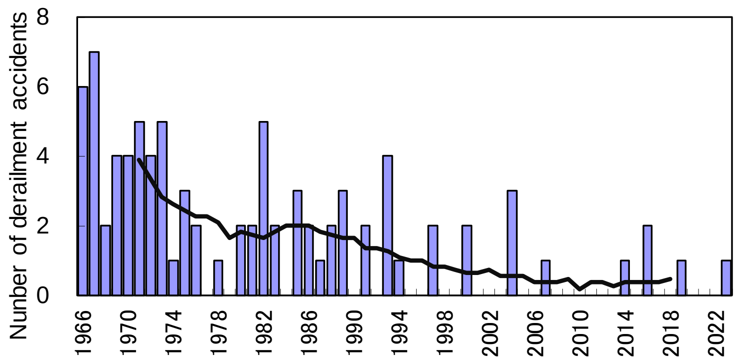


Figure 6: The time series of the numbers of train derailment accidents caused by rainfall-induced disasters

In order to test the significance of the monotonic trend in the number of natural disasters from 1966 to 2023, the Mann-Kendall test was used to test the trend. As a result, the number of natural disasters is a significant decrease trend at the significance level of 1% from 1966 to 2023.

3.1.3 Train derailments

Figure 6 shows the time series of the number of train derailments caused by rainfall-induced disasters from 1966 to 2023 in the JNR and the seven JR, and their 11-year moving average. Train derailments caused by rainfall-induced disasters occurred every year and about four times per year in the late 1960s and the early 1970s in the JNR era. In the late 1970s and 1980s, it occurred every year, but decreased to two times per year. Furthermore, it has decreased to once every few years since the 1990s in the JR era.

In order to test the significance of the monotonic trend in the number of train derailments caused by rainfall-induced disasters from 1966 to 2023, the Mann-Kendall test was used to test the trend. As a Result, the number of train derailments is a significant decrease trend at the significance level of 1% from 1966 to 2023.

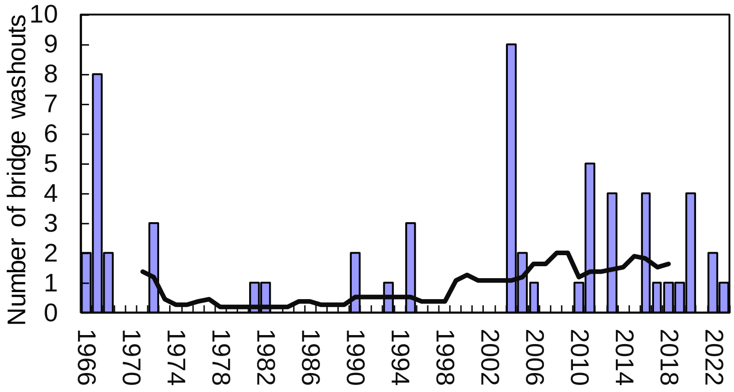


Figure 7: The time series of the numbers of bridge washouts

3.1.4 Bridge washouts

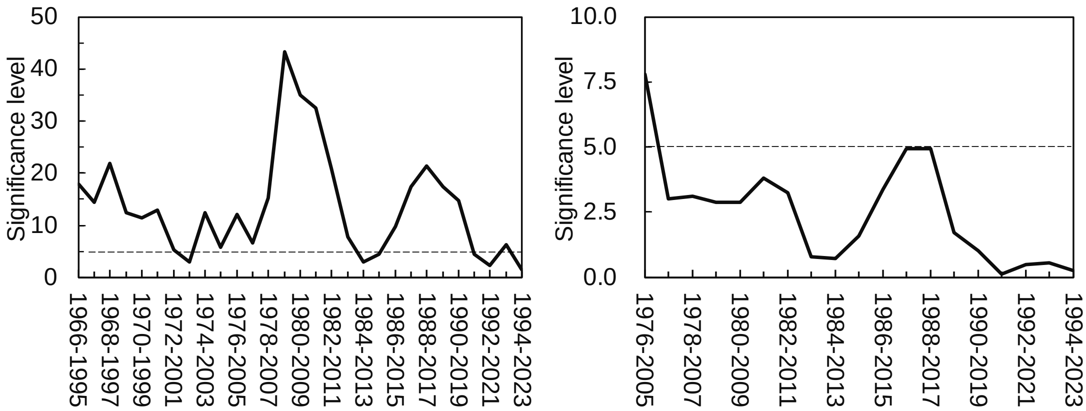
Figure 7 shows the time series of the number of bridge washouts from 1966 to 2023 in the JNR and the seven JR, and their 11-year moving average. Bridge washouts occur once every few years, but recently they have been occurring every year.

In order to test the significance of the monotonic trend in the number of bridge washouts from 1966 to 2023, the Mann-Kendall test was used to test the trend. As a result, the number of bridge washouts is a significant increase trend at the significance level of 5% from 1966 to 2023.

3.2 Analysis of the divided periods

In Section 3.1, the monotonic trends in the frequency of heavy rainfall and the number of natural disasters, derailment accidents caused by rainfall-induced disasters and bridge washouts over the entire target period were tested using the Mann-Kendall test. As a result, the frequency of heavy rainfall with daily precipitation of 100 mm or more from 1901 to 2023 and the frequency of heavy rainfall with hourly precipitation of 50 mm or more from 1976 to 2023 were a significant increase trend at the significance level of 1%. On the other hand, the number of natural disasters from 1966 to 2023 and the number of train derailments caused by rainfall-induced disasters from 1966 to 2023 were a significant decrease trend at the significance level of 1%. The number of bridge washouts from 1966 to 2023 is a significant increase trend at the significance level of 5% from 1966 to 2023.

Next, looking at the 11-year moving average values in Figures 4, 5, 6, and 7, it shows that the frequency of heavy rainfall appears to be increasing uniformly. While the number of natural disasters and the number of derailment accidents caused by rainfall-induced disasters appear to decrease rapidly before the 1980s and level off after the 1990s. Also, bridge washouts appear to be more frequent in the 1960s and after the 2000s. Therefore, we divided the period into 30 years, and tested the trend of the frequency of heavy rainfall and the number of natural disasters, derailment accidents, and bridge washouts.



(a) Daily rainfall of 100 mm or more (b) Hourly rainfall of 50 mm or more

Figure 8: Results of the Mann-Kendall test of trend for the frequency of heavy rainfall. The test results for every 30 years and shows shows the significance levels of decreasing trends.

3.2.1 Heavy rainfall

The frequency of heavy rainfall with daily precipitation of 100 mm or more from 1966 to 2023 and the frequency of heavy rainfall with hourly precipitation of 50 mm or more from 1976 to 2023 are tested every 30 years using the Mann-Kendall test. Figure 8 shows the significance levels of those increasing trends. The frequency of heavy rainfall with daily precipitation is a significant increase at the significance level of 5% for some of the 30 years from 1966 to 2023. Therefore, for each 30-year period from 1966 to 2023, heavy rainfall with daily precipitation increases or levels off, depending on the period. The frequency of heavy rainfall with hourly precipitation is a significant increase at the significance level of 5% for most of the 30 years from 1976 to 2023. Therefore, heavy rainfall with hourly precipitation increases for most of the 30-year period from 1966 to 2023.

3.2.2 Natural disasters

The number of natural disasters from 1966 to 2023 are tested every 30 years using the Mann-Kendall test. Figure 9 shows the significance levels of decreasing trends. The number of natural disasters is a significant decreasing trend at the significance level of 1% or 5% for the previous 30 years before the late 2010s. It shows no significant trend at the significance level of 5% for the previous 30 years after the late 2010s, but shows a significant increasing trend at the significance level of 5%for the period 1994-2023. Therefore, for each 30-year period from 1966 to 2023, natural disasters decrease before the 1980s, level off after the 1990s, and shows a increasing trend or the period 1994-2023.

3.2.3 Train derailments

The number of train derailments caused by rainfall-induced disasters from 1966 to

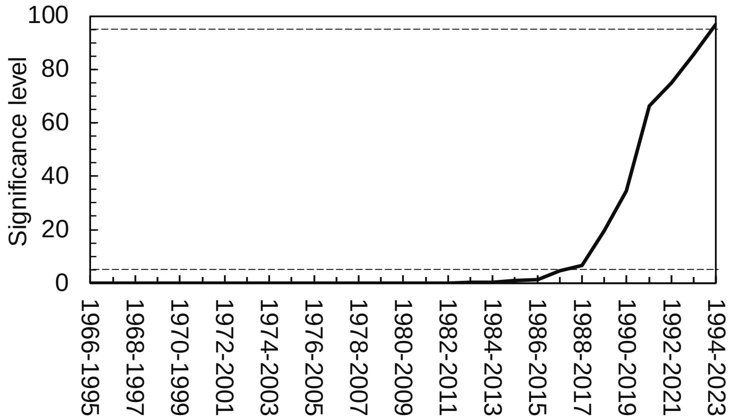


Figure 9: Results of the Mann-Kendall test of trend for the number of natural disasters. The test results for every 30 years and shows significance levels of decreasing trends.

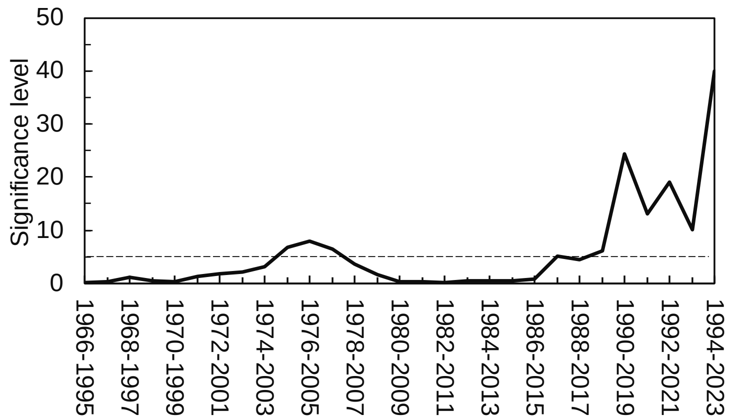


Figure 10: Results of the Mann-Kendall test of trend for the number of train derailments caused by rainfall-induced disasters. The test results for every 30 years and shows significance levels of decreasing trends.

2023 are tested every 30 years using the Mann-Kendall test. Figure 10 shows the significance levels of decreasing trends. The number of train derailments caused by rainfall-induced disasters is a significant decreasing trend at the significance level of 1% or 5% for the previous 30 years before the late 2010s, but shows no significant trend at the significance level of 5% for the previous 30 years after the late 2010s. Therefore, for each 30-year period from 1966 to 2023, train derailments caused by rainfall-induced disasters decrease before the1980s and level off after the 1990s.

3.2.4 Bridge washouts

The number of bridge washouts from 1966 to 2023 are tested every 30 years using the Mann-Kendall test. Figure 11 shows the significance levels of increasing trends. The number of bridge washouts shows no significant trend at the significance level of 5% for the previous 30 years before the 2010 but is a significant increasing trend at the

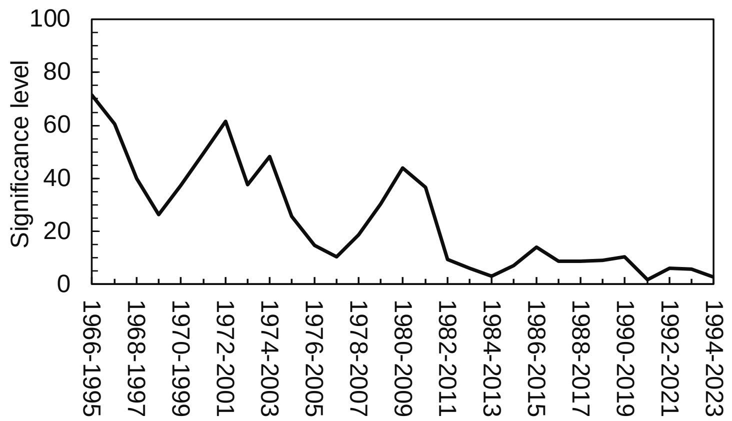


Figure 11: Results of the Mann-Kendall test of trend for the number of bridge washouts. The test results for every 30 years and shows significance levels of increasing trends.

significance level of 5% for the previous 30 years after the 2020s. Therefore, for each 30-year period from 1966 to 2023, bridge washouts level off before the 1980s and increase after the1990s.

3.3 Consideration

The increasing trend in the frequency of heavy rainfall with daily precipitation of 100 mm or more is a significant at the significance level of 1% for the entire period from 1901 to 2023 and from 1966 to 2023. Also, the increasing trend in the frequency of heavy rainfall with daily precipitation for some 30 years from 1966 to 2023 is a significant at the significance level of 5%. The increasing trend in the frequency of heavy rainfall with hourly precipitation of 50 mm or more is significant at the significance level of 1% for the entire period from 1976 to 2023 and the increasing trend for most of the 30 years from 1976 to 2023 is a significant at the significance level of 5%. Therefore, heavy rainfall is considered to increase with global warming in the period from 1966 to 2023.

As heavy rainfall increases, rainfall-related natural disasters generally increase. Nevertheless, the number of natural disasters and train derailments caused by rainfall-induced disasters has decreased. Also, the number of bridge washouts has leveled off or increase. Therefore, this chapter discusses the relationship between the trends in the number of natural disasters, train derailments caused by rainfall-induced disasters, and bridge washouts and heavy rainfall.

3.3.1 Natural disasters

The decreasing trend in the number of natural disasters is a significant at the significance level of 1% for the entire period from 1966 to 2023. On the other hand, the analysis of the divided 30 years shows that the number of natural disasters is a significant decreasing trend at the significance level of 1% or 5% for the previous 30 years before the late 2010s. It shows no significant trend at the significance level of

(a) Embankment slope protection works (b) Cut slope protection works

Figure 12: Examples of slope protection works

5% for the previ ous 30 years after the late 2010s, but shows a significant increasing trend at the significance level of 5% for the period 1994-2023. Therefore, natural disasters decreased before the 1980s, leveled off after the 1990s and shows a increasing trend or the period 1994-2023.

Railway operators have implemented hard countermeasures such as slope protection works as shown in Figure 12, to improve rainfall resistance along railway lines. Suzuki [9] pointed out that the fact that natural disasters have decreased from 1996 to 2014 is thought to be the result of improved rainfall resistance along railway lines. If the rainfall resistance along the railway line is the same, natural disasters should increase when heavy rainfall increases. Therefore, the decrease in the number of natural disasters before the 1980s despite the increase in heavy rainfall is considered to the effect of the implementation of hard countermeasures, as Suzuki [9] points out. The fact that the number of natural disasters has leveled off despite the increase in heavy rainfall after the 1990s is also considered to the effect of the implementation of hard countermeasures. However, but the number of natural disasters shows a increasing trend for the period 1994-2023. The reason why the number of natural disasters has leveled off without decreasing after the 1990s and shows a increasing trend for the period 1994-2023 may be due to the greater effect of the increase in heavy rainfall caused by global warming.

3.3.2 Train derailments

The decreasing trend in the number of train derailments caused by rainfall-induced disasters is a significant at the significance level of 1% for the entire period from 1966 to 2023. On the other hand, the analysis of the divided 30 years shows that the number of train derailments caused by rainfall-induced disasters is a significant decreasing trend at the significance level of 1% or 5% for the previous 30 years before the late 2010s, but shows no significant trend at the significance level of 5% for the previous 30 years after the late 2010s. Therefore, train derailments caused by rainfall-induced disasters decreased before the1980s and leveled off after the 1990s.

Railway operators enforce train operation control such as speed reduction and suspended operations during heavy rainfall based on precipitation observed by rain gauges to ensure safe train operation from rainfall-related disasters. Suzuki [12] pointed out the decrease in train derailments caused by rainfall-induced disasters to the improvement of the train operating control method. This is because the number of train derailments caused by rainfall-induced disasters jumped to downward in 1974, this jump occurred prior to 1984 when the number of natural disasters jumped downward, and the train operation control method in the time of heavy rainfall was greatly improved in 1973.

With an increase in heavy rainfall, it is not strange to show the probability of train derailments caused by rainfall-induced disasters increases. Therefore, the decrease in the number of train derailments caused by rainfall-induced disasters before the 1980s despite the increase in heavy rainfall is considered to the effect of the improvement of train operation control methods, as Suzuki [9] points out, in addition to the decrease in the number of natural disasters. Improvements to the train operation control method in the time of heavy rainfall have also been implemented frequently after 1973. The fact that the number of train derailments caused by rainfall-induced disasters has leveled off despite the increase in heavy rainfall after the 1990s is also considered to the effect of the improvement of train operation control methods and the implementation of hard countermeasures. However, the reason why the number of train derailments caused by rainfall-induced disasters has leveled off without decreasing after the 1990s may be due to the greater effect of the increase in heavy rainfall caused by global warming.

3.3.3 Bridge washouts

The number of bridge washouts shows no significant trend at the significance level of 5% for the entire period from 1966 to 2023. On the other hand, the analysis of the divided 30 years shows that the number of bridge washouts show no significant trend at the significance level of 5% for the previous 30 years before the 2010s, but the increasing trend is a significant at the significance level of 5% for the 30 years prior after the 2020s. Therefore, bridge washouts leveled off before the 1980s and increased after the1990s.

River managers have implemented river improvements such as raising levees, installing flood control facilities, and excavating river channels. The fact that the number of bridge washouts has leveled off before 1980 despite the increase in heavy rainfall is considered to be due to the effects of river improvement. However, the reason why the number of bridge washouts has increased after the 1990s may be due to the greater effect of the increase in heavy rainfall. Thus, Bridge washouts may already have begun to increase due to the effects of increased heavy rainfall caused by global warming.

4 Conclusions and Contributions

This study evaluated the impact of increased heavy rainfall caused by global warming on natural disasters, train derailments caused by rainfall-induced disasters, and bridge washouts from 1966 to 2023 on Japanese railway. The results are as follows.

(1) Heavy rainfall with daily precipitation of 100 mm or more increased from 1966 to 2023, and heavy rainfall with hourly precipitation of 50 mm or more increased 1976 to 2023 in Japan due to global warming.

(2) Natural disasters decreased before the 1980s, leveled off after the 1990s and shows a increasing trend for the period 1994-2023. The decrease in the number of natural disasters before the 1980s despite the increase in heavy rainfall is considered to the effect of the implementation of hard countermeasures. The fact that the number of natural disasters has leveled off despite the increase in heavy rainfall after the 1990s is also considered to the effect of the implementation of hard countermeasures. However, the reason why the number of natural disasters has leveled off without decreasing after the 1990s and shows a increasing trend for the period 1994-2023 may be due to the greater effect of the increase in heavy rainfall caused by global warming.

(3) Train derailments caused by rainfall-induced disasters decreased before the1980s and leveled off after the 1990s. The decrease in the number of train derailments caused by rainfall-induced disasters before the 1980s despite the increase in heavy rainfall is considered to the effect of the improvement of train operation control methods, in addition to the decrease in the number of natural disasters. The fact that the number of train derailments caused by rainfall-induced disasters has leveled off despite the increase in heavy rainfall after the 1990s is also considered to the effect of the improvement of train operation control methods and the implementation of hard countermeasures. However, the reason why the number of train derailments caused by rainfall-induced disasters has leveled off without decreasing after the 1990s may be due to the greater effect of the increase in heavy rainfall caused by global warming.

(4) Bridge washouts leveled off before the 1980s and increased after the1990s. The fact that the number of bridge washouts has leveled off before 1980 despite the increase in heavy rainfall is considered to the effects of river improvement. However, the reason why the number of bridge washouts has increased after the 1990s may be due to the greater effect of the increase in heavy rainfall. Thus, Bridge washouts may already have begun to increase due to the effects of increased heavy rainfall caused by global warming.

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