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ORIGINAL PAPER

Relationship between landslides and long-term rainfall trends

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Abstract

Evaluating how the changes in rainfall caused landslides is important to prevent sediment disasters. Using the soil water index (SWI) and a three-layer tank model, this study examined the relationship between the occurrence of landslides and long-term changes in rainfall in Miyagawa Village, Mie Prefecture, Japan, where shallow and deep-seated landslides have occurred at different times. The three-layer tank model detected the effects of long-term changes in rainfall on landslides. We educated that the change in the first storage tank layer indicates the potential risk of shallow landslides, while that in the second and third storage tanks indicates the potential risk of deep-seated landslides. Our method could be used to examine the effects of long-term changes in rainfall on landslides in the same region at different times, or over a wider area. Besides, these results are valid because the three-layer tank model used to calculate the SWI is applied throughout Japan, and its effectiveness has been verified.

Keywords Landslides · Rainfall characteristics · Soil water index · Three-layer tank model · Trend

Introduction

Landslides are caused by rainfall, earthquakes, and other triggers (e.g., Abuzied and Alrefaee 2019; Abuzied et al. 2016; Hong et al. 2005). In particular, rainfall-induced landslides often cause significant damage (Saito et al. 2010b). Evaluating the relationship between the occurrence of landslides and rainfall is essential to mitigate the damage caused by rainfall-induced landslides (Ibsen and Casagli 2004; Hong et al. 2005). In addition, evaluating how changes in rainfall cause landslides is important for disaster prevention, as long-term changes in rainfall, such as those induced by climate change, affect landslides (e.g., Crozier 2010; Gariano and Guzzetti 2016; Kumari et al. 2021).

Rainfall characteristics that cause landslides may be estimated using empirical methods focused on rainfall intensity and duration (e.g., Aleotti 2004; Bai et al. 2014; Caine 1980; Guzzetti et al. 2007, 2008; Martelloni et al. 2012; Saito et al. 2010b), conceptual models that consider the infiltration of rainfall into the ground (e.g., Gabet et al. 2004; Ishihara and Kobatake 1979; Okada et al. 2001; Saito et al. 2010a; Shuin et al. 2020), and physical models that include the effects of topography and vegetation, among other inherent factors (process-based models) (e.g., Baum et al. 2010; Crosta and Frattini 2003; Montgomery and Dietrich 1994; Pack et al. 1998; Wu and Sidle 1995). Most studies are based on individual rainfall events separated by a no-rainfall period, and focus on the rainfall characteristics that cause landslides. However, antecedent rainfall conditions also affect landslides, where landslides are associated with the groundwater level, pore pressure, and shear stress (e.g., Terlien 1998). Therefore, in studies of rainfall events, the antecedent rainfall is a necessary initial condition when evaluating the relationship between the occurrence of landslides and rainfall characteristics (Dahal and Hasegawa 2008; Kim et al. 2021; Mathew et al. 2014; Rahardjo et al. 2001, 2008; Rahimi et al. 2011).

A conceptual model used in Japan, the soil water index (SWI), was developed by the Japan Meteorological Agency (JMA) (Okada et al. 2001) based on the three-layer tank model proposed by Ishihara and Kobatake (1979). SWI and the three-layer tank model calculated using hourly rainfall

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represent the conceptual water stored in the soil (groundwater level). When using these methods, it is possible to assess rainfall throughout the year without separating it into distinct events. Therefore, these methods can be used to examine the relationship between landslides and rainfall, while considering the effects of antecedent rainfall. Although the SWI and three-layer tank model are conceptual models, they are used in the Japanese sediment disaster warning system (Osanai et al. 2010). Moreover, studies of the occurrence of landslides induced by heavy rainfall have demonstrated their effectiveness (Chen et al. 2017; Matsuyama et al. 2021; Saito et al. 2010a; Shuin et al. 2020).

The spatial distribution of landslide hazards is useful for improving prediction accuracy, and GIS-based studies are effective in this regard (e.g., Abuzied and Alrefaee 2019; Abuzied and Pradhan 2021; Abuzied et al. 2016). Subsurface information, in particular soil depth, over a wide area is required for these studies (e.g., Uchida et al. 2009). For shallow landslides, soil depth can be estimated from topographic information (Kuriakose et al. 2009). On the other hand, subsurface information related to deep-seated landslides is difficult to obtain over a wide area, as intensive techniques such as boring are required to obtain such data.

The JMA uses parameters related to inherent factors of the three-layer tank model to calculate the SWI; these parameters were determined in an investigation of granite regions throughout the entire country. The SWI can be applied across a wide area because only rainfall data are required. Furthermore, different regions can be compared because the parameters related to the inherent factors are uniform throughout the country.

With these considerations in mind, the aim of this paper is to examine the relationship between the occurrence of landslides and long-term rainfall trends using the SWI and three-layer tank model. The advantages of our method are demonstrated through comparison with previous studies. Here, we did not focus on prediction of the landslide distribution (e.g., Abuzied and Alrefaee 2019; Abuzied and Pradhan 2021; Abuzied et al. 2016), but instead examined the relationships of long-term trends in rainfall characteristics with the occurrence of landslides and their morphologies, based on the responses of rainfall indexes.

Materials and methods

Study area

The study area was Miyagawa Village in Mie Prefecture, Japan (307.54 km^2) (Fig. 1). This area was selected because data are available on shallow and deep-seated landslides caused by heavy rainfall, including the estimated times of occurrence. The main basement geology is the accretionary prism and metamorphic rock in this area (Kato and Saka 1997). The mean annual precipitation is about 3100 mm.

In Miyagawa Village, the shallow landslide was caused by a Typhoon *Meari* in 2004, and the deep-seated landslide was caused by a Typhoon *Talas* in 2011 (Fig. 1). Based on interviews with residents, the shallow landslide occurred at 9:30 a.m. on September 29, 2004, and the deep-seated landslide at 5:30 p.m. on September 4, 2011 (Hayashi et al. 2004; Matsumura et al. 2012).

Data collection

SWI was calculated using hourly rainfall data from 1978 to 2019 obtained by the Automated Meteorological Data Acquisition System (AMeDAS) in Miyagawa, the station nearest the study area (Fig. 1). AMeDAS is operated by the JMA, and meteorological observation data are available to the public. As AMeDAS data for Miyagawa were not available from September 28, 2004, to October 4, 2004, i.e., the period in which the shallow landslide occurred, hourly rainfall data collected at Miyagawa Dam, located southeast of the Miyagawa AMeDAS station, were used to supplement the dataset (Fig. 1).

Soil water index and three-layer tank model

The SWI is used for predicting the risk of sediment-related disasters due to rainfall. Sediment disasters (shallow landslides and debris flows) that occur due to heavy rains are closely related not only to the current rainfall, but also to the amount of water in the soil due to previous rainfall. To calculate the SWI, rainfall-runoff through the soil is represented by a three-layer tank model, assuming a perforated tank (Fig. 2). The SWI is given by the sum of the values for each storage tank:

$$SWI = S_1 + S_2 + S_3 \tag{1}$$

$$S_1(t + \Delta t) = \left(1 - \beta_1 \Delta t\right) \cdot S_1(t) - q_1(t) \cdot \Delta t + R \tag{2}$$

$$S_2(t + \Delta t) = \left(1 - \beta_2 \Delta t\right) \cdot S_2(t) - q_2(t) \cdot \Delta t + \beta_1 \cdot S_1(t) \cdot \Delta t \tag{3}$$

$$S_3(t + \Delta t) = \left(1 - \beta_3 \Delta t\right) \cdot S_3(t) - q_3(t) \cdot \Delta t + \beta_2 \cdot S_2(t) \cdot \Delta t \tag{4}$$

where S_1–S_3 are water depths (mm), β_1–β_3 are coefficients of permeability (1/h), and q_1–q_3 are the outflows from each tank. The time step is 10 min (Δt), and R is the rainfall in mm per 10-min period (mm/10 min). The amount of outflow from the side hole of each tank is given as:

$$q_1(t) = \alpha_1 \left\{ S_1(t) - L_1 \right\} + \alpha_2 \left\{ S_1(t) - L_2 \right\} \tag{5}$$

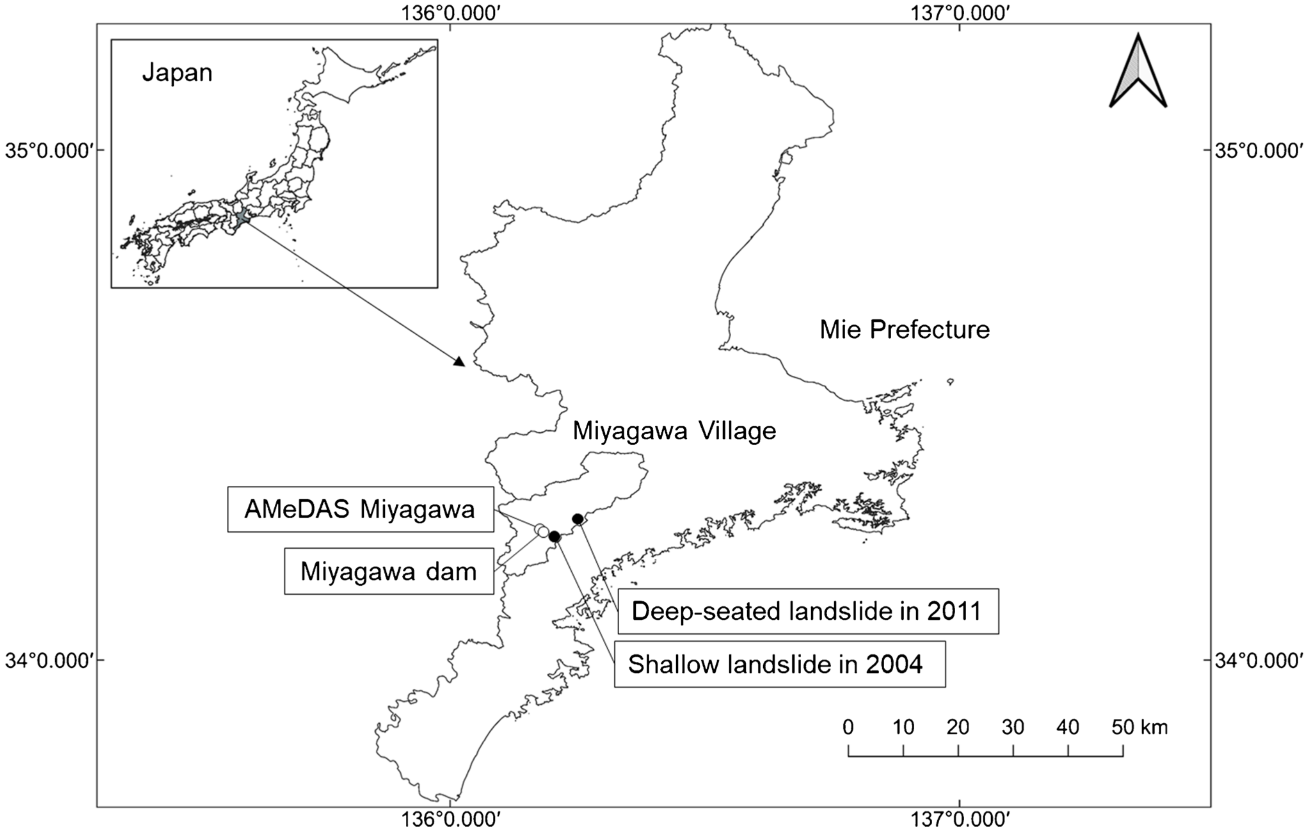


Fig. 1 Outline of study area

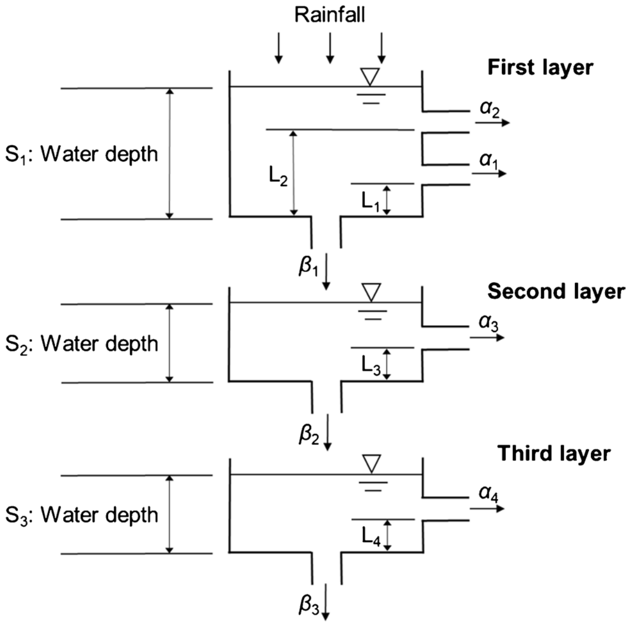


Fig. 2 Schematic diagram of three-layer tank model used in calculating the soil water index (Ishihara and Kobatake 1979)

$$q_2(t) = \alpha_3\{S_2(t) - L_3\} \tag{6}$$

$$q_3(t) = \alpha_4\{S_3(t) - L_4\} \tag{7}$$

where α_1–α_4 are the outflow coefficients (/h) and L_1–L_4 are the outflow heights (mm). The JMA uses a common set of parameters based on runoff analysis of granite distribution to calculate the SWI (Table 1). This study used the same parameters used by the JMA.

Trend analysis

The nonparametric Mann–Kendall test (Mann 1945; Kendall 1975) was used to analyze the annual maximum values, and 11-year running averages thereof, to determine long-term trends in the soil and tank storage layer SWI values. The Mann–Kendall test is widely used to detect trends in time series data, where a positive (negative) value of the standardized test statistic (Z_c) indicates an increasing (decreasing) trend in the time series. Z_c follows a normal distribution. If $|Z_c| > Z_{\alpha/2}$ (where α is the significance level), the trend is statistically significant.

Table 1 Tank model parameters of the Soil water index (Ishihara and Kobatake 1979)

Tank	First layer		Second layer		Third layer	
Outflow height (mm)	L_1	15.0	L_3	15.0	L_4	15.0
	L_2	60.0				
Outflow coefficient (1/h)	α_1	0.10	α_3	0.05	α_4	0.01
	α_2	0.15				
Coefficient of permeability (1/h)	β_1	0.12	β_3	0.05	β_3	0.01

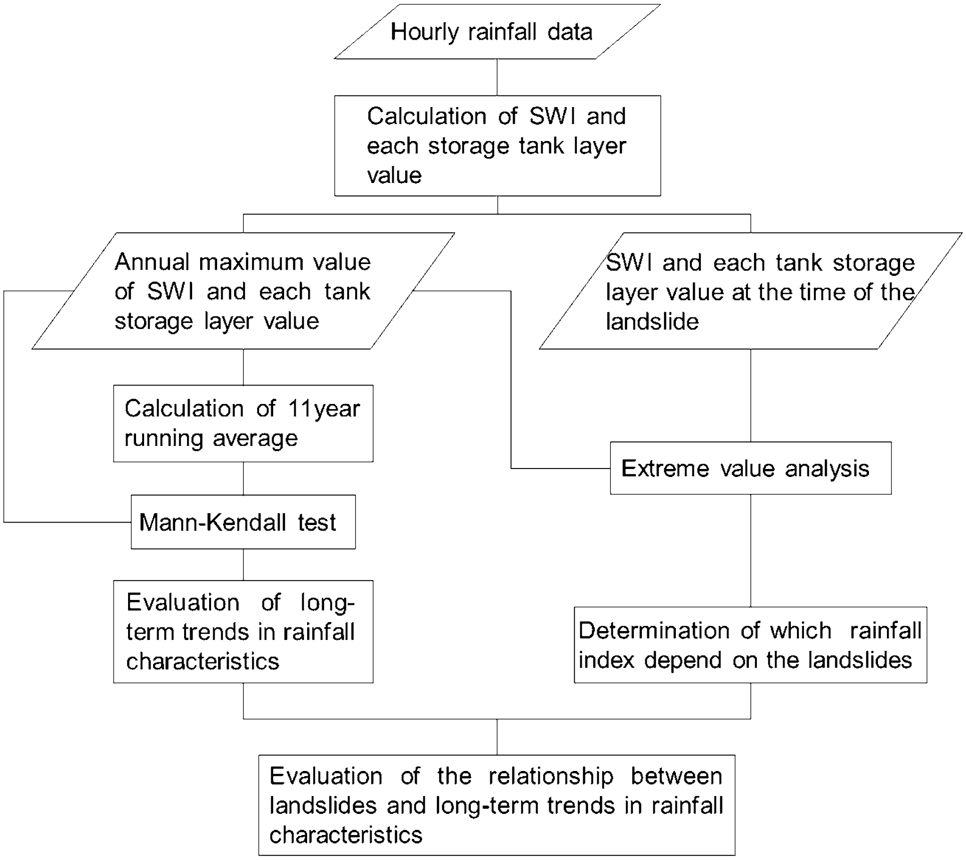
Extreme value analysis

This study used the return period (RP), calculated by extreme value analysis, to evaluate landslides because their occurrence is influenced more by probability than the amount of precipitation in a given region. The generalized extreme value distribution was estimated for the period 1981–2010 using the L-moment method. The period of parameter calculation for evaluating existing and future landslides in different regions was fixed (Shuin et al. 2020).

Analytical procedure

Figure 3 shows a flowchart of the analytical procedure. First, we calculated the SWI and each tank storage layer value. Second, we compared the RP of the SWI and each storage tank layer value at the time of the landslide with the previous maximum RP to identify the groundwater level involved in the landslide. Then, we performed trend analysis of the annual maximum values, and 11-year running averages thereof, using the Mann–Kendall test. Finally, we evaluated the relationship between landslide occurrence and long-term trends in rainfall characteristics.

Fig. 3 Analytical procedure



Results

The shallow landslide in Miyagawa on September 29, 2004

In Miyagawa, shallow landslides caused by rainfall event due to Typhoon *Meari* occurred on September 29, 2004 (Fig. 4a).

Figure 5 shows the annual maximum RP of the SWI and each storage tank layer value from 1981 to 2019, and the time series of these values for the period September 27–30, 2004 (thus including September 29, the day of the shallow landslide). Figure 5a–d show the annual maximum RP of the SWI and each storage tank layer value (in gray; RP in the year of the landslide, in indicated by an arrow; the maximum RP before the landslide). Figure 5e–h show the RP of the SWI and each tank storage layer value at the time of the landslide. The association of landslides with RP values exceeding the previous maximum is based on the assumption that when the groundwater level rises above the previous maximum, the slope is in a condition where failure can occur at any time (Kosugi 2015). As shown in Fig. 5, the maximum RP of the SWI before 2004 was 22.4 years (in 1990), which is higher than at the time of the shallow landslide (11.2 years). However, there were

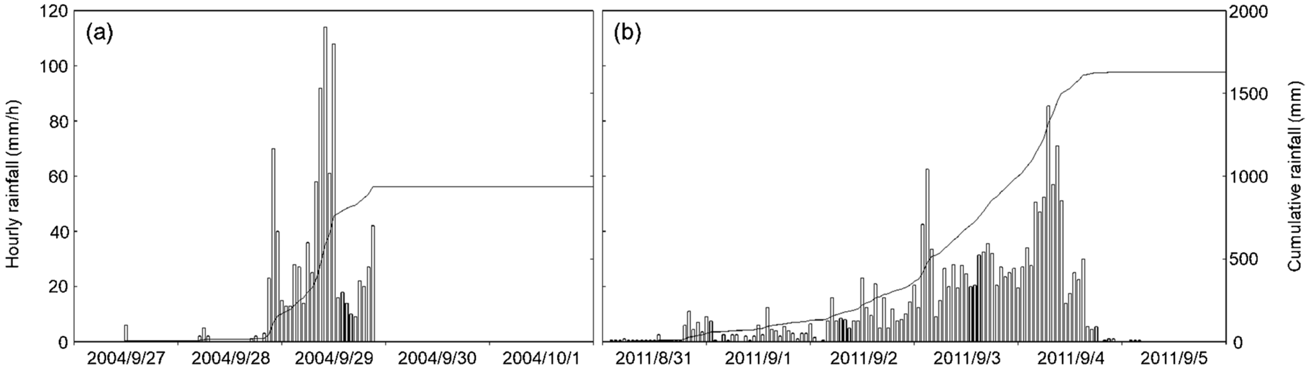


Fig. 4 Rainfall characteristics causing landslides in Miyagawa Village. **a** Typhoon Meari; **b** Talas

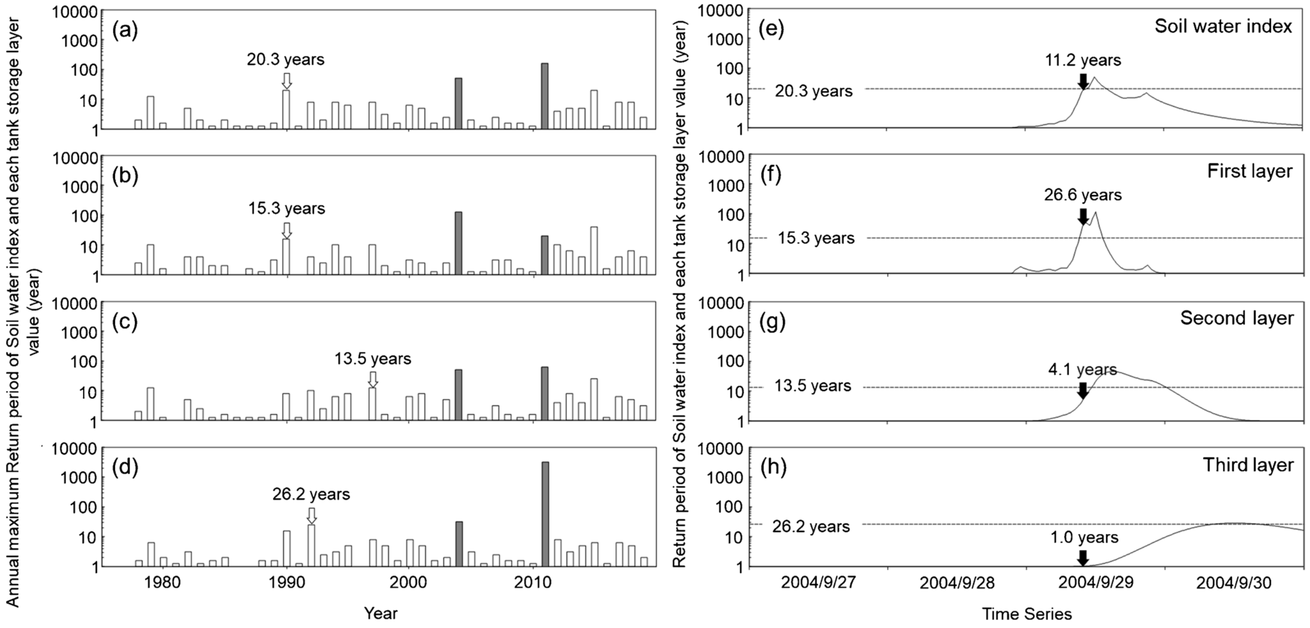


Fig. 5 Return period of annual maximum Soil water index and annual maximum each storage tank layer value from 1978 to 2019 (**a**, **b**, **c**, **d**) and time series of return period of soil water index and the time series of return period of each tank storage value between September 27 and 30, 2004 (**e**, **f**, **g**, **h**). Gray bars show the occurrence year of landslides, and white arrows indicate the maximum return period before landslides (**a**, **b**, **c**, **d**). Black arrows indicate the return period at the timing of landslides (**e**, **f**, **g**, **h**)

no shallow landslides in 1990, indicating that it is difficult to predict the timing of shallow landslides caused by short periods of heavy rainfall using the SWI alone.

Examining each tank storage layer value well as the SWI, the RP of the first storage tank layer value at the time of the shallow landslide was 26.6 years, which is higher than the previous maximum RP of 15.3 years. However, the RPs of the second and third storage tank layer values were both lower than the previous maximums. Assuming that landslides occur when the previous maximum value is exceeded, the RP of the first storage tank layer was related to this shallow landslide, and not to the values of the second and third storage tank layers.

The deep-seated landslide in Miyagawa on September 4, 2011

In Miyagawa, a deep-seated landslide caused by rainfall event due to Typhoon *Talas* occurred on September 4, 2011 (Fig. 4b). In the same area, a deep-seated landslide also occurred during Typhoon Meari in 2004, but the 2011 landslide was larger (Matsumura et al. 2012).

Figure 6 shows the annual maximum RPs of the SWI and each storage tank layer value from 1981 to 2019, and the time series of the RPs of the SWI and each tank storage layer value for the period September 2–5, 2011 (thus including September 4, the day of the deep-seated landslide). This figure also shows the maximum RP before the landslide, and the RP at the time thereof; these values were derived using the same method as in Fig. 5. As shown in Fig. 6, the RP of the SWI at the time of the deep-seated landslide was 38.9 years. The RP of the third tank storage layer value at the time of the deep-seated landslide was 1,135.4 years, which is higher than the previous maximum RP of 28.8 years, while the RPs of the first and second storage tank layer values were both lower than the previous maximum RP. Therefore, the third storage tank layer is related to this deep-seated landslide.

Trend analysis of rainfall characteristics

Figure 7 shows the temporal fluctuation in the annual maximum of SWI and each storage tank layer value in Miyagawa. The white circles indicate the annual maximums, and the bold black line indicates the 11-year running average. Table 2 shows the results of the Mann–Kendall test of the annual maximum of SWI and each storage tank layer value. As shown in Table 2, the SWI and each storage tank layer value in Miyagawa do not show significant trends. Table 3 shows the results of the Mann–Kendall test of the 11-year running averages of the annual maximum of SWI and each storage tank layer value. As shown in Table 3, all of these have a significant upward trend. The annual maximums and 11-year running averages thereof show different trends, possibly reflecting the larger year-to-year fluctuations in the former (Fig. 7).

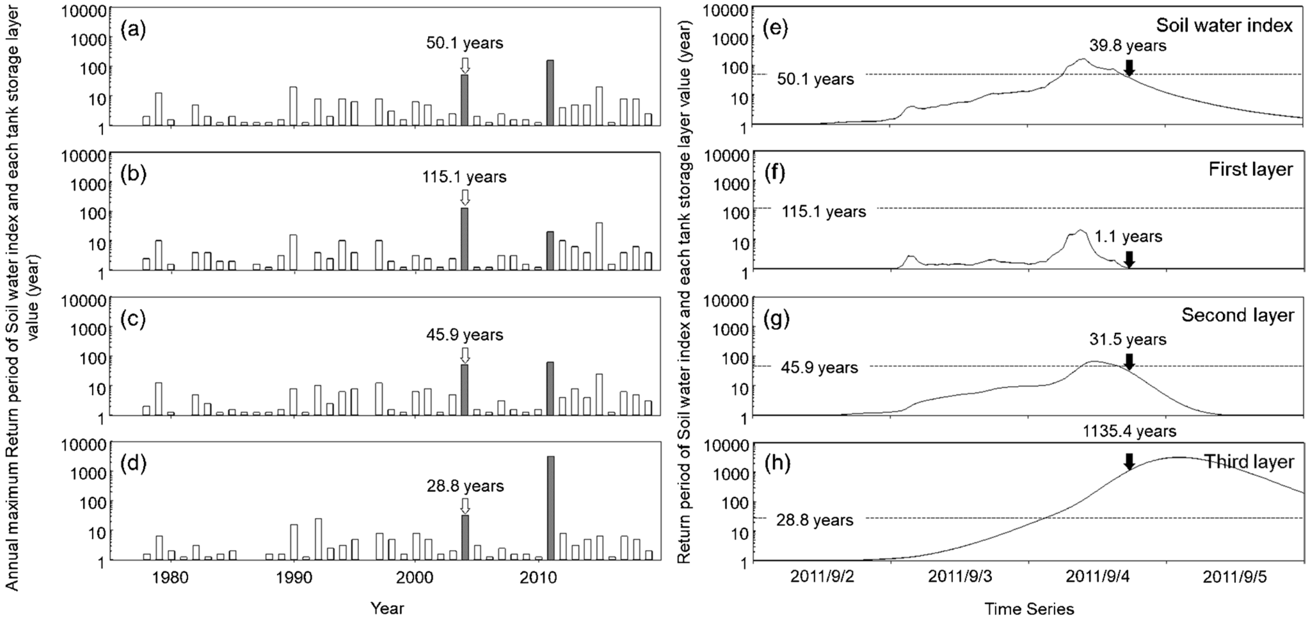


Fig. 6 Return period of annual maximum soil water index and annual maximum each storage tank layer value from 1978 to 2019 (**a**, **b**, **c**, **d**) and time series of return period of soil water index and the time series of return period of each tank storage value between September 31 and October 5, 2011 (**e**, **f**, **g**, **h**). Gray bars show the occurrence year of landslides, and white arrows indicate the maximum return period before landslides (**a**, **b**, **c**, **d**). Black arrows indicate the return period at the timing of landslides (**e**, **f**, **g**, **h**)

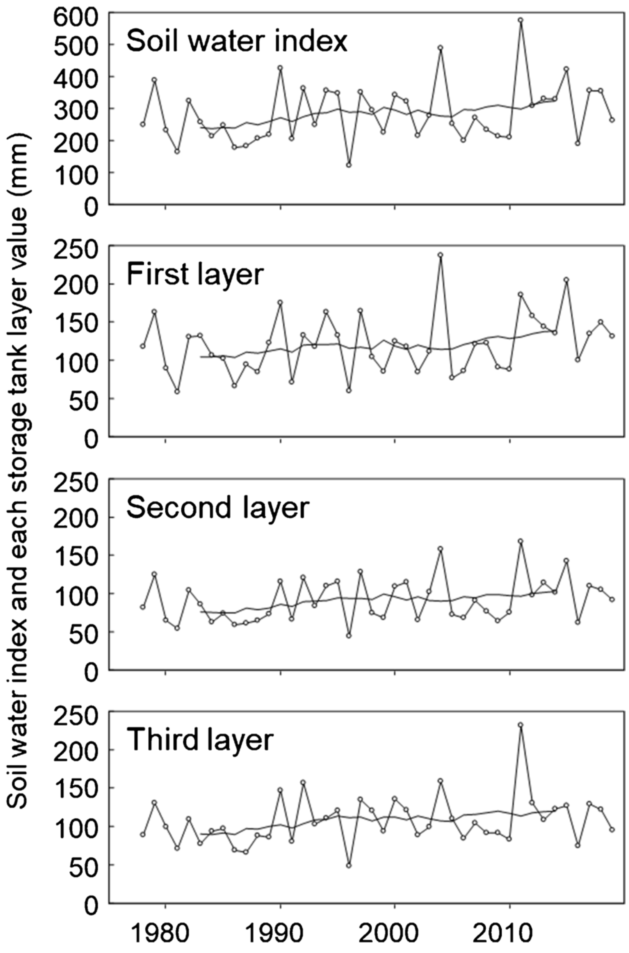


Fig. 7 Temporal fluctuation of annual maximum soil water index and annual maximum each storage tank layer value

Table 2 Result of Mann–Kendall test for annual maximum value

Annual maximum value	*n*	Z_c
Soil water index	42	1.34
First layer	42	1.78
Second layer	42	1.65
Third layer	42	1.60

Table 3 Result of Mann–Kendall test for 11 year running average

11 year running average of annual maximum value	*n*	Z_c
Soil water index	32	5.85*
First layer	32	5.43*
Second layer	32	5.89*
Third layer	32	5.89*

*Significant trends at 5% significance level of two-tailed tests

Discussions

Relationship between the occurrence of landslides and long-term rainfall trends

Landslides occurred when one of the storage tank layer values exceeded the previous maximum value before the landslide (Figs. 5 and 6). A shallow landslide occurred when the value for the first storage tank layer exceeded the previous maximum (Fig. 5), while a deep-seated landslide occurred when the value for the third storage tank layer exceeded the previous maximum (Fig. 6). Therefore, a change in the first (third) storage tank layer value indicates the occurrence of shallow (deep-seated) landslides. This pattern arises from the three-layer tank model, in which the first layer corresponds to changes in groundwater levels in shallow layers, while the second and third layers correspond to changes in groundwater levels in deeper layers (Fig. 2).

In general, shallow landslides that occur above the bottom of a wetting front are triggered by the loss of suction due to high-intensity rainfall of short duration (e.g., Iverson 2000; Ran et al. 2018; Wieczorek 1987). Vallet et al. (2016) applied wavelet analysis to the Séchilienne landslide to examine the relationship between precipitation and displacement of deep-seated landslides, and showed that displacement is not directly related to precipitation but instead to deep-seated groundwater processes. Therefore, our findings regarding the relationships of the three-layer tank model with shallow and deep-seated landslides correspond to previous hydrologic process studies.

Based on these considerations, the long-term trend in the first tank storage layer value indicates the potential risk of shallow landslides, while long-term trends in the second and third tank storage layer values indicate the potential risk of deep-seated landslides. In Miyagawa, shallow and deep-seated landslides occurred at different times (Fig. 1). The 11-year running averages of annual maximum values of the first and third storage tank layers both showed upward trends when the 2004 shallow landslide and 2011 deep-seated landslide occurred (Fig. 7). Long-term trends in rainfall are also reflected in increasing tank storage layer values.

Comparison of our method with other rainfall indexes

Antecedent rainfall is an important initial condition for predicting the occurrence of landslides (e.g., Dahal and Hasegawa 2008; Kim et al. 2021). Empirical methods such as rainfall intensity-duration analysis (Caine 1980;

Guzzetti et al. 2007, 2008; Peres and Cancelliere 2014) require definition of antecedent rainfall, as rainfall data must be separated into individual events. Physical models (e.g., Montgomery & Dietrich 1994; Pack et al. 1998) reproduce the elementary process underlying landslides, and are difficult to apply over long periods because the calculation is intensive. On the other hand, the SWI and three-layer tank model used in this study can readily incorporate the effects of antecedent rainfall, as their computation does not require individual rainfall events to be distinguished and can apply to long periods. Thus, our methods are appropriate for examining the relationship between the occurrence of landslides and long-term rainfall trends.

This study examined the effects of long-term changes in rainfall on landslides. However, the occurrence of landslides is driven by interactions of rainfall with topography, geology, and other inherent factors. Therefore, when examining the relationship between long-term changes in rainfall and landslides in a given region, a physically based model that includes the effects of local inherent factors is effective (e.g., Baum et al. 2010; Crosta and Frattini 2003; Montgomery & Dietrich 1994; Pack et al. 1998; Wu and Sidle 1995). However, our methods examine the relationship between long-term trends in rainfall characteristics and landslides using only rainfall data (Figs. 5, 6, 7). Furthermore, the results of the three-layer tank model corresponded to those from previous studies using hydro-meteorological approaches. These findings indicate that when the effects of long-term changes in rainfall on landslides in a given region are examined over time, or over a wide area with variable rainfall characteristics and inherent factors, the use of a “common scale” for evaluating landslide risk is recommended.

Climate change plays a role in landslide occurrence (e.g., Crozier 2010; Gariano and Guzzetti 2016; Kumari et al. 2021). By combining the method presented here with global climate models and spatial distributions of landslide hazards, such as landslide susceptibility maps (e.g., Abuzied and Alrefaee 2019; Abuzied and Pradhan 2021; Abuzied et al. 2016), the effects of climate change on landslides can be evaluated over a wide area. As our results were based on only a few cases, further studies in other regions are needed. Nevertheless, our results are valid, as the three-layer tank model used to calculate SWI (Okada et al. 2001; Osanai et al 2010) has been applied throughout Japan, and its effectiveness has been verified.

Conclusions

This study used the SWI and a three-layer tank model to investigate the relationship between the occurrence of landslides and long-term changes in rainfall in Miyagawa Village, Mie Prefecture, Japan, where shallow and deep-seated landslides have occurred at different times. The results show that landslides occurred when one of the storage tank layer values exceeded the previous maximum before the landslide. The three-layer tank model can detect the effect of long-term changes in rainfall on landslides, where the first storage tank layer is related to the occurrence of shallow landslides, and the other two layers to the occurrence of deep-seated landslides. Our method is effective for evaluating the relationship between the occurrence of landslides and long-term trends in rainfall.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Tadamichi Sato. The first draft of the manuscript was written by Tadamichi Sato, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Conflict of interests The authors declare no competing interests.

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