New Prediction of Sediment-related Disaster Critical Rainfall Using Meteorological Model WRF

Toshihide SUGIMOTO[1], Toshiyuki SAKAI[2] and Hiroshi MAKINO[1*]

[1] NEWJEC Inc. (2-3-20 Honjo-Higashi, Kita-ku, Osaka 5310074, Japan)
[2] Japan Weather Association (2-3-2 Minamisenba, Chuo-ku, Osaka 5420081, Japan)
*Corresponding author. E-mail: sugimotots@newjec.co.jp

A large number of sediment-related disasters have recently occurred in Japan due to record heavy rains exceeding 1,000 mm in cumulative rainfall and concentrated heavy rains equivalent to an hourly rainfall of 100 mm. These heavy rainfall events are likely to increase in frequency because of the impact of an increase in water vapor content caused by rising temperatures associated with global warming. Today, sediment disaster alert information is made public to ready people for sediment disasters. However, since calculation is based on the actually measured rainfall, announcement is generally made just before a sediment disaster occurs. There is no sufficient time left before people can leave their homes for shelter. This is one of the major problems related to the current system of sediment disaster alert information announcement. In this research, we conducted rainfall prediction based on rainfall simulation that uses numerical calculation meteorological model Weather Research and Forecasting (WRF) as a new evaluation technique that predicts a rainfall event likely to cause a sediment disaster at an early stage or two to three days in advance and made a comparative review of the simulation results with recent rainfall events that actually caused sediment disasters. Consequently the research results revealed that the technique is precise enough to clarify areas where orographic rainfall likely to cause sediment disasters will occur and suggests it may be able to provide the data qualified as sediment disaster alert information at an early stage before actual rainfall.

Key words: meteorological model, WRF, orographic rainfall, rainfall prediction, sediment-related disaster

1. Background and Purpose

A large-scale deep-seated landslide in the Kii Peninsula in 2011, a debris flow disaster in Nashizawa mountain stream, Nagiso town, in 2014, and a debris flow disaster in Serizawa area, Nikko city, in 2015, are only some of a large number of sediment-related disasters that have recently occurred in Japan due to record heavy rains exceeding 1,000 mm in cumulative rainfall or concentrated heavy rains equivalent to an hourly rainfall of 100 mm attributable to long-staying fronts that or highly powerful typhoons. Heavy rain events that trigger those sediment disasters tend to increase in frequency because of the impact of an increase in water vapor content caused by rising temperatures associated with global warming [Fujibe, 2011].

Currently, sediment disaster alert information is announced by the corresponding municipality to make citizens ready for frequent occurrence of sediment disasters. However, the present system of sediment disaster alert information has a few problems. For example, when it is announced, the guideline announcement timing is the point in time when the snake curve based on the rainfall and soil water index exceeds the critical line. Since calculation is done based on the measured rainfall, announcement is generally made just before occurrence of the actual sediment disaster. Therefore, there is no sufficient time left before people can evacuate. In recent years, precision of forecasting a few hours ahead is improving as a result of development of XRAIN and polarimetric radar. These advances, however, are not good enough to drastically improve the prediction precision of sediment disasters based on the snake curve.

Therefore, it is considered effective to evaluate and organize sediment disaster occurrence risk in relation to rainfall factors and meteorological conditions by the

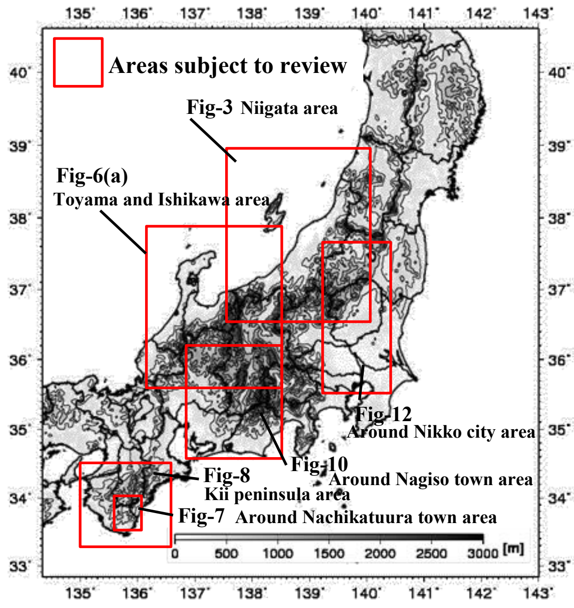


Fig.1 Areas for meteorological model calculation

topography and area in advance and judge the condition in combination with existing sediment disaster alert information [Sugimoto, 2017].

As Japan has many mountainous areas, there has been much research conducted from the meteorological and hydrological viewpoints about the relationship between rainfall and topography. It was eventually clarified that the topography has a big impact on rainfall, with a relatively long time scale in terms of daily or total rainfall or orographic rainfall phenomena where heavy rainfall stays for a long time on a windward slope or a high altitude area [Ninomiya,1977] or [Oki,1990] or [Kurihara,2009].

In this research, we conducted rainfall simulation using numerical calculation meteorological model Weather Research and Forecasting (WRF) to clarify areas where orographic rainfall will occur with respect to wind direction and velocity, compared the simulation results with the actual rainfall events that caused sediment disasters in recent years and the areas where rainfall growth occurred and verified the validity of WRF simulation for the purpose of developing a new evaluation technique that predicts rainfall likely to cause sediment disasters at an early stage, or two to three days in advance. The authors also discussed an early prediction technique of orographic rainfall that may cause sediment disasters based on the simulation results.

2. About Idealized Simulation

Idealized simulation with wind direction and velocity kept constant was conducted using WRF to study the relationship between wind direction and velocity and an increase in rainfall precipitation by the region. The calculation areas are set to longitude of 134°30′ to 143° east and latitude of 33° to 40°30′ north as shown in **Fig. 1**, and the calculation setting conditions shown in **Table 1** are used. For the initial conditions, the values obtained by Wajima Aerological Observation Station immediately before the occurrence of the heavy Niigata/Fukushima heavy rainfall in July 2011 are uniformly set to the horizontal grids in the calculation area as a vertical profile (**Fig. 2**).The interval of horizontal grids is set to 2 km so that the training that brings heavy rainfall and orographic rainfall can be represented.

Calculations were made using the assumed wind direction and velocity conditions as follows: 16 directions and 15 km/s in the rainy season and 30 m/s in the typhoon season. Since westerly and southerly winds prevail during the rainy season and typhoon season, respectively, the wind velocity measured by the Wajima and Shionomisaki Aerological Observation Station, respectively, is assumed.

3. Verification of Calculation Results

3.1 Comparison of rainfall distribution

Table 1 Calculation setting conditions

Calculation conditions	Settings
Interval of horizontal grids	2km
No. of horizontal grids	East-west 375 x north-south 425
No. of vertical layers	50 layers
Calculation integration time	4 hours
Calculation time step	10 sec
Lateral border condition	Periodic boundary
Distribution of temperature and humidity	Temperature/humidity at the Wajima Aerological Observation Station (Observation data at 9:00 am, July 28, 2012)
Soil water content	0.30 (m3/m3) uniform
Soil temperature	290 K: uniform
Wind direction	16 cases (= 16 directions)
Wind velocity	2 cases (1)15 m/s (stationary front assumed) (2)30 m/s (typhoon rainfall assumed)

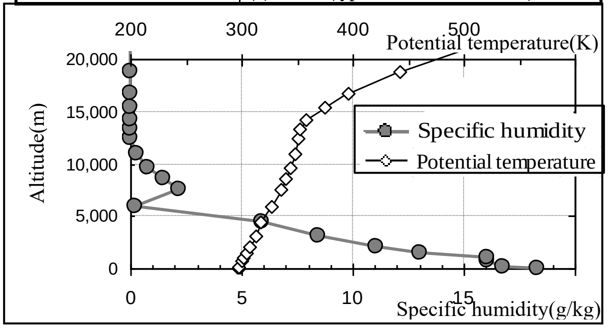
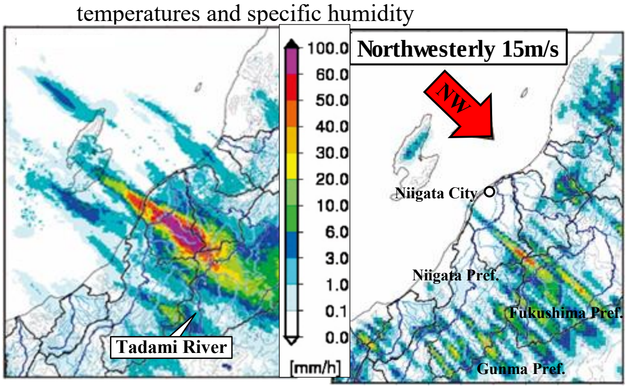


Fig. 2 Vertical profile of initial conditions of temperatures and specific humidity



(a) Actual rainfall at 11:00, July 29, 2011

(b) Simulation results

Fig. 3 Comparison of simulation results

The results of idealized simulation were compared with the rainfall condition of the Meteorological Agency's analyzed rainfall (hourly integrated values obtained by correcting the synthesized data of MLIT and MA radar data with the surface rainfall) to verify the precision of the simulation. The rainfall distribution of the Niigata and Fukushima heavy rainfall (11:00, July 29, 2011) that caused many sediment disasters because of the training is shown in **Fig. 3(a)**, while the rainfall distribution of the idealized simulation for the same area (under the condition of northwesterly wind of 15 m/s) is shown in **Fig. 3(b)**.The condition of rain area development is similar to the radar rainfall observation results. It is shown that developed rainy clouds existed near the prefectural border between Niigata and Fukushima or with Gunma particular, rain clouds stretching from around Niigata city to the Tadami

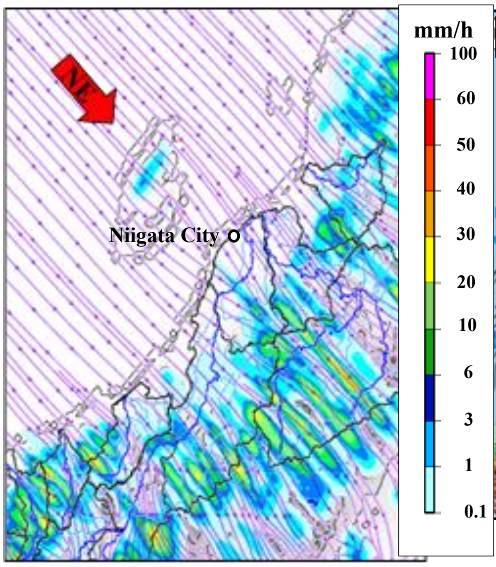


Fig. 4 Flow line graphs of surface wind
(wind direction: northwesterly; wind velocity: 15 m/s)

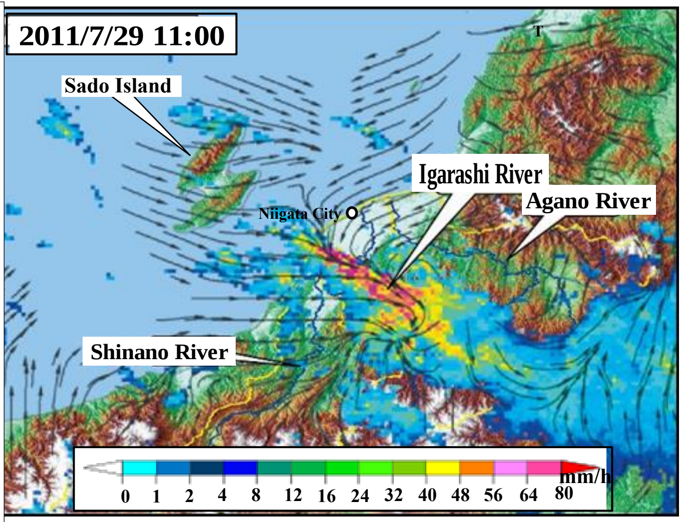
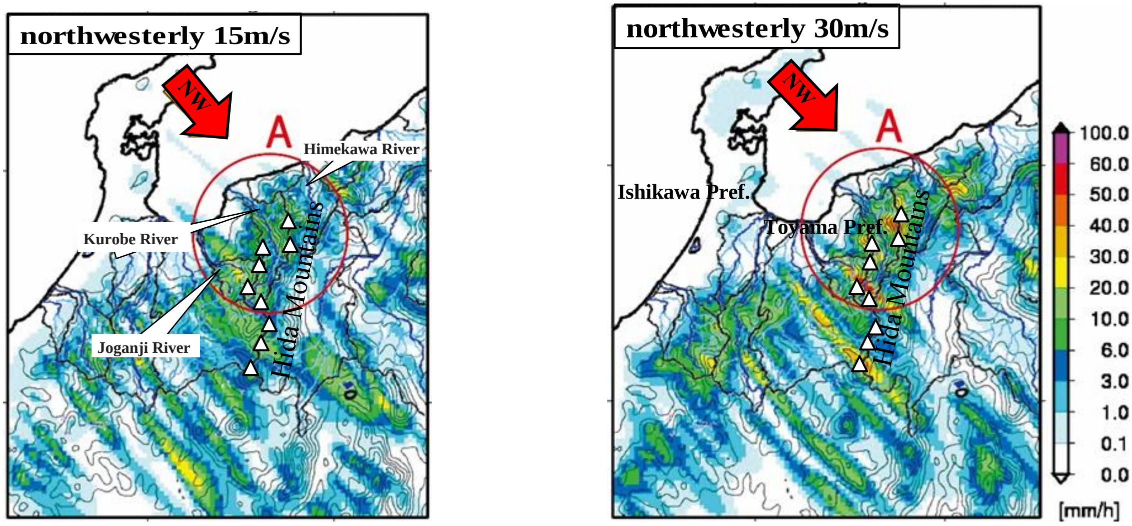
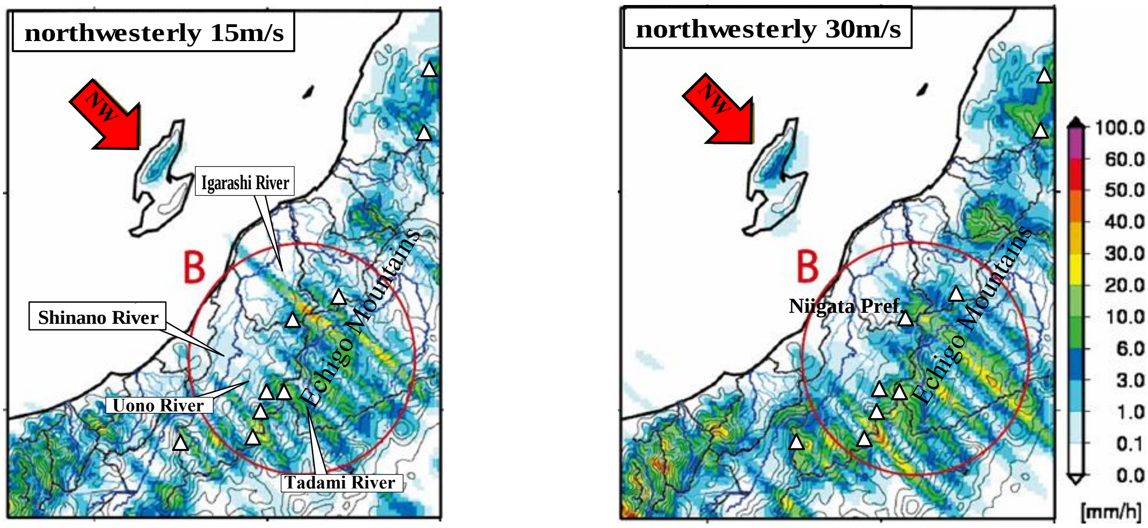


Fig. 5 Status of wind settling on the ground
(11:00, July 29, 2011)



(a) Toyama and Ishikawa area: 15 m/s in wind velocity

(b) Toyama and Ishikawa area: 30 m/s in wind velocity



(c) Niigata area: 15 m/s in wind velocity

(d) Niigata area: 30 m/s in wind velocity

Fig. 6 Comparison of rainfall area between wind velocity of 15 m/s and 30 m/s

River basin in Fukushima prefecture grew bigger and a localized strong rainy area came about near the mountainous area.

3.2 Horizontal convergence of wind by topography

Flow line graphs were prepared from the simulation results to review the condition of wind convergence by topography to study the relationship with topography. The flow line graphs of surface wind are shown in **Fig 4,** and the wind direction vectors on the ground analyzed from AMeDAS data at the peak time of the Niigata and Fukushima heavy rainfall in July 2011 (11:00, 29th) overlapped with the MA radar image are shown in **Fig. 5.** The warm and wet air currents in the horizontal direction converged from the coastal area, leeward of the Sado Island, to the flat area and flowed in along the valley of the Igarashi River. The wind then converged along the mountain slopes as it went upstream, and ascending air currents were intensified along the way to finally cause torrential rainfall. This is the estimated mechanism of heavy rainfall. The figures clearly show converging winds at the peak time of the torrential rainfall.

This actual wind convergence that occurred during the torrential rain was confirmed over the plains behind the Sado Island and along the valley of the Igarashi River as in the case of the simulation results. As explained earlier, the simulation is based on a condition where the vertical distribution of potential temperature and specific humidity is evenly set in the horizontal direction as the initial conditions as shown in **Fig. 2**. It is therefore difficult to make the simulation match the actual phenomena where temperature and humidity complicatedly change in a three-dimensional manner. The simulation, however, is still similar to the actual rainfall event when it comes to the condition of rainfall area growth from plains to mountains. The idealized simulation results are considered to be sufficiently precise in clarifying areas of orographic rainfall growth by the wind direction.

3.3 Augmentation effect of rainfall in mountains

The influence of the rainfall amplification effect of topographic conditions such as wind velocity conditions or altitude in mountains was discussed using the idealized simulation results.

Fig. 6(a)(b) show the rainfall distribution based on the idealized simulation in the Hida Mountain Range with high peaks of over 3,000 m in height under the condition of northwesterly wind of 15 m/s and 30 m/s in wind velocity, respectively. **Fig. 6(c)(d)** show the rainfall distribution in the Echigo Mountain Range with 1,500 to 2,000 m high mountains under the same conditions. For the Kurobe River, Joganji River and Hime River characterized by rapid torrents originated from 3,000 m high class mountains as shown in **A of Fig. 6(a)(b)**, when the wind velocity rises from 15 m/s to 30 m/s, the hourly rainfall in the river basin increases from 6 mm/h to 13 mm/h for the Kurobe River and 3 mm/h to 9 mm/h for the Hime River. It suggests the orographic rainfall more than doubled in precipitation because of the influence of steep mountains, and heavy rainfall is conspicuous at high altitudes. For the basins of the midstream reaches of the Shinano River, Uono River, and Tadami River shown in **B of Fig. 6(c)(d)**, orographic rainfall is developed because of the influence of the Echigo Mountain Range (1,500 to 2,000 m high mountains) under the condition of 15 m/s in wind velocity. In particular, a training is grown in the plain areas to the mountainous areas along the Ikarashi River in the lower reaches of the Shinano River. On the other hand, rain clouds move over the mountains to cause a lot of rainfall in the Tone River and Tadami River basins under the condition of 30 m/s in wind velocity. For 3,000 m class mountains, when the wind velocity increases, wet currents slide up the slope to strengthen the ascending air current and cause heavy rainfall. For 2,000 m high class mountains, the air current rode over the mountains and moved downwind. These observations indicate the height of mountains affects the location of rainfall or amplification of rainfall.

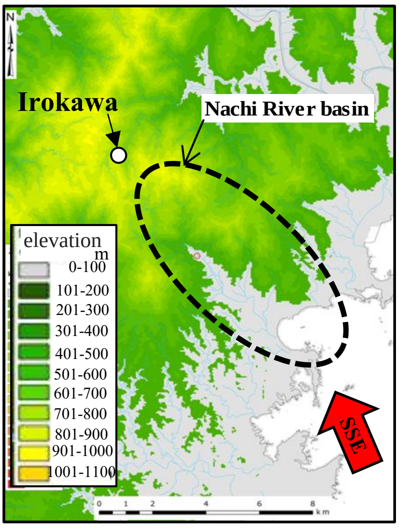


Fig. 7 Topographic map of the Nachi River basin

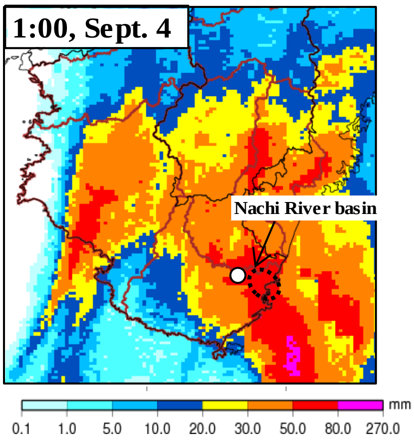


Fig. 8 Analyzed rainfall distribution map MSM

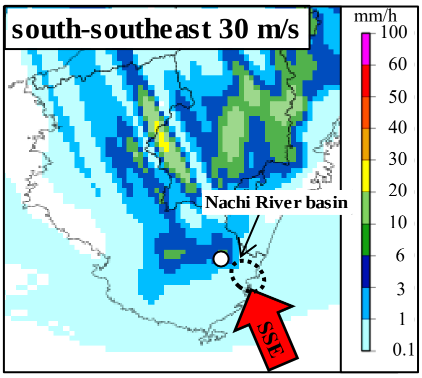


Fig. 9 WRF (south-southeasterly and 30 m/s)

4. Comparison between Calculation Results and Actual Rainfall Event That Caused Sediment-related Disasters

Three heavy rainfall disasters were selected: (1) heavy rainfall by Typhoon No. 12 that moved slow and caused large-scale deep-seated landslide in the Kii Peninsula in September 2011, (2) concentrated heavy rainfall due to a rainy season front activated by the approaching Typhoon No. 8 that caused a sediment disaster in Nashizawa stream, Nagiso town, Nagano prefecture, in July 2014, and (3) heavy rainfall by the training formed by the influence of Typhoon No. 18 and others that caused a sediment disaster in Serizawa area, Nikko city, Tochigi prefecture, in September 2015, the simulation results were compared with the aerological observation data and analyzed hyetographs of actual rainfall, and the validity of the orographic rainfall simulation was reviewed.

4.1 Sediment disaster in Nachikatsuura town, Wakayama prefecture, in September 2011

Typhoon No. 12 moved at a slow speed of about 10 km/h, landed the eastern part of Kochi prefecture, and became an extratropical cyclone in the Japan Sea in September 2011. Rain clouds surrounding this typhoon or inflow of wet air brought heavy rain with a total precipitation of 1,180.5 mm from 1:00 on Aug. 31 to 2:00 on Sep. 5 at the Irokawa Observation Station in the southern part of Wakayama prefecture. Very heavy rainfall with an hourly precipitation of 50 mm was observed at 1:00 on the 4th. A debris flow occurred in the basin of the Nachi River from around 2:00 to 3:00 on the 4th. The damage done to Nachikatsuura town included 28 dead and many destroyed houses.

At 0:00, September 4, which is about the peak of the rainfall when the debris flow occurred, the initial value of the meso numerical prediction model MSM (grid interval of 5 km) gives 500 hPa, south-southwesterly wind, 20.4 m/s in wind velocity, 850 hPa, south-southeasterly wind, and 26.5 m/s. **Fig. 8** is the analyzed rainfall distribution map at the peak time of the heavy rainfall at the Irokawa Observation Station (1:00, Sept. 4) by Typhoon No. 12, while **Fig. 9** is the result of idealized simulation under the condition of southeasterly wind of 30 m/s in velocity. It shows a strong rain area in the basin of the Nachi River in the southern part of Wakayama prefecture.

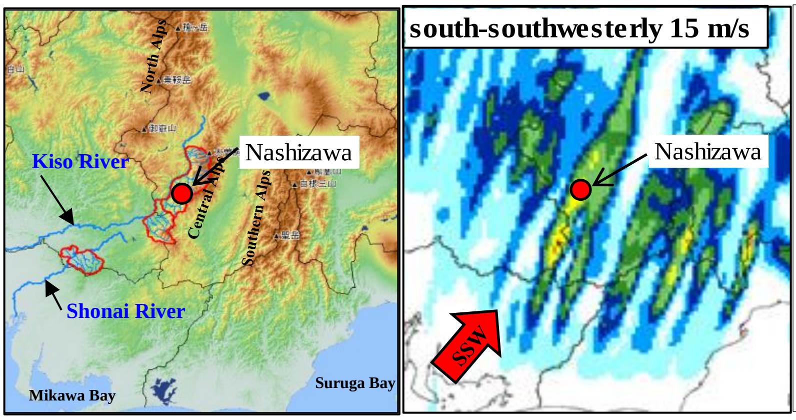


Fig. 10 WRF simulation (south-southwesterly wind of 15 m/s in velocity) and topographic map

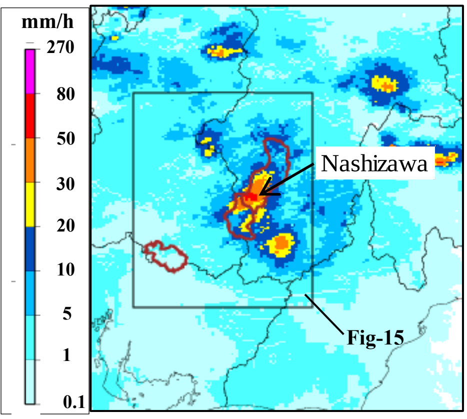


Fig. 11 Analyzed rainfall distribution map MSM (18:00, July 9)

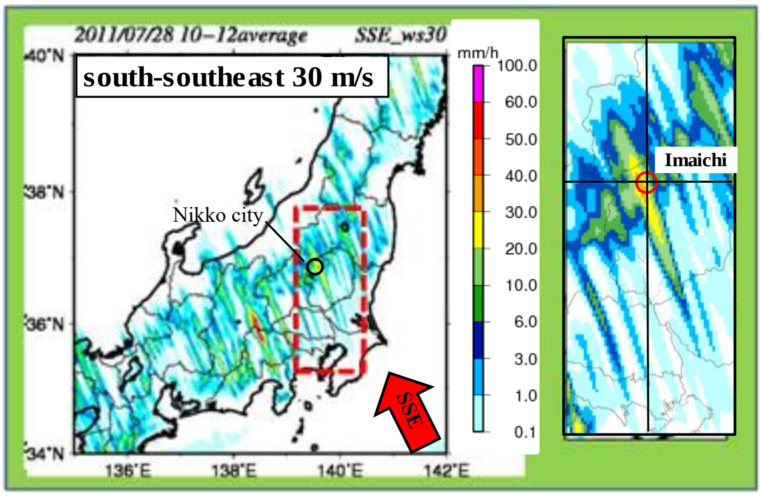


Fig. 12 WRF simulation result and enlarged map of the area around Nikko city

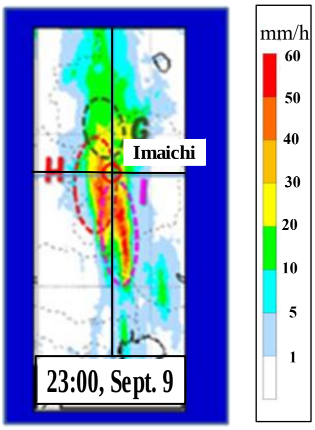


Fig. 13 Heavy rainfall in Kanto and Tohoku in September 2015
Analyzed rainfall distribution map
(23:00, September 9, 2015)

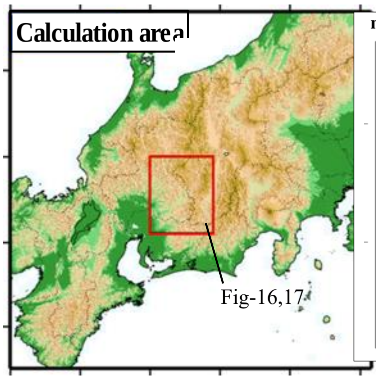


Fig. 14 Calculation area diagram

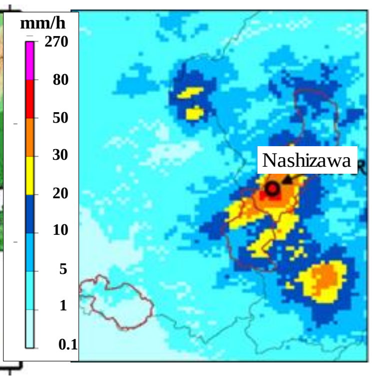


Fig. 15 Analyzed rainfall distribution map

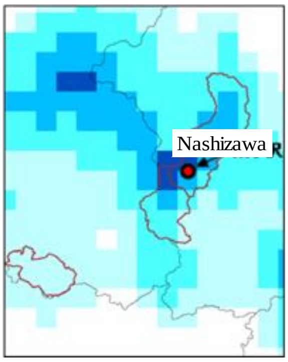


Fig. 16 MSM prediction (6 hours in advance)

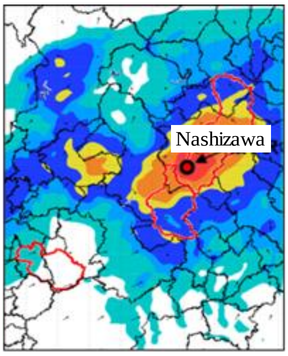
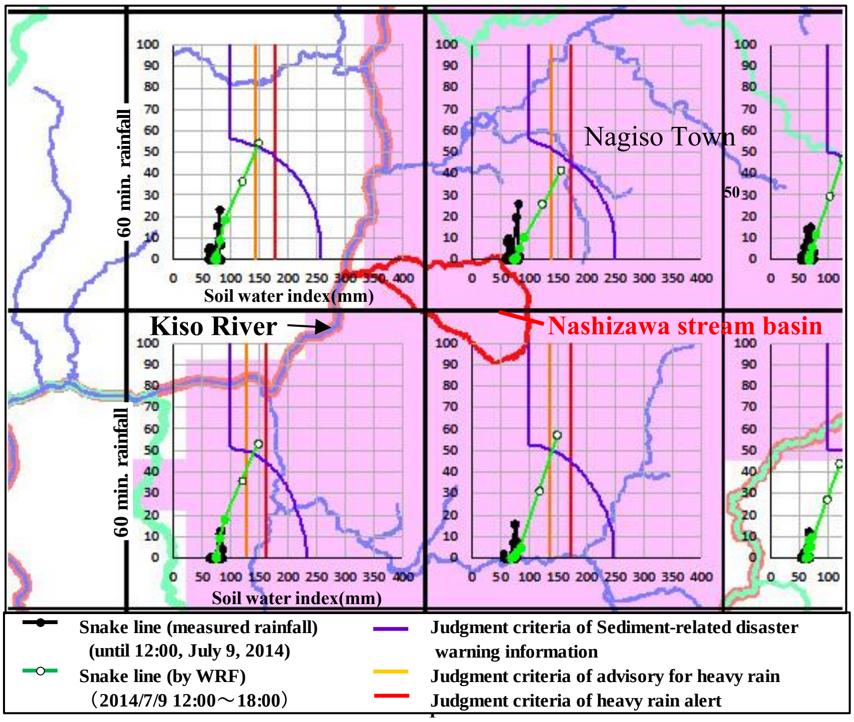


Fig. 17 WRF prediction diagram (6 hours in advance)

4.2 Debris flow disaster in Nashizawa stream, Nagiso town, Nagano prefecture, in July 2014

Warm and wet air associated with Typhoon No. 8 flowed into the rainy season front on July 9, 2014, and an hourly maximum rainfall of 55 mm (18:00, 9th) and cumulative rainfall of 119 mm (18:00, 8th, to 21:00, 9th) were recorded at the Nagiso Observation Station. A debris flow occurred in Nashizawa stream, Nagiso town, at 17:40 on the 9th, and the debris flow overflowing from the channel works damaged many houses, the JR Chuo Line railroad track, and national highway Route 19 and caused death of one person (south-southeasterly wind and 30 m/s of wind velocity).



Based on the website of the Nagano Prefectural River Sabo Information Station

(5 km x 5 km mesh)

Fig. 18 Snake line by WRF prediction six hours before the occurrence of Nagiso disaster

A rainfall observation station near Nashizawa stream, where the debris flow occurred, measured a peak rainfall of about 50 to 80 mm at around 17:00 to 18:00 on the 9th. At Shionomisaki, where one of the nearest aerological observation stations is located, wet and warm air with a relative humidity of 91% and a temperature of 18.2˚C started to enter in the lower layers (850 hPa and at an altitude of about 1,500 m) at a speed of 11 to 12 m/s from the southwest to south-southwest at around 9:00, July 9, while a cold current (-6.7˚C) at around 9:00, July 9, to become strong southwesterly wind at a velocity of 9 to 23 m/s in the upper layers (500 hPa at an altitude of about 5,700 m).

Fig. 10 shows the result of south-southwesterly wind simulation with a velocity of 15 m/s, while **Fig. 11** shows an analyzed rainfall distribution map (18:00, July 9).

As a result of the simulation, orographic rainfall developed because of south-southwesterly wind, and localized strong rain area occurred in Nagiso town, the same area where rain actually fell (18:00, July 9).

4.3 Debris flow disaster at Serizawa area, Nikko city,Tochigi Prefecture,in September 2015

In comparison with the Kanto/Tohoku heavy rainfall that caused a debris flow disaster in Serizawa area, Nikko city, a training occurred at exactly the same location as suggested by WRF simulation result (Fig. 12) in the case of 30 m/s south-southeasterly wind. Good agreement with the actual rainfall condition is achieved.

5. Advance Forecast of Heavy Rainfall in Meteorological Model WRF Simulation

For the early stage prediction technique of orographic rainfall that triggers sediment disasters, a heavy rainfall event that caused a debris low disaster in Nashizawa stream, Nagiso town, is taken as a subject of review. To be specific, WRF-based prediction simulation using MA’s meso model MSM for certain hours before the peak rainfall time of Typhoon 8/rainy season front heavy rainfall in July 2015 was conducted. Then the advance rainfall prediction results were compared with the sediment disaster alert information using the rainfall short-time forecast.

The advance heavy rainfall prediction calculation using WRF is based on a one-way nesting with a 5 km grid for the area outside the calculated area map shown in **Fig. 14** and a 1 km grid for the internal area. Assuming 18:00, July 9, which is the peak rainfall time is the target time of calculation, calculations were made in four ways for 34 hours, 24 hours, 12 hours and 6 hours before the said peak time. The results indicate that the prediction with 6 hours before the disaster occurrence as the initial time gave a rainfall area very similar to an actual strong rainfall event that exceeded 50 mm in the Nashizawa stream basin. **Fig. 15** is the analyzed rainfall distribution map at 18:00, July 9, **Fig. 16** the MSM-based prediction for 6 hours in advance, and **Fig. 17** the WRF-based prediction 6 hours in advance. **Fig. 18** shows the judgment result of sediment disaster alert information based on the WRF six-hour advance prediction. According to the rainfall short-time forecast 2 hours in advance, all the prediction snake lines face downward, which means the predicted rainfall is too small to realize advance prediction of rainfall that exceeds the judgment criteria. However, WRF-based 6-hour ahead prediction successfully predicted the result exceeding the judgment criteria of sediment disaster alert information.

6. Discussion and Results

Factors that bring heavy rainfall include typhoon, rainy front, and combined actions of both of them. Topographic characteristics are deeply related to how strong rainfall is likely to occur in which area depending on the factor. This research used three heavy rainfall disasters: the Kii Peninsula debris flow disaster in 2011, the Nashizawa debris flow disaster in 2014, and the Nikko Serizawa area debris flow disaster in 2015 to verify the prediction technique proposed in this paper. The condition of rain area growth suggested by the rainfall simulation results using numerical calculation meteorological model WRF by the wind direction and velocity turned out to be similar to the actual rainfall condition. The technique is therefore indicated to be precise enough to clarify areas where orographic rainfall that is likely to cause sediment disaster grows. In addition, when WRF-based rainfall prediction value for the Nashizawa debris flow disaster, Nagiso town, is applied to the snake curve, it is found that it is possible to make advance analysis of rainfall likely to cause a sediment disaster.

As discussed above, when real-time orographic rainfall prediction using meteorological prediction data such as WRF-based global spectral model (GSM: 20 km mesh, 264 hours ahead prediction) and meso spectral model (MSM: 5 km mesh and 39 hours ahead prediction) is conducted and its prediction value is applied to the measured rainfall that caused large-scale sediment disasters such as river blockage or to snake curves, it may help early warning of the type of rainfall that may cause a sediment disaster.

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