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# Anticipated maximum scale precipitation for calculating the worst-case floods

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## ABSTRACT

Against increasing number of unprecedented heavy rains and typhoons reflecting climate change, the Japanese Government decided saving life as the top priority considering a 'worst-case' scenario. Accordingly, the Flood Risk Management Act was amended in 2015 to use the anticipated maximum scale precipitation (AMSP) for flood inundation calculation. In order to estimate the AMSP, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) chose historical maximum areal precipitation in the form of duration–area–depth (DAD) curves rather than climate change projections' dataset d4PDF. In this paper, policy development and detailed estimation procedures for the AMSP were reviewed and discussed. It was concluded that the current climate change projections are still not accurate enough to be used as the basis for real local operations, while long accumulated ground observations and ground-based radars are available in good quality all over Japan. But at the same time, historical maximum should always be updated as past records are renewed. Also, regional partitioning should not be done at too coarse of scale for proper regionalization of DAD. Such strategy would serve as a useful reference for other nations.

**Key words:** Anticipated maximum scale precipitation (AMSP), d4PDF, Flood hazard maps, Radar-AMeDAS precipitation, Regionalization of DAD, Worst-case scenario

## HIGHLIGHTS

- To produce the flood hazard maps under the worst-case scenario, the anticipated maximum scale precipitation (AMSP) is used.
- The regionalized worst-case DAD, that is, the DAD estimated by the areal maximum precipitation observed in the history in a climatologically uniform region, is used to estimate the AMSP in any basin in the region.
- The ground observations by JMA since 1957 and the Radar-AMeDAS analyzed datasets since 1988 are considered more reliable than the d4PDF dataset assembled by climatological projections using GCMs and RCMs to be used for calculating inundation for flood hazard maps for local practice all over Japan.
- The areal maximum precipitation prescribed for a climatologically uniform region is subject to renewal in the future. Therefore, periodical updating of the AMSP is necessary. At the same time, reflection of climatological projections for the areal maximum and geographical partitioning of climatologically uniform regions should be considered.
- Ground observations and model-based climatological projections need to go hand-in-hand.

## INTRODUCTION

Climate change influences in Japan have been appearing most significantly in the form of intensification of hydro-met hazards such as heavy rains and typhoons causing serious floods, landslides and debris flows every year especially since around the turn of the century. Responding to such serious hazards, the Japanese Government has been taking a new strategy to overcome the situation. It is to anticipate the worst-case scenario and to put a highest priority on saving lives, the same strategy already introduced for earthquakes and tsunamis after the Great East Japan Earthquake and Tsunami (GEJET) on 3 November 2011. As the situation is urgent, early warning and evacuation are emphasized as the necessary action for society to take to save life while construction of durable infrastructure progresses over a longer time span.

For issuing early warning, hydro-meteorological advancement in observation and forecasting technologies has been making great strides. Also, advancement in dissemination of information through TV, radio, smart phone, etc., is highly effective such as introducing new warning messages: 'Heavy rains that have never been experienced before are coming. Take an immediate action to protect your life'.

In order to support evacuation and to guide proper land use management, reliable hazard maps are indispensable. To facilitate this, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) decided to revise hazard maps to reflect the worst-case scenario of flood-related hazards including landslides, debris flows, tsunamis, storm surges, etc. They indicate spatial extent and magnitude of floods and associated evacuation centers in detail local maps that show individual houses for all areas of Japan.

As the basis of such hazard maps, hydrological analyses for flood inundation maps were made using worst-case heavy rains called the anticipated maximum scale precipitation (AMSP). This precipitation was estimated using the historical records rather than climate change projections using advanced GCMs and RCMs. This is because the model simulation results are not yet detailed enough to calculate local flood inundation maps. This is quite an important decision and needs continued scientific assessment.

This paper reviews and discusses the soundness of the concept of the AMSP and the engineering procedure to use the AMSP for calculating anticipated inundation for the worst-case flood hazard maps. The review provides some useful implication for other nations to produce their flood hazard maps. Before coming into detail policy and technology review and discussion, the background situation of recent flood-related disasters, the hydrological models used and the current situation of hazard maps in Japan are reviewed.

## Recent flood-related disasters in Japan

In the past few decades, Japan has been experiencing increasingly extreme hydro-meteorological hazards and devastating flood-related disasters every year. Just one example from each year in the current decade illustrates the extraordinary development of flood-related disasters in Japan.

In September 2011, the Kii Peninsula Water Disaster triggered by Typhoon 12 brought heavy rain, over 2,000 mm in part of the peninsula. The number of fatalities and missing people reached 98 (MLIT, 2014a). It was only 6 months after the GEJET on 11 March 2011. In July 2012 and July 2017, twice, Northern Kyushu Torrential Rain Disasters occurred both during Baiu season, resulting in dead and missing of 32 and 42, respectively (JSCE, 2013; Cabinet Office, 2018). In October 2013, the Izu-Oshima Island was hit by Typhoon 16 and the dead and missing reached 43 people (Yamamoto *et al.*, 2014). In August 2014, Hiroshima Prefecture was hit by stationary linear rain bands formed by back-building phenomena which induced large-scale landslides and killed 77 people, the worst sedimentary disaster in Japan since 1983 July Heavy Rain hit West Shimane (JSCE, 2015).

In September 2015, Kanto and Northeast Japan Torrential Rain occurred. The stationary linear rain band was formed in Northern Kanto and caused the Kinu River flood at Josoh City, Ibaraki Prefecture. The total death toll was 8 (Cabinet Office, 2016). On 10 August 2016, Typhoon 10, the first typhoon ever to land on Northeastern Japan (first in Iwate Prefecture and later Hokkaido) directly from the Pacific Ocean that caused rare floods in Hokkaido and killed 29 people including the missing (FDMA, 2017). In July 2018, the West Japan Heavy Rain caused serious flood inundation, landslides and debris flows resulting in the dead and missing of 232 centered in Hiroshima and Okayama Prefectures (MLIT, 2018). This was the largest death toll since 2004, the year when the record breaking ten typhoons and two torrential rains hit Japan from June to October resulting in 232 deaths in West Japan, Tohoku and Hokkaido (MLIT, 2004) or, by a single event, since 1982 July torrential rain followed by Typhoon 10 hit West Japan resulting 439 death and missing (JMA website on 1982 July torrential rain and Typhoon 10).

In October 2019 again, Super Typhoon 19 (Hagibis) (JMA named East Japan Typhoon) hit Central to Eastern Japan causing serious floods and landslides by record-breaking rainfalls in large areas resulting dike breaches at 142 sites in 71 rivers and the dead and missing 107 (JSCE, 2020). In July 2020, the Baiu front stagnated over Japan and brought much rain and caused floods and landslides, first in Kyushu, especially Kumamoto Prefecture, then Chugoku and Tohoku regions and as a total 84 people died and 2 missing (Cabinet Office, 2021).

Thus, it is obvious that some fundamental actions should be taken for flood-related disaster management.

## Hydrological models to simulate discharge and flood inundation

The precipitation-runoff model used for the design and operation of public infrastructure is the 'Storage Function Model (SFM)' originally proposed by Toshiaki Kimura in the 1950s (Kimura, 1961) at the Public Works Research Institute (PWRI). It is a physically based lumped model and has been nearly exclusively used in PWRI and consulting firms for designing public infrastructure for many years and accumulated a large variety of application cases in different scales, seasons, landcover, topography, geology, landscapes, storm types, etc. (Kimura, 1978). But it has never been formally published in an academic journal. The model was never officially designated as the only model to be used in infrastructure design, either. But it was referred to as one of the recommended models in the Ministry of Construction (former MLIT) publication 'River and Sabo Works Engineering Standard', first edition, in 1984 (Ministry of Construction, 1984) that is still in use with some updates every decade.

For inundation simulation, there is no such special model. Following the determination of AMSP, a calculation manual of inundation simulation to identify the anticipated flood inundation areas was issued in 2015 (MLIT, 2015d) which was the 4th revision of the original manual issued in 2001. Newly added were methods to calculate inundation duration, houses collapse areas, etc. In 2016, its simplified version was also issued for small- to medium-scale rivers (MLIT, 2016).

To get an inundation map for current flood hazard maps, the worst-case dike breach in some selected points are produced with 25 m resolution (suggested) and the resultant maps are overlaid to get the one that envelops all the worst cases (MLIT, 2015d).

## Flood hazard maps

The first flood hazard map was produced in Japan by Masahiko Oya in the form of his work 'Water-disaster morphology classification map of Nobi Plain, Kiso River Basin' in 1956 (Oya, 1956). This map was basically a geomorphological map showing the classified topography and soil types of the area affected by repetitive floods in the past. This Nobi Plain geomorphological map was proven useful to indicate the area affected by the flood of the Ise Bay Typhoon in 1959 which brought the severest storm surge and floods in modern Japanese history. Since then, the water-disaster morphology classification maps have been produced in many river basins in Japan and eventually in various other countries (NIED website).

It was on the occasion of flooding in the Abukuma River in August 1998 when the first investigation was made to identify the effect of availability of flood hazard maps on the citizens' evacuation behavior in Koriyama City, Fukushima Prefecture by Katada (1999). He found that the people who had seen the flood hazard map before the flood had evacuated, on average, about an hour earlier than the people who had not.

With this evidence, MLIT moved to seriously consider the use of flood hazard maps in disaster management operations and the government made the amendment to the Flood Risk Management Act in June 2001 to make use of flood hazard maps compulsory in so-called flood forecasting rivers (298 minister designated rivers and 128 prefectural governor designated rivers that have large basins and potential to cause serious losses to national economy). In 2005, this was extended to so-called water level warning rivers (150 minister designated rivers and 1,491 prefectural governor designated rivers that have, in addition to flood forecasting rivers, potential to cause serious losses to national economy and assigned to issue the water level warning when river has reached to the inundation risk level) (MLIT website on flood forecasting rivers).

The specific floods to be considered for calculating inundation areas for hazard maps in each river basin were specified in the 'Basic Plan for Implementation of Construction Works' of each basin before 1997 according to the River Law of 1964. After 1997, the River Law of 1997 changed the 'Basic Plan' above into the 'Basic River Management Policy'. Incidentally, the difference between the 1964 and the 1997 river laws was in their decision-making process with or without inviting local stakeholders' requests before deciding the basic plan. Also, in the latter, it was clearly stated that the plan should be completed within 20–30 years and publicized in more detail in each river basin.

### Issuance of hazard maps

Using the AMSP, discharge simulation is conducted followed by inundation simulation along rivers and lakes. In order to make hazard maps from inundation maps that have inundation area and depth information, evacuation centers should be added by cities, towns and villages in consultation with local communities. Then finally, the hazard maps are issued by those local governments.

By September 2018, the hazard maps under the 2001 amendment of Flood Risk Management Act were completed in 98% (1,316/1,340) of cities, towns and villages in Japan. Now, following the amendment of flood risk management act of May 2015, the revision of the maps using the AMSP is taking place. As of September 2018, only 20% (268/1,340) of cities, towns and villages were completed (MLIT website on flood hazard maps). Note that this completion includes identification of evacuation centers for each hazard for each local community.

## REVIEW

### Strategies to address a new stage of flood-related disasters

#### Preparation for the worst-case scenario

Intensification of flood-related hazards as stated in the previous section is believed in general to be associated with progression of climate change. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japanese Government considered that the nation came into a new stage of socio-geohazards relationships and established an informal committee on 'Disaster prevention and mitigation responding to the new stage' in October 2014 which submitted a report in January 2015 (MLIT, 2015a).

The basic strategy of the report 'Disaster prevention and mitigation responding to the new stage' was to specify that the nation had to prepare against the worst-case hazards, similar to earthquakes and tsunamis management already decided after the GEJET. The policy adopted for managing tsunami hazards was the L1 and L2 approach, where L1 stands for the level 1 tsunami as frequent as about once every 100 years for which all life, property and livelihood should be protected and L2, the level 2 tsunami as rare as about once every 1,000 years for which at least life should be saved (Central Disaster Management Council, 2011; MLIT, 2012).

The report recommendation was, similar to L2, to anticipate the maximum scale floods and prepare life-saving actions. It pointed out that since structural means cannot protect all life and property against the worst-case hazards, it is necessary to put highest priority to protect human lives and avoid the catastrophic losses even in the case where great property damages are inevitable. In practice, a standard was proposed to consider the maximum scale precipitation and avoid facing unanticipated events.

In order to implement such a policy against hydro-met hazards, the Government decided to revise the hazard maps throughout Japan, employing a new design precipitation standard called the 'Anticipated Maximum Scale Precipitation (AMSP)' and, in accordance, the 'Partial amendments to Flood Risk Management Act and others' was promulgated on 20 May 2015, where others include the Sewerage Act (MLIT website on Flood Risk Management Act).

### Base data for estimating the AMSP

In the amendment, it was stated that the flood inundation maps should be drawn using the AMSP that conform with the criteria given by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). These criteria were presented by MLIT prior to enforcement of the act in the November 2015 guideline 'Design method for anticipated maximum scale precipitation to produce anticipated inundation (floods and inland floods), etc.' in July 2015 (MLIT, 2015b).

In this guideline, the precipitation data to be used was specified in the form of the depth–area–duration (DAD) curves estimated by the historically observed maximum areal precipitation records instead of simulated climate change projections. This selection was an important decision for estimating the AMSP, instead of using outcomes of great efforts that had been put to climate change projections, especially to impacts on heavy rains and typhoons using GCMs and RCMs.

The historically observed data used in the guideline were the Radar-AMeDAS dataset available since 1988 and other selected extreme records observed by MLIT and other ministries since 1957. The Radar-AMeDAS data are the radar observed precipitation calibrated by the ground observations measured by the Automated Meteorological Data Acquisition System (AMeDAS) and MLIT and other ministries observed precipitation data.

Note that this strategy does not at all claim that the future worst-case hazard can be represented by the historical maximum. But rather, as will be explained in the next section, if the historical maximum precipitation was less than 1/1,000 probability of occurrence, including 1/10,000 or even less, then it would be socially acceptable to consider it as the worst-case precipitation. Furthermore, if such an outrageous precipitation fell some part of the region, the same magnitude of precipitation is anticipated in any part of the region. It is also only a temporary measure to be replaced by the reliable climate projections in the future. This philosophy should not be interpreted simply as historical maximum can be considered as the worst-case especially where historical observations are limited.

## Methodology for estimating the AMSP

### Regional partitioning for regionalization unit

The method of identifying the AMSP was specified by the guideline (MLIT, 2015b) that uses the DAD estimated by the largest ever observed areal precipitation in the past that is available in the network of observation stations of Japan Meteorological Agency (JMA), instead of extreme values that are derived from rainfall projections under a future greenhouse gas emission scenario.

The detailed methodology utilizes the concept of regionalization of the worst-case DAD of hydro-meteorological extremes. That is, instead of using the local historical maximum areal precipitation observed in the concerned basin, the regional maximum in a larger region where the concerned basin is situated is used. The larger region for each basin was determined by dividing Japan into 15 climatologically uniform regions based on historical statistics of rainfall including the dendrogram analyses of basin climate. There is no way to have really 'climatologically uniform' region but this term is used for convenience. The parameters used for dendrogram analyses are the ratio of slopes of depth–duration (DD) curve, average and coefficient of variation (CV) of annual maximum precipitation per 3 hours, 24 hours and 48 hours precipitation (MLIT, 2015c). Figure 1 depicts the resultant regional partition. Here, it is interesting to see Okinawa belonging to the North-west Kyushu region which is heavily affected by the climate of both Mainland China and Siberia. There are many other climatological partitions possible for different uses.

### Regionalization of DAD diagram

The AMSP for any basin **B** is determined by the rainfall DAD map identified by the data collected from the larger region **K** introduced above that includes the concerned basin **B**. The methodology of identifying the DAD diagram is as follows: (refer **A**, **D** and **P** in Figure 2).

1. Select a partitioned region K (1, …, 15).
2. Select an area A in region K.
3. Select a duration D (1, 2, 3, 6, 12, 24, 48 and 72 h).
4. Within partitioned region K, move area A around as one area, not separated, but changing freely its shape and find the maximum ever observed areal average precipitation depth P for duration D in the whole data length.
5. Plot P against A with parameter D in the DAD diagram of region K.
6. Repeat the process 3–5 to cover all duration D.
7. Repeat the process 2–6 for all area A.
8. Repeat the process 1–7 for all region K.

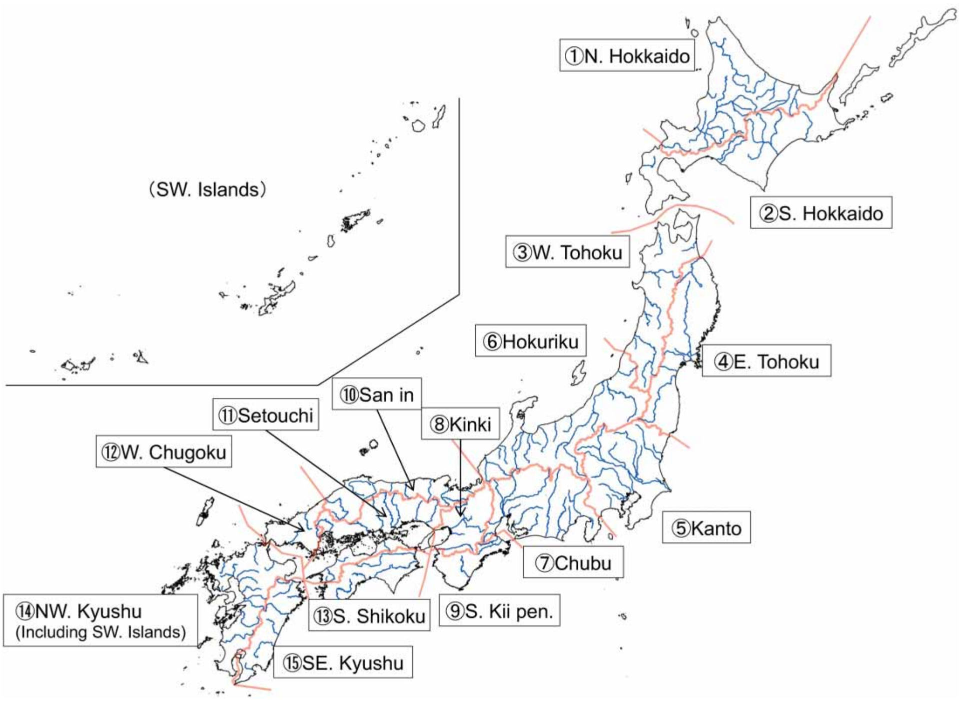
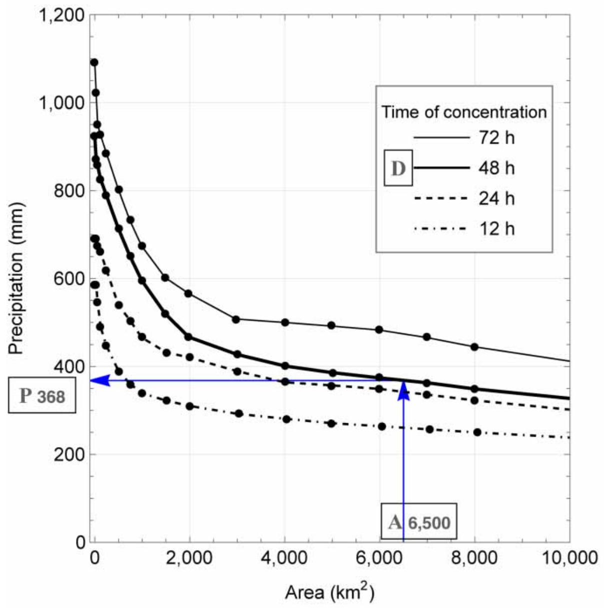



**Fig. 1** | Fifteen climatologically uniform regions for AMSP classification (after MLIT (2015b)).




| 48 hours | |
|---|---|
| Area (km2) | Prec. (mm) |
| 1 | 925 |
| 31 | 872 |
| 62 | 857 |
| 123 | 826 |
| 247 | 789 |
| 494 | 715 |
| 741 | 651 |
| 988 | 596 |
| 1,483 | 520 |
| 1,978 | 467 |
| 3,007 | 427 |
| 4,009 | 401 |
| 4,998 | 386 |
| 5,991 | 374 |
| 6,993 | 363 |
| 7,990 | 349 |

Interpolation method is used for obtaining precipitation on 6,500 $km^2$ because 6,500 $km^2$ is not shown. Using 374 mm and 363 mm on 5,991 $km^2$ and 6,993 $km^2$, respectively, precipitation 368 mm on 6,500 $km^2$ is obtained as follows.

$$374 + (363 - 374) \times \frac{6{,}500 - 5{,}991}{6{,}993 - 5{,}991} = 368$$

**Fig. 2** | Specific calculation of AMSP from a DAD curve of a concerned region (**A**rea: 6,500 $km^2$, **D**uration: 48 h, to determine **P**recipitation: 368 mm, in Region: **K**) (after MLIT (2015b)).

In step 4, a 'grid point method' (referred to as the flexible elements method (FEM) in the guideline) was suggested as a concrete computer calculation method by WMO (1969). The DAD diagram of region K as depicted in Figure 2 is produced smoothly connecting the plotted points with interpolation between points and minor extrapolation at the end of lines for all 15 regions in Japan.

## The AMSP for calculating flood inundation

In order to produce a hazard map of any target area, its anticipated inundation area should first be identified. Using the identified DAD diagram, the AMSP for the basin where the target area is located is selected simply reading value P at basin area A and its concentration time D. The procedure of identifying the AMSP for a basin of area 6,500 $km^2$ and concentration time 48 h resulting in a value of 368 mm is depicted in Figure 2. If the exceedance probability of the AMSP thus estimated for a basin is much more than 1/1,000 per year probability of occurrence, it is advised to adjust it to the one equivalent to 1/1,000 per year probability of occurrence (MLIT, 2015b).

The methodology of identifying the probability value of precipitation in Japan is unique and has not been formally published anywhere in an academic journal, but has been exercised in practice as a national standard for many years, at least since the Basic Plan for Implementation of Construction Works started in exercise in 1997. The latest official recommendation to use this methodology was given in the MLIT administrative directive 'The past examples and others to be referred to develop the basic river management policy' issued in 2015 by Water and Disaster Management Bureau, MLIT (MLIT Administrative Directive, 2015). It lists 'The Yabe River basic river management policy' (MLIT, 2014b) as a recommended example case. The Yabe River example suggests to utilize a set of probability distribution functions selected from 5 categories of 7 different probability distribution functions (12 types all together if distributions with different parameter estimation methods are counted) listed in Table 1 that clear the goodness-of-fit criteria Standard Least Squares Criterion SLSC $< 0.040$ (Tanaka & Takara, 1999). Among the acceptable distributions listed in Table 1, the distribution of the smallest jackknife estimator (Quenouille, 1949) is selected that gives the most stable estimate for resampled data, from which the precipitation return value is decided against a given non-exceedance probability. The parameter estimation method for each distribution is selected from the product moment maximum-likelihood method, PWM or L-moment as also shown in Table 1. The plotting position to be used is Cunnane's (Stedinger *et al.*, 1993).

### Hyetograph identification by enlarging method

Given the design precipitation amount for the given duration (concentration time) in the target basin, the hyetograph for drawing the anticipated inundation map is selected again from the historical cases, the hyetographs of the worst-case that was experienced in the past and assumed to create the maximum losses in the future in the target basin. The worst-case usually corresponds to the precipitation event resulting in either the largest total volume of flood discharge or the highest peak discharge depending on the impacts on socio-economic damages in the basin.

As the total precipitation of the selected historical case in the concerned basin has less than or equal to the areal precipitation identified by the AMSP, the selected historical hyetographs are to be enlarged to meet the AMSP. Such modification is made by so-called enlarging method which has long been exercised in practice by MLIT. The procedure is depicted in Figures 3 and 4.

Figure 3 indicates the cases for modifying the shape of hyetograph, (a) the case where the duration of the selected historical hyetograph is less than the concentration time D of the sub-basin and (b) the case the duration of the selected is longer than D. If less than D, the historical hyetograph is simply enlarged at all time interval points of the observed values in equal proportion to meet the AMSP during D and if longer than D, only the central (largest) part within D is enlarged in proportion to meet the AMSP.

Figure 4 depicts the rare case that needs some additional modification. If the historical hyetograph that corresponds to the worst disastrous case has an exceptional shape that the normal enlarging method leads to an excessively high precipitation per hour or per 10 minutes, an arrangement is made to limit the maxima less than 220 mm/h and 60 mm/10 min, the highest values over which physical reality is unthinkable under any extreme situation (Ninomiya, 2001). This is to avoid the enlarging method to come into any exceptional case ending up in totally unrealistic values.

**Table 1** | Probability distribution functions and their parameter estimation methods to be used to estimate probability precipitation (Tanaka & Takara, 1999; MLIT, 2014b).

| Distribution | Parameter estimation method |
|---|---|
| GEV | LM |
| Gumbel distribution | LM |
| SQET | MLE |
| LN2 | LM, PM |
| LN3 | LM, PM Ishihara-Takase, QM, QM Iwai |
| LN4 | PM |
| LPIII | PM with logarithmic sample, PM with original sample |

GEV, Generalized extreme value distribution; SQET, Square root exponential-type distribution of maximum; LNn, *n*-parameter type log-normal distribution; LPIII, Log-Pearson type III distribution; LM, L-moment method; MLE, maximum-likelihood estimation; PM, product moment method; QM, quantile method.

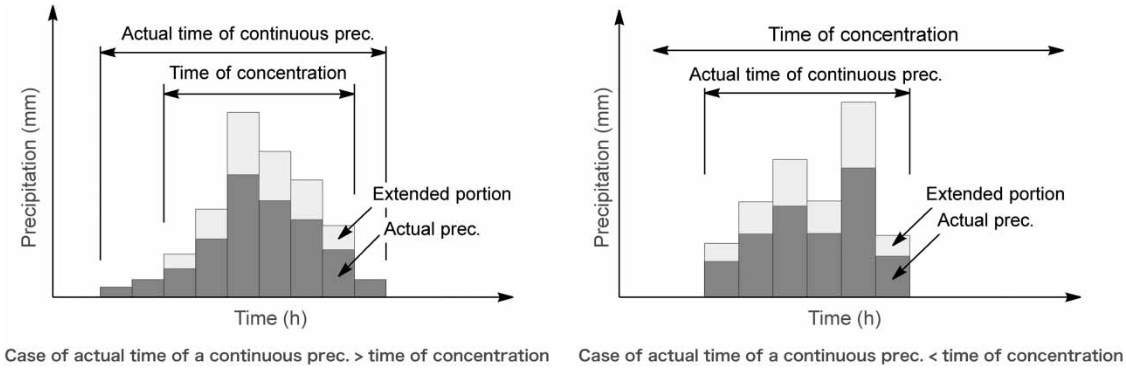



**Fig. 3** | Precipitation enlarging methods (MLIT, 2015b).

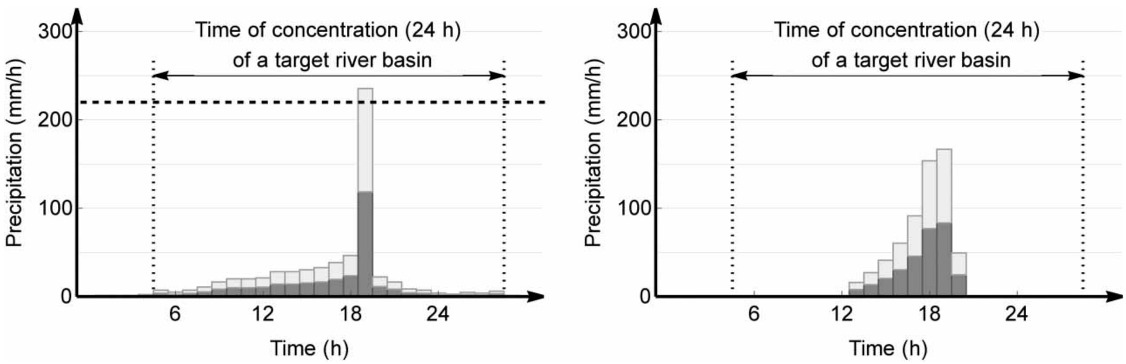



**Fig. 4** | Examples of excessively irrational enlargement of temporal precipitation pattern (MLIT, 2015b).

## Discharge and inundation simulation

The precipitation-runoff model to be used is the SFM. As it is a lumped model, if a target basin is larger than several hundred $km^2$ or so, the basin should be divided into sub-basins in the order of tens to a hundred $km^2$ area or so and the model should be applied to sub-basins and discharges from each sub-basin are routed to the concerned point. In case of the Tone River at Yattajima, for example, the upstream catchment (referred to as the Yattajima basin) is 5,150 $km^2$ which is divided into 39 sub-basins (MLIT website on the Tone River design flood verification).

The AMSP of the Yattajima basin is decided by the DAD of the Kanto region at area 5,150 $km^2$ and concentration time 3 days, which gives 491 mm/3 days. The next step is estimating the hyetographs necessary for SFM calculation for discharge from each sub-basin. The distribution of hyetographs over all sub-basins is selected as the one that gives most unfavorable discharge at Yattajima station by comparing several historical flood cases that caused large disaster damages in the Tone River basin in the past. The historical worst-case flood was by Typhoon Kathleen in September 1947 which should be included in comparison. The areal average precipitation of any case selected must be less than or equal to the AMSP at Yattajima so that the enlargement ratio is calculated and the same enlargement ratio is applied to all hyetographs of 39 sub-basins so as to make the areal precipitation of the Yattajima basin the same as the AMSP.

Various other parameters of the SFM of each sub-basin such as initial precipitation loss $R_0$, initial delay of discharge $T_l$, saturation precipitation Rsa, storage function constant K, storage function power p, etc., are decided as a robust set at each sub-basin under its representative flood cases (MLIT website on the Tone River design flood verification).

## DISCUSSION

In the previous section, a series of developments in Japan for climate change adaptation were reviewed, namely, policy priority to save life anticipating the worst-case scenario, hazard maps based on the AMSP, use of observed precipitation data rather than climatological projections to estimate the AMSP, regionalization of DAD curves for the AMSP estimated by historical maximum areal precipitation, distribution of hyetographs in sub-basins selected from the past disaster cases, enlargement method for hyetograph adjustment, and finally discharge and inundation simulation for hazard maps. Among others, the following questions need further discussion:

1. Is it reasonable to choose observed data for estimating the AMSP while climatological projection technologies have been advancing remarkably?
2. Is it reasonable to choose the historical maximum areal precipitation as the AMSP of the worst-case scenario?
3. Is it reasonable to use the worst-case DAD estimated in a region to use for the AMSP at any basin in the region? In other words, is regionalization of the worst-case DAD reasonable?
4. Is it proper to select a distribution of sub-basin hyetographs from historical events? No need to consider any other distribution?

To follow are some critical discussions on those questions.

### Observation records vs simulated climate projections

The basic conceptual issue that poses a dilemma for all planners, practitioners, engineers and scientists is how to develop new flood protection standards under a non-stationary climate. Should the new engineering standards be based on historical observations, using procedures developed for a stationary climate? Or, should the criteria and standards for flood frequency analysis and typhoons be based on climate change projections of GCMs and RCMs?

The methodology adopted in Japan is twofold: One is to protect life by early warning and evacuation by anticipating the worst-case hazards that should be estimated by the historical maxima, and the other is to protect life, property and livelihood as a whole as much as possible by strengthening the physical infrastructure considering the anticipated increase in hazards estimated by GCMs and RCMs.

This policy is considered reasonable as saving life is an urgent matter to be addressed without delay while strengthening physical infrastructure needs much time and money so that the investments should be adaptive to the progress of climate change as well as changing economic conditions. In order to invest a large amount of social capital for infrastructure development, such an adaptive approach is indispensable.

Now, are the historical ground observations trustable while model simulated projections are not? Indeed, in the research field, there have been significant research conducted for climate change projections using various GCMs and RCMs with the funding provided by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Ministry of Environment and others in recent decades. The resultant projections were compiled into datasets called Database for Policy Decision-Making for Future Climate Change (d4PDF) which has been put to public use since 2016 (MIROC website on d4PDF). The datasets are available for the globe and Japan area. The ones for Japan area are 20 km mesh 60 years hourly projections with the global-mean surface temperature being current (1951–2010), plus 2 K (2030–2091) and plus 4 K (2050–2111) degrees for 50, 54 and 90 ensemble series, respectively, under RCP8.5 scenario. They are well prepared for use.

However, according to the reproducibility experiments of the annual maxima statistics of the present climate by Tanaka *et al.* (2019), the reproducibility was found poor in Kyushu, Shikoku and Kii Peninsula areas where the heavy rains matter most. In other regions, it was better. This finding seems quite reasonable because those areas have strong orographic effects with frequent visits of typhoons and frontal activities for which spatial resolution 20 km would not be fine enough. Thus, the use of d4PDF to estimate the AMSP is not recommended for producing hazard maps for local community use, which requires more detailed local information.

On the other hand, the reliable ground observations are available for long time periods since the start of meteorological observations by Japan Meteorological Agency in 1875. The number of observation stations were about 50 (average about 90 km grids) in 1900 and about 150 (average about 50 km grids) in 1970 covering all Japan (Ishii, 2019). From 1974, the Automated Meteorological Data Acquisition System (AMeDAS) started and, in 1979, it was completed with 1,316 stations (average about 17 km grids) every 10 min observation intervals for all of Japan.

Besides, JMA started the use of radars for precipitation measurement in 1954 and covered the entirety of Japan with 20 microwave radars (5 GHz band) by 1971 (Sato, 2007). Their measurements are calibrated by AMeDAS and other MLIT and prefectural observation data, and the 'Radar-AMeDAS Analyzed Precipitation' dataset have been produced since 1988. The resolution of these data was 5 km grids till 2001, 2.5 km till 2005, and has been 1 km since 2006 (JMA website on analyzed precipitation; Kuroyoshi *et al.*, 2005).

Since the Radar-AMeDAS Analyzed Precipitation dataset provides the radar-based interpolation where no ground observations available such as high mountainous areas, it is considered the most accurate observation data. It was therefore natural to choose this observed precipitation data as the basis of estimating historical maxima to calculate the AMSP.

## Historical maximum precipitation for the AMSP in the worst-case scenario

The worst-case flood may mean different things in different nations. In the Netherlands, the probability of non-exceedance levels 1/4,000 or 1/10,000 per year are used to protect sea dikes against storm surges, and for rivers, 1/1,250 or 1/2,000 probability (Jonkman *et al.*, 2008). But, in Japan, such high safety levels would not be reasonable for infrastructure design considering the current level of safety achieved and the necessary investment to construct and maintain it. Also, the incremental height of the dike for increasing safety probability would be in general much higher in Japanese rivers than continental rivers. For example, the necessary increase of dike height from the safety level 1/15 to 1/50 per year probability, in the Tone River at Yattajima is 2 m and the same in the Saine River at Paris is 1 m. In Japan, the cost of safety increase is relatively more expensive than continental countries mainly because the steep slopes and narrow width of rivers relative to discharge.

But for hazard maps for emergency preparation and evacuation to save lives, the maps must be uniform in anticipating the worst-case scenario, avoiding no unanticipated events to happen. The key question is what is the real worst-case? The ultimate worst-case would be heavy rains based on the maximum vapor that the atmosphere can theoretically hold, falling at once everywhere in a basin. But such a case is clearly unrealistic and nobody would disagree. The historical maximum during some generations of experiences must be the most popular and psychologically acceptable worst-case in practice. Following this notion, the historical maxima were used to identify the DAD for the AMSP to be decided in the MLIT guideline (MLIT, 2015b). The data used were the partial maxima series of areal precipitation observed from 1957 to 1987 by JMA or MLIT precipitation observation stations and from 1988 to 2014 by Radar-AMeDAS datasets. However, 50 years of records are considered to be the minimum acceptable level of rainfall data for uniformly available data all over Japan. In order to comply with this constraint acceptable in using the historical maximum as the worst-case scenario, the following regionalization concept was added.

**Regionalization of the worst-case DAD for any basins in the region**

About the use of historical areal maximum precipitation, the following question would arise. That is, 'We were lucky that the heaviest rain occurred in a distant basin rather than here this time. But in the future, wouldn't it be possible for similar areal precipitation to occur in our basin?' The answer must be a big 'yes', at least within the same climatologically uniform region. This is the reason why the worst-case DAD identified in a large region is used for the AMSP of any sub-basin in the region. This is called here 'regionalization of the worst-case DAD' or simply 'regionalization of DAD'. That is, instead of using the local historical areal maximum observed in the concerned basin, the regional areal maximum in a larger region where the concerned basin is situated is used. This simply means that the heaviest rain area in a basin may come to any other basin if it is in the same region shown in Figure 1, where the entire Japan is divided into 15 climatologically uniform regions.

Such an assumption may be quite difficult to formally justify in a scientific sense. But there are some pieces of supporting evidence. One is that recent heavy rains observed are quite often the ones that 'have never been experienced before' in a particular basin, but the regional maxima are not so frequently broken even by recent new climate conditions such as stagnated linear rain bands or super typhoons. In fact, according to MLIT (2020), the Abukuma River basin received unprecedented areal precipitation by Super Typhoon 19 of 2019, and dike breach occurred at as many as 53 sites. Nevertheless, there were no cases of areal rainfall exceeding the DAD of East Tohoku Region. Also, it says that that same typhoon in the whole nation, impacted station records of 6-h rainfall were renewed at 89 stations, 12-h rainfall at 120 stations, 24-h rainfall at 103 stations and 48-h rainfall at 72 stations. However, the national records were broken only in Hakone's 12-, 24- and 48-h point rainfall and 24-h areal rainfall at the Shiroyama-dam catchment (1,201 km$^2$). It means that the national records are not often broken even under the current climate change developments (JMA website on nationwide ranking of historical records). The other evidence to support regionalization would be that a regional areal maximum rainfall often exceeds once over many thousands of years if evaluated by probability distributions listed in Table 1. It means that regionalized DAD gives extremes that are appropriate for the AMSP.

Thus, the regionalization of DAD for extreme areal precipitation would be a reasonable strategy for drawing the worst-case local inundation maps.

But the Hakone and Shiroyama-dam catchment cases have very important messages, too. The DAD for the AMSP in the Kanto region was issued in 2015. But only 4 years later, during the Super Typhoon 19 in 2019, the areal rainfall of the Shiroyama-dam catchment in Kanagawa and the point rainfall at Hakone, Kanagawa, were well above the past records, making the worst-case DAD no longer the worst (JSCE, 2020). As long as using the historical maxima, such cases are inevitable and unanticipated events will keep happening. It means that continuous periodic updating is necessary, although it is not a simple matter. The revision of the regional DAD means the renewal of hazard maps and community responses. To avoid frequent revision needs, climate change impact on defining of DAD should necessarily be reflected.

Another more serious question in relation to defining DAD would be the appropriateness of partitioning of the country into 15 regions shown in Figure 1. There are many other cases where similar geographical classifications are made. For instance, JMA seasonal weather forecasts use classification of 7 regions for 1–3 months precipitation forecasts and the warm season (June to August) forecast (JMA website on seasonal forecasts). If the number of partitions is smaller, more severe DAD would result for larger regions and heavier areal rainfall would be anticipated. In fact, if such an option is selected the cases that the AMSP being much less than 1/1,000 per year would appear much less frequently. In other words, selection of the number of regional partitioning is critical to this method and scientific analyses on the soundness of partitioning is necessary.

In both cases above, identification of areal maxima and regional partitioning, climate change impact should be considered. In other words, the criteria of identification should not be only the historical similarity but potential meteorological projections under climate change, including the occurrence of stagnated linear rain bands and super typhoons. This would enhance the rationale of regionalization of DAD.

### Selection of the distribution of sub-basin hyetographs from historical cases

The distribution of hyetographs over sub-basins is the one which brought the worst disaster in the concerned basin in the past. In practice, several disaster cases are examined and the most unfavorable distribution pattern to the concerned basin outlet (Yattajima in the example above) is selected. In order to adjust the total amount into the AMSP, the enlargement rules depicted in Figures 3 and 4 are used. This method is quite heuristic, but it is reasonable as an engineering sense and there would not be any better way.

But again, as long as this process is based on historical events, more serious cases should be anticipated in the future. Especially, climate change will quite likely bring unexperienced areal rainfall patterns and hyetographs distributions over various sub-basins. This also implies the need of examining climate change impacts beyond the hazard.

## CONCLUSION

Under the potential for climate change rapidly increasing the magnitude and frequency of hydro-meteorological extremes, it is necessary to take immediate action to prepare for saving lives and avoiding catastrophic economic losses prior to developing proper physical infrastructure.

For such a critical goal, it is quite reasonable to anticipate the worst-case scenarios for floods, landslides, debris flows, similar to earthquakes, tsunamis, volcanic eruptions, etc., so that people can prepare for such emergencies and evacuate early enough to protect their lives.

In Japan, the historical precipitation observations have been accumulated since the establishment of JMA in 1875 and the radar-AMeDAS database since 1988 in high density and accuracy all over Japan. Under such circumstances, the use of observed data would be more reliable to identify local scale extreme statistics as compared with the current level of climate projections by GCMs and RCMs assembled in 20 km mesh d4PDF datasets for Japan area.

The use of historical areal maxima as the AMSP through regionalization of DAD in the worst-case scenario is a unique heuristic approach. It considers that the heaviest areal precipitation that has occurred in a climatically uniform region can occur anywhere in the region. It is a reasonable assumption to use historical records for the worst-case scenario appropriate for local communities.

Nevertheless, climate change is occurring. The stationary assumption does not hold and hydrologists cannot challenge 'Stationarity is dead' although this does not 'wither water management' (Milly *et al.*, 2008). The state of the art in climate change projections should be assessed not just by scientific achievements but from the local practice point of view. Unfortunately, the current state is not satisfactory enough for local practical use all over Japan. Under such circumstances, the current Japanese engineering solution is an art, a beautiful art but it is an intermediate state to be more closely connected with meteorological sciences. Connection would still be difficult and meanwhile the accumulated ground observations and engineering experiences can well serve society.

In developing countries, however, there is often a lack of observation data and it is impossible to use historical data for drawing local anticipated inundation maps. In such cases, the interpolation and extrapolation of observed data in the surrounding area and the use of reanalysis data is an inevitable alternative. The direct use of GCM projection data would also be an option using the CMIP6 (ESGF Website) or d4PDF datasets. But even in such cases, the ground observation is the indispensable basis for real actions. Even a few years of observations would provide a precious means for verification to those estimated or projected data.

In any region where no ground observation network is installed, it is an urgent matter to develop it in a decent density. The ground observation data are necessary to formulate development policy, to use scientific models as well as to use remote-sensing data. But, in order to estimate the worst-case meteorological hazards through regionalization, such as for once in several hundred years to a thousand years, the long observation data of at least 50 years extent would be necessary as in the case of Japan (WMO, 2009).

It cannot be overstated that the importance of ground observations, in developed or developing countries, should not be overshadowed by advanced sciences, models and remote sensing. They rather increase their effectiveness.

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