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Regional Rainfall Intensity-Duration-Frequency Relationships For Ungauged Catchments Based on Scaling Properties

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Synopsis

This study developed regional Intensity–Duration–Frequency (IDF) relationship for ungauged locations based on the scaling theory. The scaling properties of extreme rainfall are examined to establish scaling relationship behavior of statistical moments over different durations. The results show that a rainfall property in time does follow a simple scaling process. A scale invariance concept is explored for disaggregation (or downscaling) of rainfall intensity from low to high resolution and is applied to the derivation of scaling IDF curves. These curves are developed for gauged sites based on scaling of the Extreme Value type 1 (EV1) or Gumbel probability distributions. The IDF relationships are deduced from daily rainfall with the scaling approach, which shows good results in comparison with the IDF curves obtained from traditional techniques. The spatial distribution maps of three parameters: the scaling exponent and two statistical parameters are constructed. These maps are used to derive the rainfall intensity duration frequency at ungauged sites.

Keywords: Rainfall Intensity-Duration-Frequency relationship (IDF), Scaling invariance, Regional frequency analysis, Design rainfall.

1. Introduction

The Intensity Duration Frequency (IDF) relationship of heavy storms is one of the most important hydrologic tools utilized by engineers for designing flood alleviation and drainage structures in urban and rural areas. Local IDF equations are often estimated on the basis of records of intensities abstracted from rainfall depths of different durations, observed at a given recording rainfall gauging station. In some regions, there may exist a number of recording rainfall gauging stations operating for a time period sufficiently long to yield a reliable estimation of the IDF relationships; in many other regions, especially in developing countries, however, these stations are either non-existent or their sample sizes are too small. Because daily precipitation data is the most accessible and abundant source of rainfall information, it seems natural, at least for the regions where data at higher time resolution are scarce, to develop and apply methods to derive the IDF characteristics of short-duration events from daily rainfall statistics.

There have been considerable attentions and researches on the IDF relationship: Hershfield (1961) developed various rainfall contour maps to provide the design rain depths for various return periods and durations. Bell (1969) proposed a generalized IDF formula using the one hour, 10 years rainfall depths; P_1^{10}, as an index. Chen (1983) further developed a generalized IDF formula for any location in the United States using three base rainfall depths: P_1^{10}, P_{24}^{10}, P_1^{100}, which describe the geographical variation of rainfall. Kouthyari and Garde (1992) presented a relationship between rainfall intensity and P_{24}^{2} for India. Koutsoyiannis *et al.* (1998) cited that the IDF relationship is a mathematical relationship between the rainfall intensity I the duration D and the return period T. Sivapalan and Bloschl (1998) proposed an approach for constricting catchments IDF curves based on the spatial correlation structure of rainfall. Nhat *et al.* (2006a and 2006b) estimated IDF curves, constructed the parameter contour maps of IDF functions and generalized IDF formulas for monsoon area of Vietnam, which allow incorporating data from recording stations for constructing the IDF curves at ungauged sites.

Over the last two decades, concepts of scale invariance have come to the fore in both modeling and data analysis in hydrological precipitation research. Gupta and Waymire (1990) studied rainfall spatial variability by introducing the concepts of simple and multiple scaling to characterize the probabilistic structure of the precipitation processes. Burlando and Rosso (1996) showed that both the simple scaling and multiscaling lognormal models can be used to derive Depth Duration Frequency (DDF) curves of point precipitation. Van-Nguyen, T. V. *et al.* (1998) proposed a Generalized Extreme Value distribution model for regional estimation of short duration rainfall extremes base on the scaling theory. Menabde *et al.* (1999) developed a simple scaling methodology to use daily rainfall statistics to infer the IDF curves for rainfall duration less than 1 day. The scaling hypothesis was verified by fitting the model to two different sets of data (from Australia and South Africa). Pao-shan, *et al.* (2004) is an example of methodology in which the theories of scaling properties and employed to infer the IDF characteristics of short-duration rainfall from daily data. Kuzuha *et al.* (2005) showed the scaling framework and regional flood frequency analysis. Nhat *et al.* (2006c and 2007) showed the existence of the simple scaling in time and space.

The purpose of this study is to investigate 'scale invariance' or 'scaling' properties of rainfall for derivation of IDF relationships. The scaling properties of extreme rainfall are examined to establish scaling behavior of statistical moments over different durations. The results show that a rainfall property in time does follow a simple scaling process. A scale invariance concept is explored for disaggregation (or downscaling) of rainfall intensity from low to high resolution and is applied to the derivation of scaling IDF curves. These curves are developed for gauged sites based on scaling of the Extreme Value type 1 (EV1) or Gumbel probability distributions. The IDF relationships are deduced from daily rainfall with the scaling approach, which shows good results in comparison with the IDF curves obtained from traditional techniques. The spatial distribution maps of three parameters: the scaling exponent and two statistical parameters are constructed. These maps are used to derive the rainfall intensity duration frequency at ungauged sites.

2. Definitions

In this section, a general theoretical framework for the simple scaling is introduced. The scaling or scale-invariant models enable us to transform data from one temporal or spatial model to another one, and thus, help to overcome the difficulty of inadequate data. A natural process fulfills the simple scaling property if the underlying probability distribution of some physical measurements at one scale is identical to the distribution at another scale, multiplied by a factor that is a power function of the ratio of the two scales. The basic theoretical development of scaling has been investigated by many authors including Gupta and Waymire (1990) and Kuzuha *et al*. (2005).

The random field rainfall intensity with duration *D, I*(*D*) exhibits ***a simple scale invariance*** behavior if

$$I(\lambda D) \overset{d}{=} \lambda^{H} I(D) \quad (1)$$

holds. The equality " $\overset{dist}{=}$ " refers to identical probability distributions in both sides of the equations; λ denotes a scale factor and H is a scaling exponent. Referring for simplicity to a one dimensional random field $I(D)$. The Equation (1) is also defined as simple scaling property. From (1) comes that: Moment of the statistical distribution scale with a simple scaling law.

$$E[I^{q}(\lambda D)] \overset{d}{=} \lambda^{qH} E[I^{q}(D)] \quad (2)$$

Where the $E[]$ is expected value operator, q is the moment order and λ is a scale factor. The random field $I(D)$ exhibits a ***simple scale invariance in a wide*** *sense* if Equation (2) holds. If H is a non-linear function of q, the $I(D)$ is a general case of multi-scaling (see Fig.1).

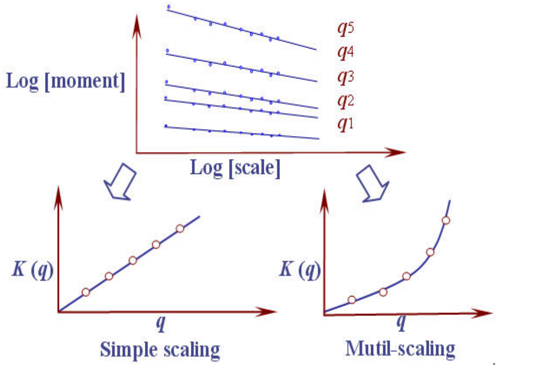

Fig.1 Simple and multiscaling in term of statistical moments. First step, moments of different orders q are plotted as function of scale in a log-log plot. From the slope, values of the function $K(q)$ are obtained. If $K(q)$ is linear, the process is simple scaling. If $K(q)$ is non-linear, the process is multi-scaling.

The moments $E[]$ are plotted on the logarithmic chart versus the scale λ for different moments' order q. The slope function of order moment $K(q)= f(q)$ is plotted on the linear chart versus the moment order q. If the resulting graph is a straight line, the field is simple scaling, while in other cases, the multi-scaling approach has to be considered (Gupta, V. K. and Waymire, E., 1990).

3. Study area and rainfall data

The Yodo River Catchments (approximately 7281 km^2) was selected as study area. The rainfall data for analysis herein were collected from 12 hourly rain gauges of which locations are indicated in Fig. 2. The name and record length for recording rain gauge are listed in Table 1. The Annual Maximum Rainfall Intensity (AMRI) series for various durations, including 1, 2, 3...24 h; were taken from Automated Metrological Data Acquisition System (AMeDAS).

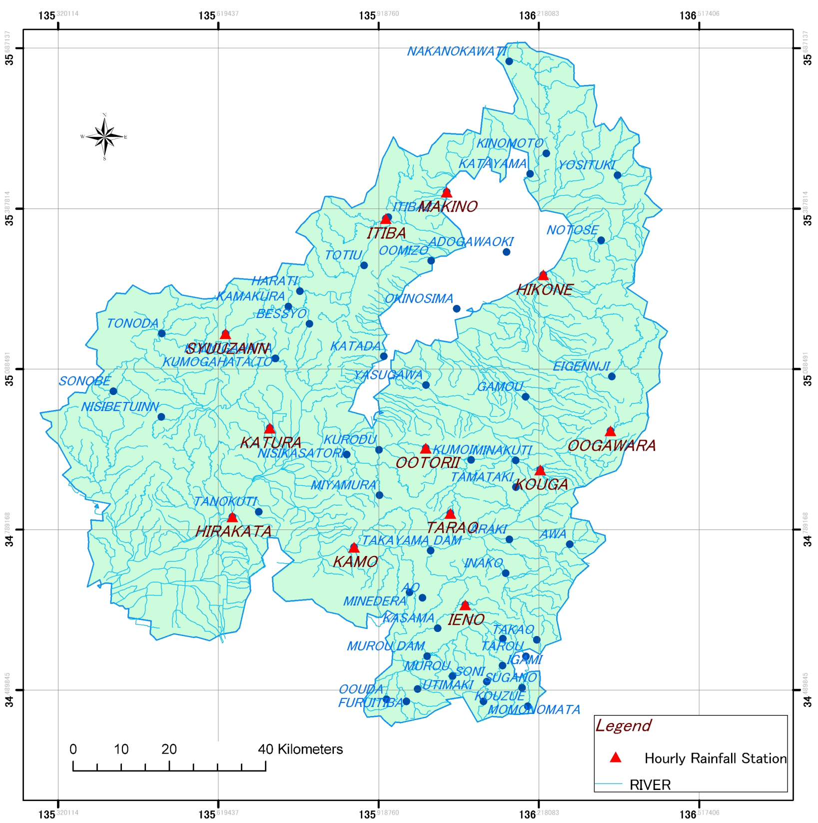

Fig. 2 Study area and rain gauge locations for analysis.

Table 1 The stations and length of data.

No	Name of stations	Length of data
1	Ieno	1982-1996
2	Itiba	1982-2002
3	Oogawara	1982-2002
4	Ootorii	1982-2002
5	Katura	1982-2002
6	Kamo	1982-2001
7	Kouga	1982-2002
8	Syuuzann	1982-2002
9	Tarao	1982-1997
10	Hikone	1982-2002
11	Hirakata	1982-2002
12	Makino	1982-2002

4. Scale invariance of short duration data in the Yodo River Cathment

The data in the Yodo River area was analyzed to ensure that they did indeed conform to the simple scaling. Annual maximum rainfall intensity series (AMRI) data for Hikone station, with complete records from 1h to 24h durations, were analyzed. From Equation (2), the simple scaling in the wide sense can be expressed as Menabde *et al.* (1999):

$$E[I^q(D)] = f(q)D^{-Hq} \tag{3}$$

where $f(q)$ some function of q (the q^{th} moment); $E[I^q(D)]$ is q^{th} moment of the intensity data (mm/h); D is the duration (hour) and H is the scale exponent.

The scaling properties of rainfall data was investigated by computing the moment for each durations and then by examining the log-log plots of the moments against their duration. The record lengths are 21 years and ranged from 1982 to 2002. The analysis was performed on annual maximum rainfall series for storm durations from 1 hour to 24 hours, with λ=1, 2...24. For illustration, in Fig. 3 the qth moment of the intensity (mm/h) is plotted against the duration for the Hikone station located in the Yodo River Catchment.

It is clear that the data is linearly related, and there is not a break between the short and long duration data. In order to determine if the data follows simple scaling or multi-scaling, the scaling exponent, Hq, was plotted versus the moment, q, as illustrated in Fig.4 shows the scaling exponent decreases with the order of moment and a linear relationship exists between scaling exponents and orders of moment, which implies that the property of wide sense simple scaling of rainfall intensity exists in this station. Once again the data were linearly related, with an R^2 value of 0.9999 for the Hikone station.

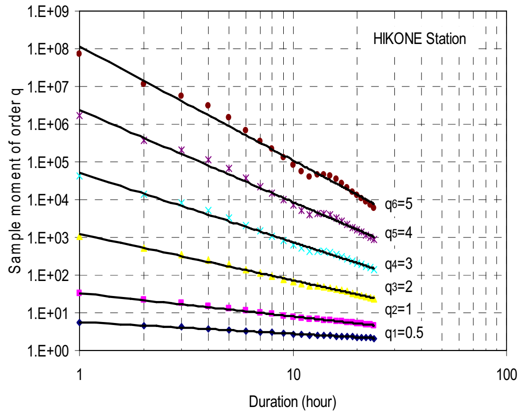

Fig.3 Linear relationships indicate scaling may be applicable at Hikone station in The Yodo River catchment, Japan.

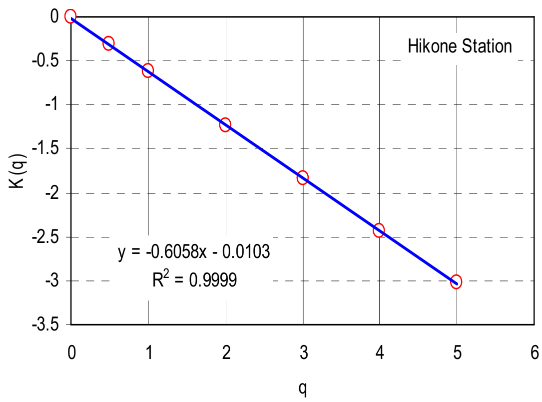

Fig.4 Relationship between *K(q)* and the sample moment order *q*.

Therefore, the simple scaling can be assumed in this situation. (Nonlinear data would have indicated multiscaling.) The slope of this line is the scale exponent parameter, which has a value of 0.605 for the Hikone station (Nhat, *et al.* 2007).

5. Derivation of IDF for Short Duration

All forms of the generalized IDF relationships assume that rainfall depth or intensity is inversely related to the duration of a storm raised to a power, or scale factor (Chow, V.T., 1988). There are several commonly used functions found in the literature of hydrology applications. Koutsoyiannis *et al.* (1998) have modified the IDF relationship for a given return period as particular cases, using the following general empirical formula

$$I = \frac{w}{(D+\theta)^{\eta}} \tag{4}$$

where i denotes the rainfall intensity for duration d and w, θ and η represent non-negative coefficients. In fact, these arguments justify the formulation of the following general model for the IDF relationships:

$$i = \frac{a(T)}{b(D)} \tag{5}$$

In Equation (5), $b(D) = (D + \theta)^{\eta}$ with $\theta>0$ and $0<\eta<1$, whereas $a(T)$ is completely defined by the probability distribution function of the maximum rainfall intensity. The form of Equation (5) is consistent with most IDF empirical equations estimated for many locations (Kothyari, U. C. and Grade, R.J, 1992): For example (Nhat *et al.* 2006a) established the IDF curves for precipitation in the monsoon area of Vietnam.

The random variable rainfall intensity $I(D)$ for duration D, has a cumulative probability distribution CDF, which is given by

$$\Pr(I(D) \le I) = F_D(I) = 1 - \frac{1}{T(I)} \tag{6}$$

According to the scaling theory by Menabde *et al.*, (1999) the scaling property in a strict sense can be written explicitly using the CDF:

$$F_D(I) = F_{\lambda D}[\lambda^{-H} I] \tag{7}$$

For many parametric forms, left hand side of Equation (7) may be expressed in terms of standard variant, as in

$$F_d(I) = F\left[\frac{I-\mu}{\sigma}\right] \tag{8}$$

Where $F(.)$ is a function independent of D. Under this form, it can be deduced from Equation (7) that

$$\mu_D = \lambda^{-H} \mu_{\lambda D} \tag{9}$$

$$\sigma_D = \lambda^{-H} \sigma_{\lambda D} \tag{10}$$

Substituting Equations (9), (10) and (7) into Equation (8) and investing with respect to I, one obtains:

$$I_{D,T} = \frac{\mu_{\lambda D}(\lambda)^{-H} + \sigma_{\lambda D}(\lambda)^{-H} F^{-1}(1-1/T)}{D^{-H}} \tag{11}$$

By equaling Equation (11) to the general model for IDF relationship, given by Equation (4), it is easy to verify that

$$\eta = -H \tag{12}$$

$$\theta = 0 \tag{13}$$

$$b(D) = D^{\eta} \tag{14}$$

$$a(T) = \mu_{\lambda D}(\lambda)^{-H} + \sigma_{\lambda D}(\lambda)^{-H} F^{-1}(1-1/T) \tag{15}$$

$$\begin{cases} I_{D,T} = \dfrac{\mu + \sigma F^{-1}(1-1/T)}{D^{\eta}} \\ \mu = \mu_{\lambda D}(\lambda)^{-H} \\ \sigma = \sigma_{\lambda D}(\lambda)^{-H} \end{cases} \tag{16}$$

The μ and σ are constants. It is worthwhile to note that the simple scaling hypothesis leads to the equality between the scale factor and the exponent in the expression relating rainfall intensity and duration.

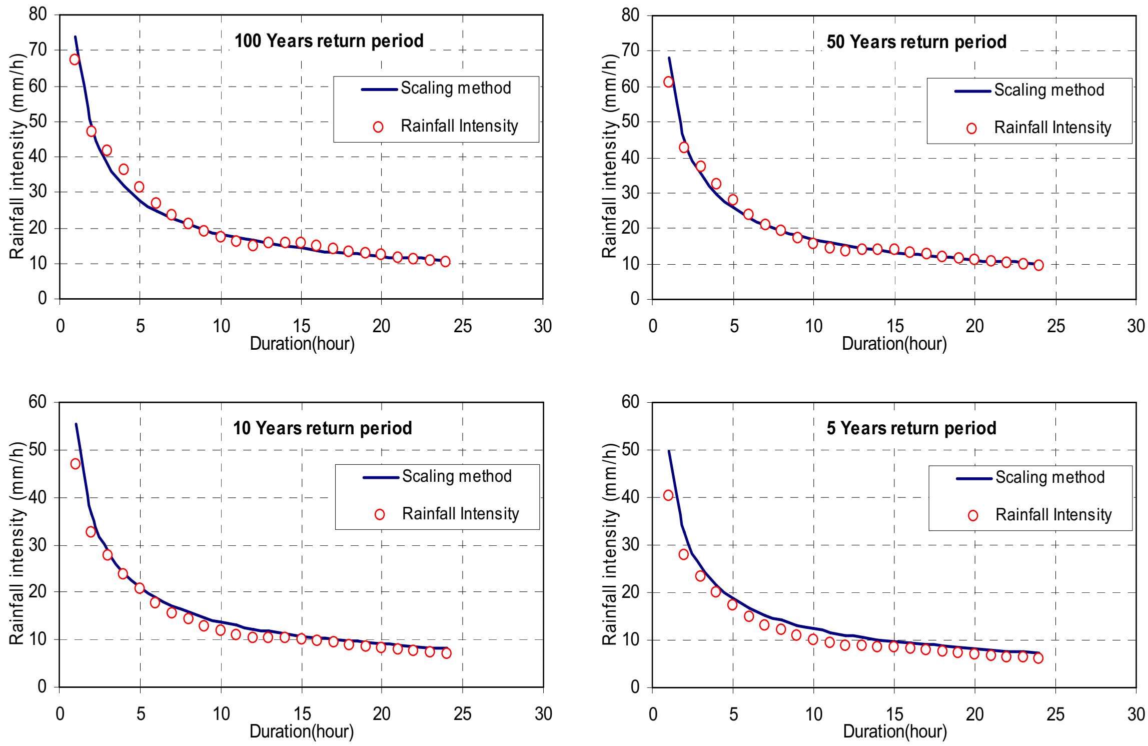

Fig. 5 The Rainfall Intensity Frequency Curves at the Hikone station by the scaling method.

With application of the simple scaling model for rainfall intensities at the Hikone station, the scale factor can be estimated H=-0.6058. The IDF relationship for a short duration rainfall can be deduced from daily data by Equation (16) with the estimates of μ_D and σ_D with D=24h. From 24-hour data collected at the Hikone recording station, the parameters of statistical can be estimated for the sample of 21 years of 24 hours annual maximum rainfall intensity yields :

- The location parameter μ_D=3.8724
- The scale parameter σ_D=1.288

Back with these estimates and the Gumbel inverse function, the deduced IDF relationship for the location of Hikone may be written as Equation (16) with μ=26.52 and σ=8.82,the rainfall IDF can be derived as:

$$I_D^T = \frac{26.52 - 8.82\ln(-\ln(1-1/T))}{D^{0.605}} \qquad (17)$$

The rainfall Intensity Duration Frequency curves for the Hikone station can be reconstructed by scaling methods with Equation (17). Figure 5 shows well matching between the IDF relationships calculated by Equation (17) and plots obtained by the historical data as the return periods from 5 to 100 years. The scale factor H along with the statistical parameters μ and σ may be interpreted as regional climatic characteristics.

6. Regional the scale invariance of rainfall in time and derivation of IDF formulas.

The formula of IDF curves (Equation 16) can be derived from scaling invariance of rainfall. It is a function of scaling exponent H, and the 2 maps of statistical parameters: Location parameter μ of 24 hour rainfall and scale parameter σ of 24 hour rainfall.

$$I_D^T = f\ (H,\ \mu,\sigma) \qquad (18)$$

Where T is return periods and D is duration of rainfall intensity.

The regional IDF formula can be developed based on the three parameters above. First, the scaling exponent H needs to be examined for all stations in the Yodo River catchment. Base on the testing results, it is likely to conclude where the simple scaling if existing for areas or regions.

Second, the two parameters of statistical analysis: μ and σ can be deriving from distribution of 24h ARMI data series.

Using the values of three parameters of all stations, three maps of spatial distribution are constructed with the GIS interpolations technique. The IDF relationship for any point (ungauged) can be derived base on these maps.

To this end, after verification of scaling of IDF estimates at Hikone stations in the Yodo River catchment, the assumption of scaling was examined at a representative sample of stations throughout the Yodo River catchment. The available data at these stations are one-hour continuous one which recording by AMeDAS. An AMRI data set was derived from the continuous data, and the first five moments were calculated for durations of 1hour up to 24 hours. As with the Hikone data, these moments were plotted against duration on a log–log scale to determine whether scaling could be assumed.

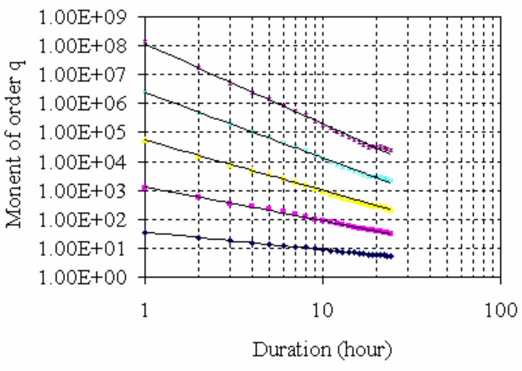

Fig. 6 Relationship between moment of order q and duration (hour) at Ootorii station.

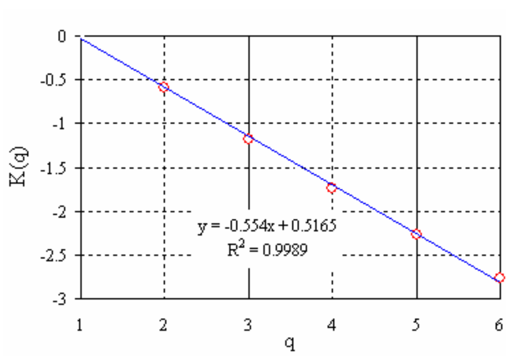

Fig. 7 Relationship between $K(q)$ and the sample moment order q at Ootorii station.

Fig. 6 shows the scaling of the moments for the Ootorii station in central of The Yodo River catchment. The linearity of the moments seen here is similar to the other 12 stations that were examined, indicating that for durations greater than 1h, scaling appears to be applicable throughout The Yodo River catchment. For each station, the scaling exponent, Hq, was plotted versus the moment, q, to determine if the simple scaling is applicable and to estimate the scale exponent for stations throughout the catchment.

As shown in Fig. 7, the scaling exponent coefficient for the Ootorii station is found to be 0.55, with an R^2 value of 0.9989. This indicates that the simple scaling could be assumed at this station instead of the more complex multi-scaling.

Data from other gauges showed a similar scaling relationship, indicating that scaling may be applicable in the Yodo River area for the durations considered. In the Table 2, the results of the scaling exponent factor H of the 12 stations in the Yodo River catchment are shown with the high coefficients of determination for each station ranging from 0.98 to 1. The result indicates a strong validity of the simple scaling property of the extreme rainfall in time series.

The scaling coefficient for the Ootorii station of 0.55 was typical for the 12 stations examined, with a mean value of 0.62 and a standard deviation of 0.07. However, a few stations had significantly higher scalar exponents, with the highest being 0.77 (Itiba station). These stations were generally located on the northern part of the Yodo River Catchment, located on the mountain, as seen in Fig. 8, indicating that the effect of the mountain or topography should be studied further. It can also be seen in Fig. 9 that the scaling coefficients were generally lower in the eastern part of the Yodo River catchments.

Construction of the three maps can be interpolated by using Geographical Information System (GIS) ACR-Map with Inverse-Distance Weighted interpolation method. The Fig.8 to Fig.10 displayed maps of spatial distributions of the scaling exponent parameters generated by twelve stations the simple scaling properties in time of rainfall maximum.

The location parameter μ and the scale parameter σ of the EV1 (Gumbel) distribution of 24 hour of AMRI can be derived by statistical analysis. With the same technical, 2 maps of statistical parameters can be constructed.

It is expected that those three maps can be applicable for any ungauged location. Further study is required to verify these maps for regional IDF relationships.

Table 2 The values scale exponent of 12 stations at Yodo River Catchment.

No	Name of stations	The scale exponent (H)
1	Ieno	0.66860
2	Itiba	0.77030
3	Oogawara	0.55010
4	Ootorii	0.55400
5	Katura	0.66130
6	Kamo	0.68900
7	Kouga	0.55190
8	Syuuzann	0.52600
9	Tarao	0.53210
10	Hikone	0.60580
11	Hirakata	0.67751
12	Makino	0.60280

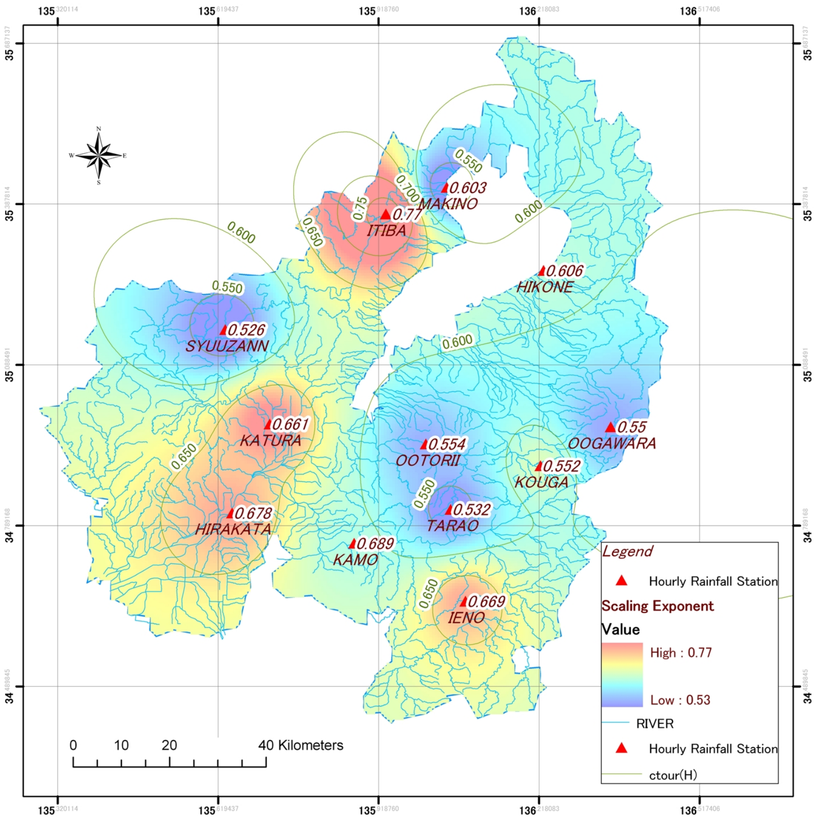

Fig. 8 Spatial distribution maps of scale exponent H.

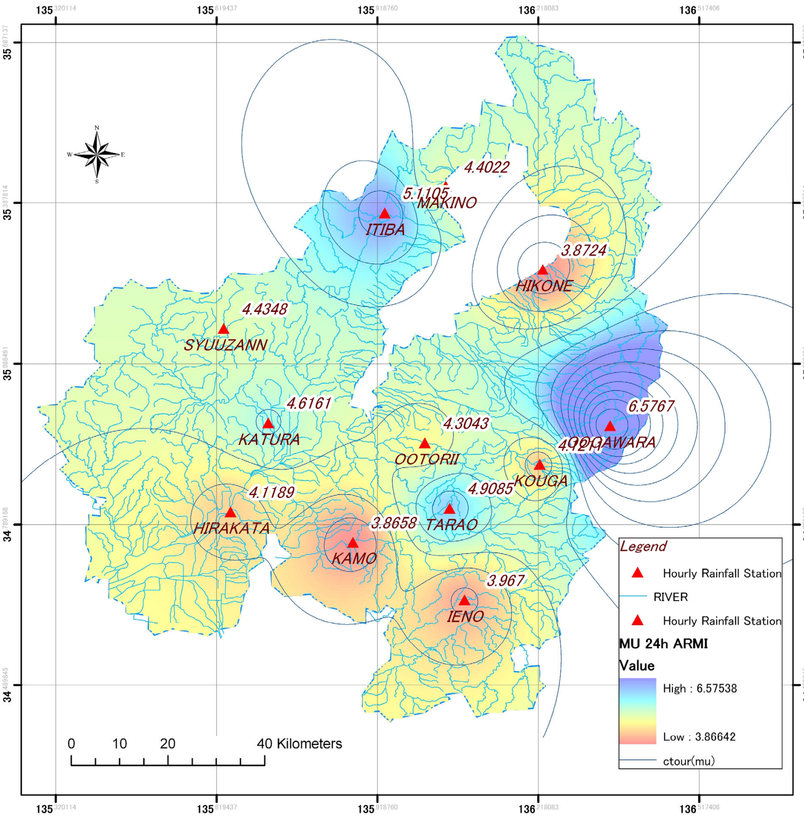

Fig. 9 Spatial distribution maps of the statistical parameters: the location parameter (μ) of 24h rainfall AMRI.

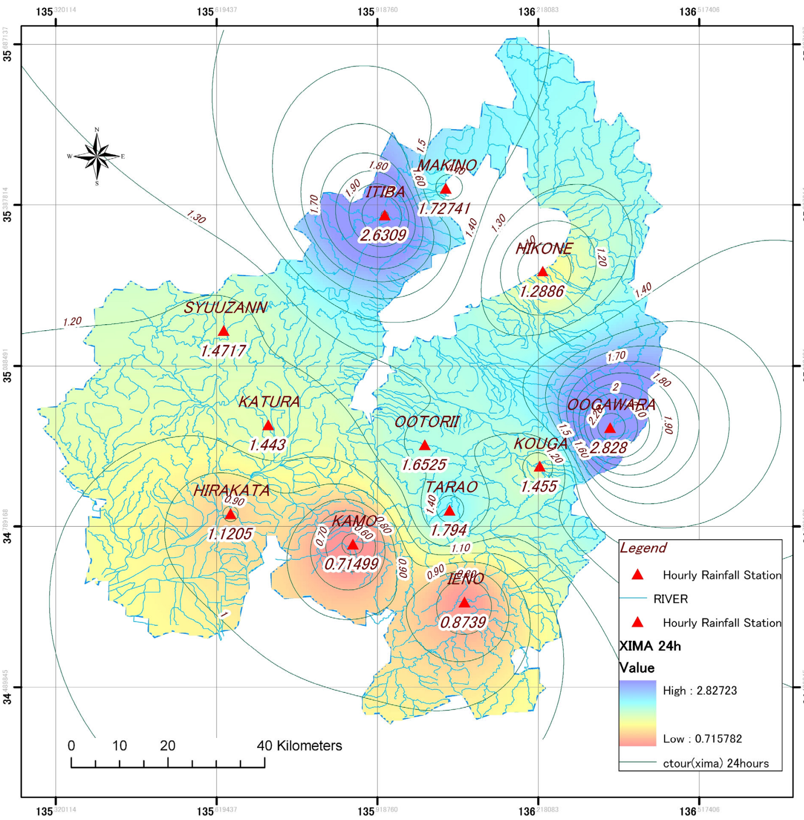

Fig. 10 Spatial distribution maps of the statistical parameters: the scale parameter (σ) of 24h rainfall AMRI.

7. Conclusion

The major findings of the present study can be summarized as follows: The properties of the time scale invariance of rainfall quantiles are examined in the Yodo River basin: for time scaling, rainfall properties follows the simple scaling; then, according to Menabde *et al.*(1999) the rainfall IDF curves for a short duration (hourly) were derived from 24-hour data. The simple scaling properties are verified by local data; the IDF relationships are deduced from daily rainfall, which shows good results in comparison with the IDF curves obtained from at-site short-duration rainfall data. Results of this study are of significant practical importance because statistical rainfall inferences can be made with the use of a simple scaling in time. Furthermore, daily data are more widely available from standard rain gauge measurements, but data for short durations are often not available for the required site.

The hypothesis of piecewise simple scaling combined with Gumbel distribution was used to develop the IDF scaling formulas depend on three parameters: the scaling exponent, the two statistical parameters: location and scale parameters of 24 hour rainfall. The spatial distribution maps of these parameters are used to derive the rainfall intensity duration frequency at ungauged points which were interested for designing analysis.

This study established the regional rainfall intensity duration frequency relationship for ungauged catchments based on three spatial distribution maps from scale invariance of rainfall in time. These analyzed results required validation of the scaling from daily to hourly data, the simulations and verifications should be studied further.

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観測の不十分な流域のためのスケール特性に基づく降水強度－期間－頻度関係

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要　旨

観測の不十分な流域における水工設計のために，スケール特性を基にしたIntensity-Duration-Frequency (IDF)関係を構築した。降水の極値水文量のスケール特性を分析し，異なる降水期間の極値水文量の積率の関係を確認した。また,低時間分解能データを高時間分解能データにダウンスケーリングするためにスケール不変性が概念（Simple Scaling）を用い，異なる降水期間に対するIDF曲線を得た。IDF曲線は極値分布Ｉ型あるいはガンベル分布をもとに導出される。分析の結果，降雨の極値水文量はシンプルスケーリングを用いて時間スケール特性を表現することが可能であることが示され，シンプルスケーリングを用いて推定された極値水文量は，直接データから推定した極値水文量とよく対応することがわかった。Ungauged な地点における降雨強度のＩＤＦ曲線を推定するための３つのパラメータの空間分布図を淀川流域を対象として作成した。

キーワード：降雨IDF関係，スケール不変性，地域頻度解析，計画降雨