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Establishment of Intensity-Duration-Frequency Curves for Precipitation in the Monsoon Area of Vietnam

Le MINH NHAT*, Yasuto TACHIKAWA, and Kaoru TAKARA

*Graduate school of Urban and Environment Engineering, Kyoto University

Synopsis

The rainfall Intensity-Duration-Frequency (IDF) relationship is one of the most commonly used tools in water resources engineering, either for planning, designing and operating of water resource projects, or for various engineering projects against floods. The establishment of such relationships was done as early as in 1932 (Bernard). Since then, many sets of relationships have been constructed for several parts of the globe. However, such map with rainfall intensity contours has not been constructed in many developing countries, including Vietnam. There is a high need for IDF curves in the monsoon region of Vietnam. This research is to construct IDF curves for seven stations in the monsoon area of Vietnam and to propose a generalized IDF formula using base rainfall depth, and base return period for Red River Delta (RRD) of Vietnam.

Keywords: Rainfall intensity, Design rainfall, Intensity-Duration-Frequency relationship (IDF), Vietnam.

1. Introduction

The rainfall Intensity-Duration-Frequency (IDF) relationship is one of the most commonly used tools in water resources engineering, either for planning, designing and operating of water resource projects, or for various engineering projects against floods. The establishment of such relationships was done as early as in 1932 (Bernard, 1932). Since then, many sets of relationships have been constructed for several parts of the globe. However, such map with rainfall intensity contours has not been constructed in many developing countries, including Vietnam. There is a high need for IDF curves in the monsoon region of Vietnam but unfortunately the adequate long historical data sets are frequently not available.

A rainfall intensity-duration-frequency (IDF) relationship is commonly required for designing of the water resource projects. There has considerable attention and research 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* (or, equivalently, the annual frequency of exceedance, typically referred to as ‘frequency’ only).

This paper proposes the approach to the formulation and construction of IDF curves using data form recording station by using empirical equations, and comparison the equations, choosing what equation can be used in the monsoon area of Vietnam. Normally, rainfall intensity-duration-frequency relationship is derived from the point rain gauges, the network of daily rainfall recording rain gauges in Vietnam has higher density than short duration (hourly or minutes) rain gauges . The regional IDF formula parameters are generated for ungauged areas to estimate rainfall intensity for various return period and rainfall duration. The method proposed in this study is reasonably applicable to ungauged rainfall locations, which is concluded from the verification of additional rain gauges. More specifically, this research is to study the generalized IDF formula using some base rainfall depth and base return period.

Two main procedures are presented in this study. The first produces the set of IDF curves at 7 stations by using empirical functions. The second produces a generalized IDF equation for location area.

The paper is organized in five sections, the first being this introduction. In Section 2 we give the traditional methods to establish IDF curves using empirical equations and regional parameters of equations. Section 3 deals with generalization rainfall intensity duration frequency formulas. Section 4 demonstrates the proposed procedures with applications using real world data (Red River Delta in Vietnam). Conclusions are drawn in Section 5.

2. Methods to establish intensity duration frequency curves for precipitation

For many hydrologic analyses, planning or design problems, reliable rainfall intensity estimates are necessary. Rainfall intensity duration frequency relationship comprises the estimates of rainfall intensities of different durations and recurrence intervals. The typical technique for establishment the IDF curves of precipitation is conducted via three steps.

The first step is to fit a Probability Distribution Function (PDF) or Cumulative Distribution Function (CDF) to each group comprised of the data values for a specific duration. It is possible to relate the maximum rainfall intensity for each time interval with the corresponding return period from the cumulative distribution function. Given a return period *T*, its corresponding cumulative frequency *F* will be:

$$F = 1 - \frac{1}{T} \quad \text{or} \quad T = \frac{1}{1-F} \qquad (1)$$

Once a cumulative frequency is known, the maximum rainfall intensity is determined using chosen theoretical distribution function (e.g. GEV, Gumbel, Pearson type III distributions). The Pearson type III distribution that is commonly used in Vietnam for frequency analysis is utilized in this study.

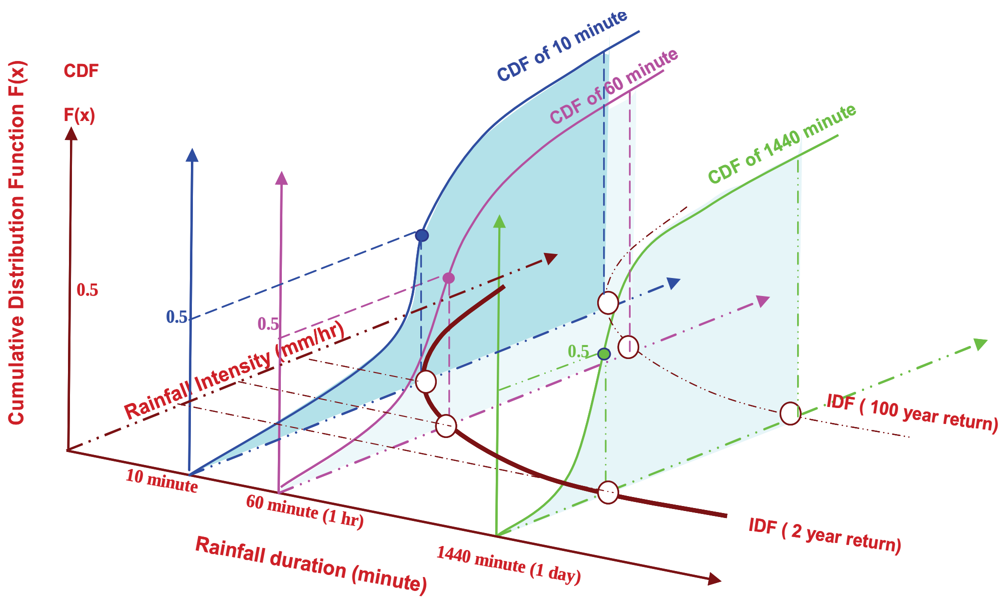


Fig. 1. The transformation of the CDF into the IDF curves.

In the second step, the rainfall intensities for each durations and a set of selected return periods (e.g. 5, 10, 20, 50,100 years, etc.) are calculated. This is done by using the probability distribution functions derived in the first step. The figure 1 show the transformation of the CDF into the IDF curves.

In the third step, the empirical formulas (Section 2.1) are used to construct the rainfall IDF curves. The least-square method is applied to determine the parameters of the empirical IDF equation that is used to represent intensity-duration relationships.

2.1 Empirical IDF formulas

The IDF formulas are the empirical equations representing a relationship among maximum rainfall intensity (as dependant variable) and other parameters of interest such as rainfall duration and frequency (as independent variables). There are several commonly used functions found in the literature of hydrology applications (Chow *et al.*, 1988), four basic forms of equations used to describe the rainfall intensity duration relationship are summarized as follows:

Talbot equation:

$$i = \frac{a}{d+b} \tag{2}$$

Bernard equation:

$$i = \frac{a}{d^e} \tag{3}$$

Kimijima equation:

$$i = \frac{a}{d^e + b} \tag{4}$$

Sherman equation:

$$i = \frac{a}{(d+b)^e} \tag{5}$$

where i is the rainfall intensity (mm/hour); d is the duration (minutes); a, b and e are the constant parameters related to the metrological conditions.

These empirical equations show rainfall intensity decreases with rainfall duration for a given return period. All functions have been widely used for hydrology practical applications. The least-square method is applied to determine the parameters of the four empirical IDF equations that are used to represent intensity-duration relationships. The value of parameters in the rainfall IDF equations were chosen on minimum of Root Mean Square Error (RMSE) between the IDF relationships produced by the frequency analysis and simulated by the IDF equation.

2.2 Regionalization of the parameter of rainfall intensity duration frequency equations

The rainfall IDF curves are derived from the point rain gauges; only sets of IDF curves at point are established. However, we need the IDF curves at any point, as the network of daily rainfall recording rain gauges in Vietnam has higher density than recording rain gauges.

The regional IDF formula parameters are generated for ungauged areas to estimate rainfall intensity for various return period and rainfall duration. The method proposed in this study had reasonable application to ungauged rainfall location, which was concluded from the verification of additional rain gauges. After determining the parameters of IDF formula such as parameters a, b and parameter e, for the same return period, using Arc view/GIS interpolating the parameter contour maps, That map can generated for the parameters which can then be used for ungauged rainfall with return periods.

For that map, it is possible to estimate the parameter set of any point in this area, the rainfall IDF curves can be constructed by using these parameters map.

3. Generalized rainfall intensity duration frequency formula

A set of Intensity-Duration-Frequency (IDF) curves constitutes a relation between the intensity (more precisely, the mean intensity) of precipitation (measured in mm/h), the duration or the aggregation time of the rainfall (in min) and the return period of the event. The return period of an event (here the rainfall intensity or depth) indicates how rate/how frequent this event is and is defined by the inverse of the annual exceedance probability. Denote by i the rainfall intensity (mm/h), d the duration of the rainfall (min) and T the return period (years). The IDF relation is mathematically as follows:

$$i = f(T, d) \qquad (6)$$

The rainfall intensity is a function of the variables T and d. 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 (or, equivalently, the annual frequency of exceedance, typically referred to as 'frequency' only). The typical IDF relationship for a specific return period is a special case of the generalized formula as given in equation (7)

$$i = \frac{a}{(d^{v} + b)^{e}} \qquad (7)$$

where a, b, e and ν are non-negative coefficients. Thus, the equation that is more general: with ν=1 and e=1 it will be Talbot equation; ν=1 and b=0 is Sherman; e=1 is Kimijima equation and ν=1 is Sherman. This expression is an empirical formula that encapsulates the experience from several studies. An numerical study shows if assumed ν=1, the corresponding error is much less than the typical estimation errors which results equation (8)

$$i = \frac{a}{(d + b)^{e}} \qquad (8)$$

Bell (1969) proposed a generalized IDF formula using the one hour, 10 years rainfall depths; P_1^{10}, as an index. Cheng-lung Chen (1983) further developed a generalized IDF formula for any location in the United States using three base rainfall depths: *1-hour* rainfall depth, *10- year* returns P_1^{10}; *24-hours* rainfall depth, *10-years* returns P_{24}^{10}, and *24-hours* rainfall depth, *100-years* returns P_1^{100}, which describe the geographical variation of rainfall. Bell developed generalized IDF relationships for high intensity short-duration rainfall. Bell established two general relationships:

$$\frac{P_d^T}{P_{60}^T} = 0.54 d^{0.25} - 0.50 \quad (5<d<120 \text{ min}) \qquad (9)$$

$$\frac{P_d^T}{P_d^{10}} = 0.21 \ln T + 0.52 \quad (2 \leq T \leq 100 \text{ years}) \qquad (10)$$

The IDF relationship produced by frequency analysis at each recording rain gauge was fitted to the following equation suggested by Bell (1969) and Chen (1983) may consider expressions of the type:

$$\frac{I_d^T}{I_{d'}^{T'}} = f_1(T) f_2(d) \qquad (11)$$

where T is the return period (year), d the rainfall duration; T' is a constant return period (year) as the base value; d' a constant rainfall duration as the base value. I_d^T is the rainfall intensity with a T year return period and d minute rainfall duration. $I_{d'}^{T'}$ is the rainfall intensity with a base T' year return period and a base d' minute rainfall duration. $f_1(T)$ is a function of only return period T and assumed to be the ratio of I_d^T to $I_d^{T'}$. Here the function does not depend on the duration d. $f_2(d)$ is a function of only duration d and assumed to be the ratio of is the ratio of I_d^T to $I_{d'}^T$. Here the function does not depend on the return period T.

Bell (1969), Chen (1983) and Koutsoyiannis *et al.* (1998) proposed the function of the return period $f_1(T)$ is the ratio of I_d^T to $I_d^{T'}$ proposed by :

$$f_1(T) = \frac{I_d^T}{I_d^{T'}} = \frac{I_{d'}^T}{I_{d'}^{T'}} = c + \lambda \ln T \qquad (12)$$

And $f_2(d)$ is the ratio of I_t^T to $I_{t'}^T$ and is a function of the rainfall duration

$$f_2(d) = \frac{I_d^T}{I_{d'}^T} = \frac{I_d^{T'}}{I_{d'}^{T'}} = \frac{a}{(d + b)^{e}} \qquad (13)$$

After combining Equation (11), (12) and (13), the generalized formula of rainfall intensity frequency can be written as

$$I_d^T = I_{d'}^{T'} (c + \lambda \ln T) \frac{a}{(d + b)^{e}} \qquad (14)$$

The equation 14 is generalized formula of rainfall intensity frequency formula using base on rainfall intensity with *d'-min* rainfall duration, and *T'-year* return period.

4. Application

Based on the above methodology, we present the real part of Vietnam. The Red River and Thai Binh River systems in the North have a basin area of 169,000 km^2. The Red River Delta area is 5,540 km^2. Annual rainfall strongly varies over the Red river area in a range 1200-2500 mm/year.

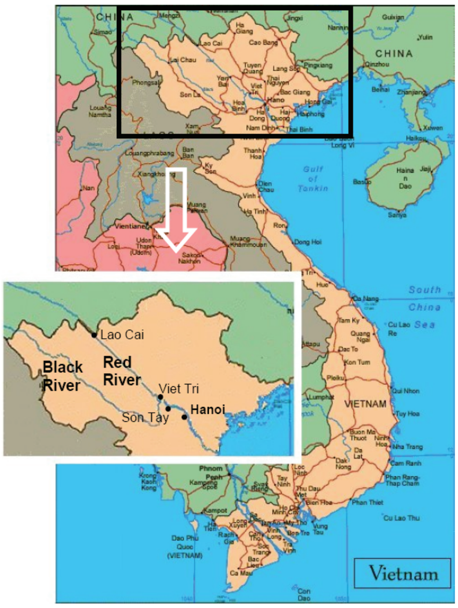


Fig. 2 Location of Red River Delta.

A 30 years record (from 1956 to 1985) of the seven stations: Hanoi (Lang), Bacgiang, Haiduong, Namdinh, Ninhbinh, Thaibinh, Vanly located at the Red River Delta in Vietnam (Figure 2) was used. The length of record for recording rain gauges is list in Table 1. The annual maximum series for various rainfall durations, i.e. 10 min, 20 min, 30 min, 45 min, 1h, 2h… 24h, were taken from the Vietnam Institute of Meteorology and Hydrology (VNIMH).

4.1 Establishment of IDF curves and comparison equations

Frequency analysis techniques are used to develop the relationship between the rainfall intensity, storm duration, and return periods from rainfall data. Analysis of distribution for rainfall frequency is based on the Pearson Type III distribution, which is commonly used in Vietnam for this kind of analysis. The Pearson Type III distribution is written as:

$$f(x) = \frac{1}{|\alpha|\Gamma(\lambda)}\left[\frac{x - x_0}{\alpha}\right]^{\lambda-1} \exp\left[-\frac{x - x_0}{\alpha}\right] \qquad (15)$$

where x_0 is the location parameter, α is the scale parameter, λ is the shape parameter. The Pearson Type III probability model is used to calculate the rainfall intensity at different rainfall durations and return periods to form the historical IDF curves for each station. Figure 3a using this frequency distribution functions, the maximum rainfall intensity for considered durations and 2, 5, 10, 20, 50,100 and 200 years return periods, have been determined. The results are shown in Figure 3b at Hanoi station. The relationship between the maximum rainfall intensities and the durations for every return periods are determined by fitting empirical functions.

Table 1. List of recording rain gauges used in the analysis.

No	Name of Station	Longitude (E)	Latitude (N)	Elevation	No. of year record
1	Hanoi (Lang)	105. 48	21.01	5.2	30
2	Bacgiang	106.12	21.17	7.1	30
3	Haiduong	106.18	20.56	2.7	30
4	Namdinh	106.10	20.26	3.2	30
5	Ninhbinh	105.58	20.14	2.1	30
6	Thaibinh	106.21	20.27	3.6	30
7	Vanly	106.30	20.02	2.3	30

Source: Vienam Institute of Meteorology and Hydrology (VNIMH)

The IDF curves for seven stations were constructions by using equations (2) to (5): Talbot, Bernard, Kimijima and Sherman. Least square method is applied to determine the parameter of four empirical IDF equations used to represent intensity-duration relationships. The value of parameter in the Rainfall IDF equations were chosen on the minimum of Root Mean Square Error (RMSE) between the IDF relationship produced by the frequency analysis and that simulated by the IDF equations. The RMSE (mean square error) was defined as

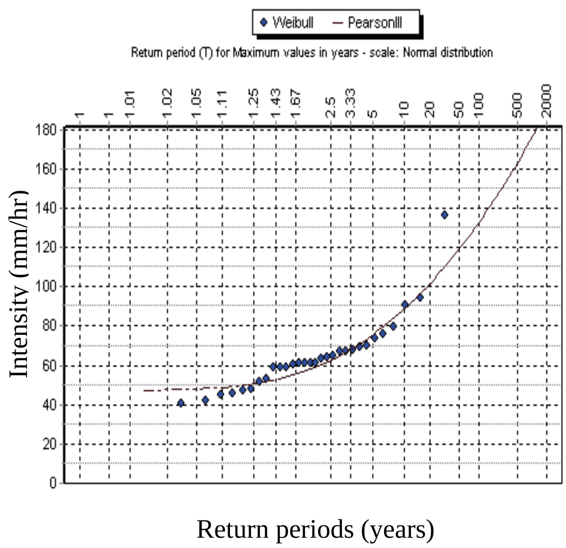
$$RMSE = \sqrt{\frac{\sum_{j=1}^{m}\sum_{k=1}^{n}\left(I_{ij}^{k} - I_{ij}^{k*}\right)^{2}}{mn}} \qquad (16)$$

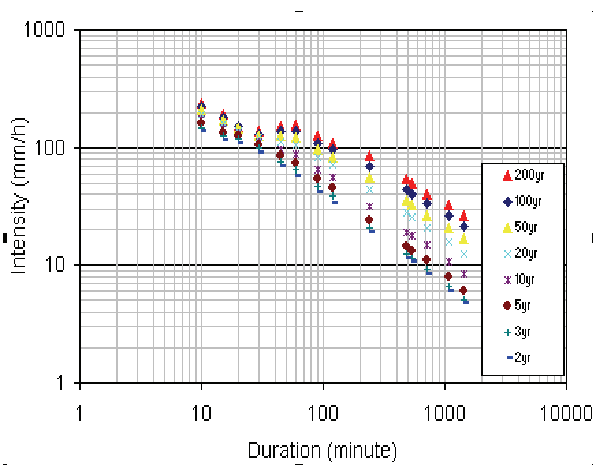
where m is the number of various rainfall durations (m=14, from 10 minutes to 24 hours), n is the number of various return periods (n=8, from 2 year to 200 year return period), $I^{k}{}_{ij}$ is the rainfall intensity derived by Pearson type III distribution for j hour duration, k year return period at the I station, and $I^{k*}{}_{ij}$ is the rainfall intensity estimated by Equation, for j hour duration, k year return period at the i station.

At the Hanoi station, the parameters of four empirical equations were determined. The IDF curves for the Hanoi station was constructed with the Kimijima equation are shown in Figure 4. The parameters are determined, presented in Table 2.

Table 2. The parameters of Kimijima equations as IDF curves

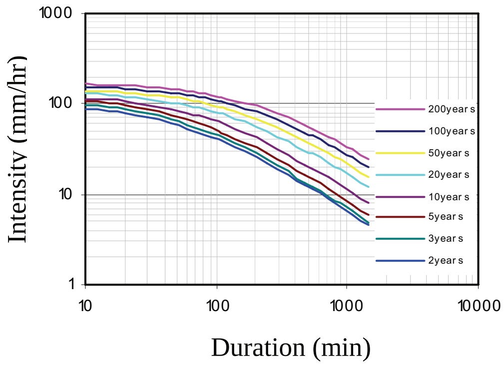
Return periods T (years)	a	b	e
200	7084.931	28.843	0.754
100	5506.794	22.112	0.752
50	4553.066	18.121	0.762
20	3934.044	15.565	0.782
10	3410.582	13.471	0.821
5	3111.113	12.510	0.853
3	2767.134	11.335	0.863
2	2349.924	9.810	0.851



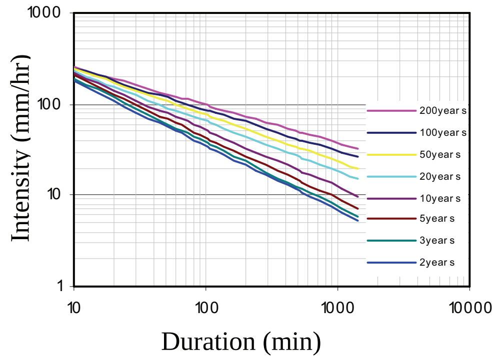


a) **b)**

Fig. 3. a) Distribution rainfall intensity (60 minutes) analysis (Pearson Type III) at Hanoi station. b) Maximum rainfall intensities for different time intervals and return periods obtained from the cumulative density function Pearson type III.



a)



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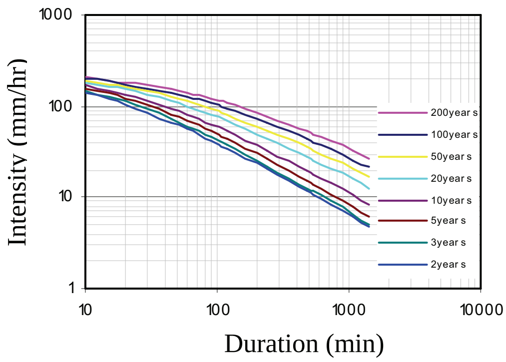

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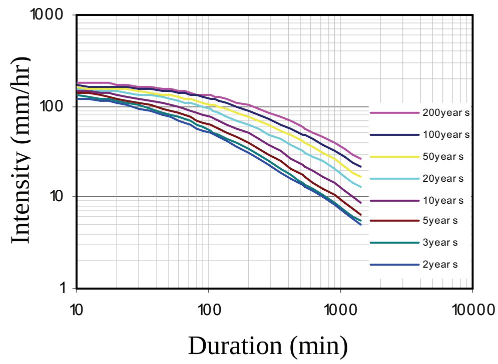

d)

Fig. 4 Rainfall Intensity Duration Frequency (IDF) curves at the Hanoi Station a) Talbot equation b)Bernard equation c) Kimijima Equation d) Sherman Equation.

Table 3 Constant parameters with 4 empirical equations at the Hanoi with 100 years return period.

Function	*a*	*b*	*e*	RMSE	R
Talbot	32979	206.22	-	5.674	0.989
Bernard	697.77	0.453	-	4.536	0.961
Kimijima	5506.7	22.112	0.752	3.217	0.998
Sherman	38183	200.62	1.011	3.801	0.99

Comparison of the results for the four empirical methods and seven stations: Table 3 and Figure 5 shows that Kimijima and Sherman equations may fit well at the Hanoi station that has Root mean square error (RMSE) only 3.2 to 4.7 mm/hour and its relative coefficient R is approximated 0.99. The results are that the Kimijima and Sherman equations are acceptable fit to the IDF relationship in Vietnam. The root mean square error with Sherman and Kimijima are less than 5 mm/ hour. The empirical IDF equations likes Kimijima and Sherman can be used for monsoon area of Vietnam. Two equations are acceptable fit to the IDF relationship in Vietnam.

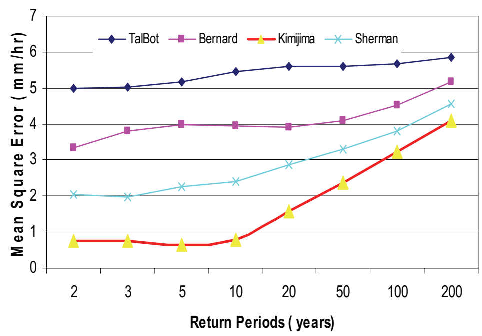

Fig. 5 Comparison Root Mean Square Error with four equations.

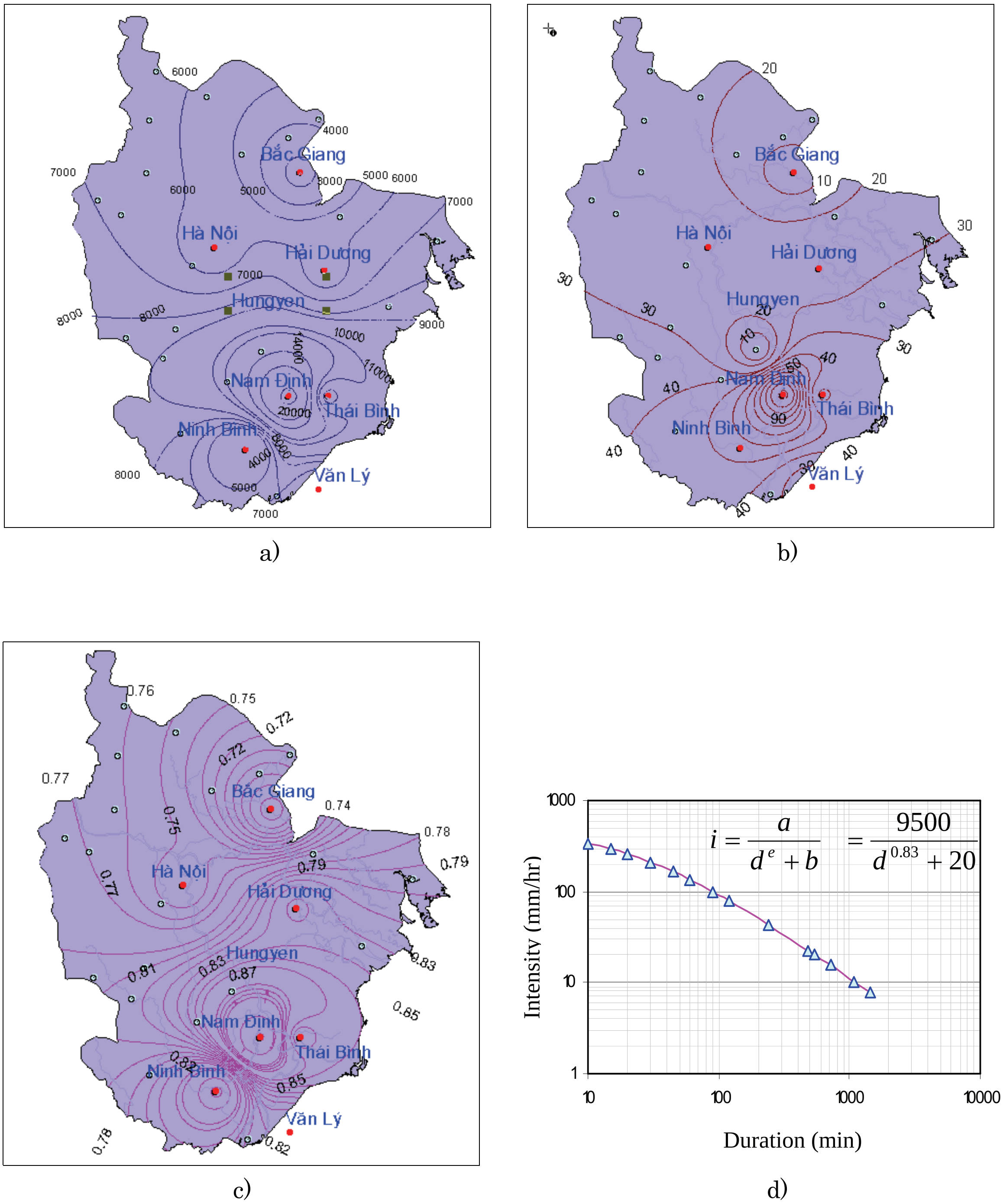

Fig. 6 Contour map of parameter of Kimijima equation with 100 years returns period and IDF curves at un - gauge point. a) Parameter a contour map b) Parameter b contour map c) Parameter e contour map and d) Rainfall IDF curves at Hungyen (ungauge location) using parameter contour maps.

4.2 Regionalization the parameter of rainfall intensity duration frequency equations

After determining the parameters of IDF formula such as parameters a, b and parameter e, for the same return period, using Arc view/GIS interpolating the parameter contour maps, that map can generated for the parameters which can then be used for ungauged rainfall with return periods.

The regional IDF formula parameters are generated for ungauged areas to estimate rainfall intensity for various return period and rainfall duration. The method proposed in this study had reasonable application to ungauged rainfall location, which was concluded from the verification of additional rain gauges. The parameters contours map for Kimijima equation created, as shown in Figure 6.

Rainfall intensity duration frequency at Hung yen (ungauged location) can determined. Parameters set: a=9500, b=20 and e=0.83. The IDF curve at Hung yen can be follow equation for 100 year return period:

$$i = \frac{a}{d^e + b} \quad = \frac{9500}{d^{0.83} + 20} \qquad (17)$$

The rainfall IDF curves for Hung yen by using that map established at figure 6.d with 100-year return.

4.3 Generalized rainfall intensity duration frequency formula at Hanoi station

(1) Intensity-Frequency Ratios

The function f_1 (T) is the ratio of I_d^T to $I_{d'}^{T'}$ and is a function of the return period (equation 11). The Hanoi station is used to illustrate how to define the generalized IDF formula. For this example: T'=100 years as the base return period. The ratio of $I_d^T \,/\, I_d^{T'=100\,years}$ for various durations and return periods are given in Table 4. The ratios show little variation with duration, and are a function of period.

Table 4 Average relationship between rainfall intensity and duration (Ratio of $I_t^T \,/\, I_t^{T'=100\ years}$) same duration at Hanoi station.

Year Return	2	3	5	10	20	50	100	200
Ratios *f*1(T)	0.41	0.45	0.5	0.6	0.74	0.86	1	1.14

The parameter λ is slope value of linear regression relationship between the log-transformed values of return periods (T) and the ratios of rainfall intensity:

$$f1(T) = \frac{I_d^T}{I_d^{100\ yr}} = 0.272 + 0.364 \log T \qquad (18)$$

The parameter λ=0.36 and *c*=0.272 with correlation coefficient value r=0.99.

Table 5. The Ratio of *I(T,d)* to *I(T,1h)* at Hanoi Station.

Duration (min)	Return period(years)										
	200yr	100yr	50yr	20yr	10yr	5yr	3yr	2yr	Ave value	StD	Coeff. variation
10	1.470	1.579	1.706	1.857	2.105	2.311	2.446	2.509	1.998	0.402	0.161
20	1.321	1.386	1.460	1.545	1.681	1.787	1.853	1.876	1.614	0.216	0.047
30	1.213	1.252	1.295	1.344	1.420	1.478	1.511	1.521	1.379	0.120	0.014
45	1.092	1.107	1.123	1.141	1.167	1.187	1.198	1.200	1.152	0.042	0.002
60	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000
90	0.866	0.850	0.833	0.814	0.788	0.770	0.761	0.759	0.805	0.042	0.002
120	0.771	0.747	0.721	0.694	0.657	0.631	0.619	0.618	0.682	0.060	0.004
240	0.557	0.523	0.490	0.455	0.409	0.379	0.366	0.366	0.443	0.075	0.006
480	0.379	0.348	0.317	0.286	0.245	0.220	0.210	0.211	0.277	0.066	0.004
540	0.353	0.323	0.293	0.263	0.224	0.200	0.190	0.192	0.255	0.063	0.004
720	0.296	0.269	0.242	0.215	0.180	0.159	0.150	0.151	0.208	0.057	0.003
1080	0.228	0.206	0.183	0.160	0.131	0.114	0.107	0.108	0.155	0.047	0.002
1440	0.188	0.169	0.149	0.129	0.104	0.090	0.084	0.085	0.125	0.041	0.002

(2) Intensity-Duration Ratios

The intensity-duration ratios (or depth-duration ratios) are calculated for each available data. The calculations are made in order to obtain the average value of the ratios each considered durations. Table 5 shows ratios 60-minute rainfall intensity and duration (Ratio of $I_t^T / I_{t'=60'}^T$) for same return period T. The ratios show little variation with return periods, and are a function of the rainfall duration.

The ratio *f2* was fitted by Sherman equation:

$$f_2(d) = \frac{I_d^T}{I_{d'}^T} = \frac{I_d^{T'}}{I_{d'}^{T'}} = \frac{88.93}{(d+76.31)^{0.945}} \qquad (19)$$

The parameter a=88.93, b=76.31 and *e*=0.945 with correlation coefficient value r=0.99 and RMSE=13.56 (mm/hr).

Combining equation (18), (19) the generalized Intensity Duration Frequency formula at Hanoi (Hanoi), with rainfall intensity in 60 minutes and 100 years return is 125.59 mm/hr, gives:

$$I_d^T = 125.59(0.272 + 0.364 \ln T)\frac{88.93}{(d+76.31)^{0.94}}$$

Generalized rainfall intensity duration frequency formula at Hanoi station as:

$$I_d^T = \frac{3037.8 + 4065.4 \ln T}{(d+76.31)^{0.94}} \qquad (20)$$

The rainfall intensity can calculate from (20) equation for any duration (d) and return periods (T) at Hanoi station.

5. Conclusions

This study has been conducted to the formulation and construction of IDF curves using data form recording station by using empirical equations, four empirical functions used to represent Intensity-Duration-Frequency relationship for Red River Delta (Vietnam). In general, the 3 parameters functions (Kimijima and Sherman) showed acceptable fitting to the rainfall intensity quartiles.

The regionalization of the parameters of rainfall intensity-duration-frequency equations were generated for ungauged areas to estimate rainfall intensity for various return period and rainfall duration. The parameter contour maps were made to estimate ungauged rainfall with return periods. More specifically, this research is to generalize IDF formula using some base rainfall depth and base return period.

In fact, IDF curves give the rainfall intensity at a point. Storm spatial characteristics are important for larger catchments. Intensity-Duration-Area-Frequency curve (IDAF) is studied for the evaluation of design storms using a scaling approach.

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Notation

The following symbols are used in this paper:

- I_d^T = rainfall intensity for t-min duration and T-year return periods;
- I_{60}^T = rainfall intensity for 60-min duration and T-year return periods;
- I_d^{100} = rainfall intensity for t-min duration and 100-year return periods;
- i = rainfall intensity (mm/hr)
- P = rainfall depth (mm)
- T = return period (years); and
- d = rainfall duration (min).

モンスーン域ベトナムにおける降水の強度－期間－頻度曲線の構築

Le minh NHAT *・立川康人・宝　馨

＊京都大学大学院工学研究科都市環境工学専攻

要　旨

降水の強度－期間－頻度曲線（rainfall Intensity-Duration-Frequency (IDF) relationship）は，水工計画や水工設計，様々な水資源プロジェクトにおいて最も共通に使われる有用なツールである。IDF曲線の構築はBernard(1932)によって初めてなされ，それ以来，多くの関係式が世界中で提案されてきた。しかしながら，そのような関係式を用いた降水の等値線図は，ベトナムを含めてアジアモンスーン域の多くの発展途上国で極めて需要が高いにも関わらず，充分作成されていない。本研究ではベトナムにおける7箇所の降雨観測所におけるIDF曲線を構築し，一般化IDF曲線をベトナム Red River Delta (RRD)を対象に構築する。

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