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Estimation of regional intensity–duration–frequency relationships of extreme rainfall by simple scaling in Thailand

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ABSTRACT

In 2022, Thailand was subjected to extensive flooding all over the country in both urban and rural areas, which caused tremendous losses. Better design and construction of infrastructures for timely and sufficient drainage can help mitigate the problems. This requires accurate intensity–duration–frequency (IDF) relationships at or near the problem areas. To obtain an IDF curve, a continuous rain record from an automatic gauge of the area is needed. Some automatic rain-gauge stations are scattered all over the country and are much fewer in number than the daily-reading rain-gauge stations. By applying a simple scaling theory, we can construct IDF curves from the daily rain records. The 37 automatic stations distributed the scaling exponent over the country. Gumbel location and scale parameters, from 30-year rainfall records, were determined. These three parameters were mapped throughout the country and are ready to be used for creating an IDF curve at any location in the country. We verified these parameters to generate IDF curves for three sites in different regions and found very good agreements. The majority of the errors were less than 15%.

Key words: extreme rainfall intensity, regional IDF relationship, simple scaling, Thailand

HIGHLIGHTS

- Flooding is always a big problem in Thailand.
- This requires accurate intensity–duration–frequency (IDF) relationships at the problem areas.
- By application of simple scaling theory, we can construct IDF curves from the daily rain records.
- Gumbel location and scale parameters were mapped throughout the country and ready to be used for creating an IDF curve at any location in the country.
- The errors by majority were less than 15%.

INTRODUCTION

As a tropical and monsoonal climate country, Thailand is subjected to flooding every year of various degrees and locations. The rainy season spans 6 months from May to October, with the first half dominated by convective rain and the second by tropical cyclones. The rainfall characteristics of the first half are therefore heavy but short-lived, while those of the second are milder but for longer periods. Both flash floods and river floods can occur in Thailand. For example, in 2011, the country's flood claimed 681 lives and caused USD 46.5 billion in damage (Poaponskorn & Meethom 2013). Recently, in 2022, both flash and river floods had cumulative humanitarian impacts on the Thai people. Much of the flooding was exacerbated by major dams being pushed to their capacities, which resulted in raised river levels downstream through the urgent release of water (IFRC 2023). Flood preventions all over the country therefore urgently need to be revised and improved with updated information.

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The intensity–duration–frequency (IDF) relationship is a basic tool for flood prevention and other water resource management tasks. It is used to calculate maximum rainfall intensity at a specified rainfall duration and return period. The IDF relationship is normally presented in a graphical form, called an IDF curve, with rainfall intensity on the *X*-axis and duration on the *Y*-axis, with a series of return periods. An IDF curve is created from an automatic rainfall record spanning at least 30 years. The maximum annual series of rainfall intensities, extracted from the records for each duration, are related to return periods using probability theory such as Extreme Value Type 1 (EV1). The number of automatic recorders in the whole country is not as large as that of daily recorders, therefore by using the scaling property, we can convert daily IDF relationships to sub-daily ones.

The IDF curves were long studied and established in Thailand, but they were only applied to a small portion of the nation. As a result, Mustonen (1969) first suggested 14 curves: 5 for the Northeast; 2 for the Northern, Central, Eastern, and Southern regions; including 1 for the Western region. The Royal Irrigation Department (RID), Thailand's primary institution in charge of irrigation and drainage, released a complete analysis of IDF curves for all 59 curves, with 20 curves for the North, 10 for the Northeast, 5, 8, 4, and 12 curves, respectively, for the Central, East, West, and South (Bumpenkit 1999). In addition to the developed equations for rainfall intensity, Rittima *et al.* (2013) updated the IDF curve for rainfall durations of 0.25, 0.50, 0.75, 1, 2, 3, 6, and 12 h, covering 19 provinces and 11 catchment areas. The IDF curves under climate change uncertainty for the Bangkok area were created by Shrestha *et al.* (2017). Utilizing the Long Ashton Research Station Weather Generator (LARS-WG), a stochastic weather generator, and the rainfall disaggregation tool Hyetos, they investigated a methodology based on the spatial downscaling-temporal disaggregation method (DDM) to develop future IDFs. Additionally, Yamoat *et al.* (2022) developed IDF curves for six regions of Thailand, i.e., the Northern, Northeastern, Central, Western, Eastern, and Southern regions. They found that using accurate historical sub-hourly rainfall time series to create a set of IDF curves would be more reliable than using forecasted rainfall modeling. However, these IDF curves can be used in a regionally averaged way. If we could find the specific IDF curve for ungauged sites, that would be excellent.

The ability of these techniques to estimate the IDF characteristics for ungauged sites is constrained. They could not transfer the IDF features from gauged sites to other sites. This is due to the fact that at sites where rainfall records are not available or the data sample is small, the 'Simple Scaling' method should be used. Here are some examples. Nhat *et al.* (2008) developed the regional IDF curves based on scaling properties for the Yado River catchment in Japan. Bara *et al.* (2009) approximated the IDF curves of extreme rainfall by using simple scaling in Slovakia. Chang & Hiong (2013) estimated the sub-daily IDF curves in Singapore using simple scaling. Galiatsatou & Iliadis (2022) studied the IDF curves at ungauged sites in a changing climate for sustainable stormwater networks in the village of Fourni, which is in the northeastern part of the island of Crete in Greece. Casas-Castillo *et al.* (2022) presented a simple scaling analysis of rainfall in Andalusia (Spain) under different precipitation regimes. Yuksek *et al.* (2022) created the regional IDF curves with the emphasis of Eastern Black Sea basin in Turkey. In summary, the results of these studies showed the good performance of the regional IDF curves.

The purpose of the study is to investigate the scale variance (or scaling properties) of rainfall for the derivation of IDF relationships at ungauged sites. To determine the scaling behavior of statistical moments over various durations, the scaling properties of intense rainfall are explored in this study, along with the updating of IDF curves across the entire country of Thailand. Firstly, using the annual maximum rainfall intensity (AMRI) records for varying durations and return periods at the 37 selected stations spread all over Thailand, the scaling exponent for each gauge site and the space variation of the scale exponents were explored. The scale exponent and two statistical parameters of 24-h rainfall data can be used to construct the IDF relationships. Secondly, the IDF relationships at any location are constructed by interpolating these parameters from their contour maps. Finally, the regional scaling model's IDF relationships at the ungauged locations are investigated.

STUDY AREA

The study area was the whole country of Thailand. The rainfall data for analysis herein were collected from 37 continuous rain gauges (from 1990 to 2019). The locations of rain gauge stations are shown in Figure 1. The name and location for recording rain gauges are listed in Table 1. The AMRI series for various durations, including 0.25, 0.5, 0.75, 1, 2, 3, 6, 12, and 24 h, were taken.

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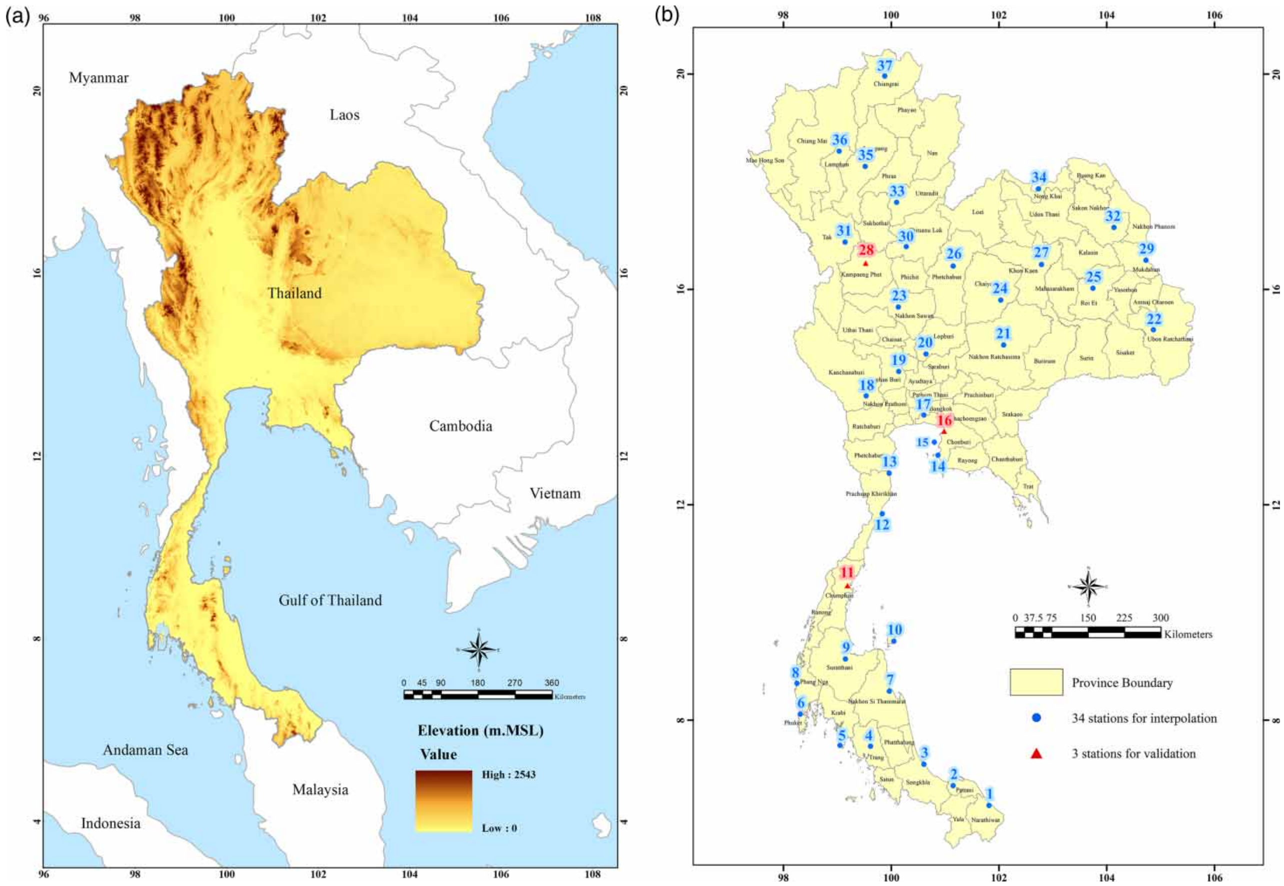

Figure 1 | Study area and rain gauge locations. (a) Spatial extent of the study area, (b) the locations of rain gauging stations analyzed. Remark: Dots are those stations used to develop relationships, and triangles are those used for validation.

METHODS

Simple scaling hypothesis

Hydrologic data from one time scale was converted to another using scaling models in order to avoid the problem of insufficient data. Numerous scholars have looked into the fundamental theoretical development of scaling, including Gupta & Waymire (1990) and Kuzuha *et al.* (2005). The rainfall intensity $I(d)$ with duration d shows the following equation holds true.

$$I(\lambda d) \overset{dist}{=} \lambda^{H} I(d) \tag{1}$$

The equality '$\overset{dist}{=}$' refers to identical probability distributions in both sides of the equation; λ denotes a scale factor which can alter the duration d to another duration, and H is a scaling exponent (Menabde *et al.* 1999). From Equation (1), it leads to a simple scaling law in a wide sense

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

where $E[\,]$ is the expected value operator and q is the moment order. If Equation (2) is true, the random variable $I(d)$ displays simple scale invariance in a wide sense. If H is a non-linear function of q, the I(d) is a general case of multi-scaling. For each moment order q, the moments $E[\,]$ are plotted on a logarithmic chart against the scale λ. Whereupon, the slope function of the order moment $K(q)$ is plotted on the linear chart against the moment order q. If the plotted results are on a straight line

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Table 1 | The stations and locations

	Name of stations	Latitude	Longitude
1	Narathiwat	6°25′00.0″	101°49′00.0″
2	Pattani	6°47′00.0″	101°09′00.0″
3	Songkhla	7°10′55.6″	100°36′27.7″
4	Trang	7°31′00.0″	99°37′00.0″
5	Kho Lanta	7°32′00.0″	99°03′00.0″
6	Phuket Airport	8°06′38.0″	98°18′45.0″
7	Nakhon Si Thammarat	8°32′16.0″	99°57′50.0″
8	Takua Pa	8°41′03.0″	98°15′08.0″
9	Surat Thani	9°08′08.0″	99°09′07.0″
10	Samui	9°28′00.0″	100°03′00.0″
11	Chumphon	10°29′55.5″	99°11′18.5″
12	Prachuap Khiri Khan	11°50′00.0″	99°50′00.0″
13	Hua Hin	12°35′10.0″	99°57′45.0″
14	Pattaya	12°55′12.0″	100°52′10.0″
15	Koh Sichang	13°09′42.0″	100°48′07.0″
16	Chon Buri	13°22′00.0″	100°59′00.0″
17	Bangkok	13°39′59.0″	100°36′22.0″
18	Kanchanaburi	14°01′21.0″	99°32′09.0″
19	Suphan Buri	14°28′28.0″	100°08′20.0″
20	Lop Buri	14°47′59.0″	100°38′42.0″
21	Nakhon Ratchasima	14°58′05.9″	102°05′09.7″
22	Ubon Ratchathani	15°15′00.0″	104°52′00.0″
23	Nakhon Sawan	15°40′18.6″	100°07′56.5″
24	Chaiyaphum	15°48′00.0″	102°02′00.0″
25	Roi Et	16°01′12.0″	103°44′38.0″
26	Phetchabun	16°26′00.0″	101°09′00.0″
27	Khon Kaen	16°27′40.0″	102°47′23.0″
28	Kamphaeng Phet	16°29′12.5″	99°31′37.1″
29	Mukdahan	16°32′29.0″	104°43′44.0″
30	Phitsanulok	16°47′41.3″	100°16′45.5″
31	Tak	16°52′42.0″	99°08′36.0″
32	Sakon Nakhon	17°09′00.0″	104°08′00.0″
33	Uttaradit	17°37′00.0″	100°06′00.0″
34	Nong Khai	17°52′01.8″	102°43′58.9″
35	Lampang	18°17′00.0″	99°31′00.0″
36	Lamphun	18°34′02.0″	99°02′02.0″
37	Chiang Rai	19°57′41.0″	99°52′53.0″

through the origin, the random variable shows simple scaling. Otherwise, the multi-scaling approach must be considered (Gupta & Waymire 1990).

The extreme value type I (EVI) distribution, created by Gumbel, is still the most often used distribution by many national meteorological services worldwide to represent rainfall extremes. The IDF curves are frequently fitted to this distribution. In this study, it will be utilized in conjunction with the method of moments. The annual maximum rainfall intensity $I(d)$ has a

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cumulative probability distribution (CDF), which is given by

$$F[I(d)] = 1 - 1/T = \exp[-\exp\{-[I(d) - \mu]/\sigma\}] \quad (3)$$

$$I(\lambda d) = \mu - \sigma \ln(-\ln T) \quad (4)$$

where T is the return period. The location parameter μ and scale parameter σ to be calculated from data series based on the L-moment method.

$$\mu = \bar{x} - 0.5772s \quad (5)$$

$$\sigma = \sqrt{6}s/\pi \quad (6)$$

where $\bar{x}$ and s are mean and standard deviation of the annual maximum intensity series. According to the scaling theory, the IDF formula can be derived (Menabde *et al.* 1999) with

$$I_{d,T} = \{\mu_d + \sigma_d[-\ln(-\ln(1 - 1/T))]\}/d^{-H} \quad (7)$$

$$\mu_d = \lambda^{-H}\mu_{24} = (d/24)^{-}H\mu_{24} \quad (8)$$

$$\sigma_d = \lambda^{-H}\sigma_{24} = (d/24)^{-}H\sigma_{24} \quad (9)$$

where the μ_{24} and σ_{24} are parameters of 24-h data series. It is worthwhile to note that the simple scaling hypothesis leads to equality between the scale factor and the exponent in the expression relating rainfall intensity and duration. The scale exponent, the location, and the scale parameters of the EVI distribution can be used to derive the IDF relationship from a 24-h data series.

Spatial distribution of scale exponent

The scaling invariance of rainfall can be used to generate the IDF relationship. It depends on the scaling exponent H, the location parameter μ_{24}, and the scale parameter σ_{24} of the 24-h rainfall

$$I(d, T) = f(H, \mu_{24}, \sigma_{24}) \quad (10)$$

where T is the return period and d is the duration of rainfall intensity. The regional IDF relationship can be developed based on three parameters. Firstly, the scaling exponent H was to be examined for 37 stations in Thailand. Secondly, the two parameters of statistical analysis: μ_{24} and σ_{24} were derived from the distribution of the 24-h AMRI data series. With the values of these parameters at 34 stations, spatial distributions of these parameters are constructed by using the GIS interpolation technique. The IDF relationship for any ungauged point can be derived based on these maps and Equations (7)–(9). To this end, the assumption of scaling was tested at a representative sample of stations across Thailand after the scaling of IDF estimates was confirmed at three sites. The available continuous data at these stations was recorded by the Thai Meteorological Department. An AMRI data set was derived from the data, and the first five moments were calculated for the duration of 0.25- to 24 h. These moments were plotted against duration on a log–log scale to ascertain whether scaling could be assumed.

Estimation of the parameters at ungauged sites

The maps of the three parameters (H, μ_{24}, and σ_{24}) can be constructed by using the inverse-distance-weighted (IDW) interpolation method in ArcGIS. The IDW is an exact local deterministic interpolation for estimating spatial data based on the principle that the data from nearby locations are spatially correlated. This technique calculates an unknown value using the linear sum of known values from other locations and weighting by distance. The nearest known data value will be the most significant or weighted value in estimating the unknown value, and this weighted value will change as the distance between the unknown location and the next known location increases (ESRI 2008). The estimated values were obtained.

$$Z^* = \Sigma\, Z_i d_i^{-p} / \Sigma\, d_i^{-p}, \quad i = 1, 2, \ldots, n \quad (11)$$

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where d_i is the distance from each of the n observed locations to the location being estimated, and Z_i is the observed values at those locations. The parameter is the power value (p), determined by minimizing the RMSE using the cross-validation technique.

The values of the parameters (H, μ_{24}, and σ_{24}) were estimated from isoline maps of the study area. Then the root-mean-square errors (RMSE) and mean absolute relative percentage errors (MRPE) estimation values were obtained.

$$\mathrm{RMSE}(d, T) = \sqrt{\left(\sum (I_i(d, T)^* - I_i(d, T))^2\right)/n}, \quad i = 1, 2, \ldots, n \tag{12}$$

$$\mathrm{MRPE}(d, T) = \left\{\sum |[I_i(d, T)^* - I_i(d, T))]/I_i(d, T)|/n\right\} \times 100\%, \quad i = 1, 2, \ldots, n \tag{13}$$

where $I_i(d,T)^*$ indicates the rainfall intensity of duration d and return period T estimated by the regional scaling model and $I_i(d,T)$ indicates the rainfall intensity from the EV1 distribution.

RESULTS AND DISCUSSION

The aim of the study was to ascertain whether simple scaling could be used to represent regional IDF relationships for ungauged locations. According to the behavior of scaling relationships in statistical moments over various durations, the scaling properties of extreme rainfall were explored.

Spatial distribution of scale exponent

The results of the spatial distribution analysis show the strong validity of the simple scaling properties of the extreme rainfall in time series. For example at the Bangkok station, which is in the central region of Thailand, the qth moment of the intensity is displayed against the duration in Figure 2. It shows the linear relationship between the data and the fact that there is no break as regards the 0.25- to 24-h duration data. The linearity of the moments exhibited here is comparable to the other 36 stations that were analyzed, demonstrating that scaling appears to be relevant throughout Thailand for the 0.25- to 24-h duration. To examine whether or not the basic scaling applies and to estimate the scale exponent, H, for stations

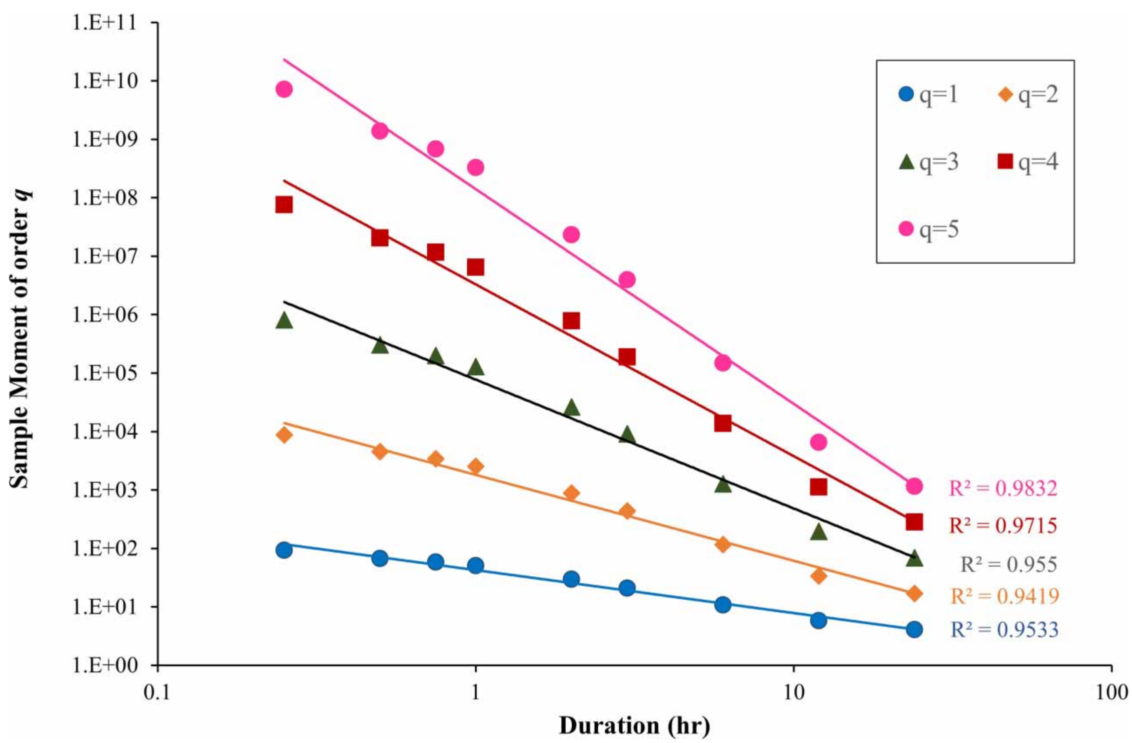

Figure 2 | Relationship between moment of order q and duration at the Bangkok station.

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throughout the catchment, the slope function, $K(q)$, was plotted against the moment, q, for each station. The scaling exponent coefficient for the Bangkok station is 0.755, with an R^2 value of 0.9999, as shown in Figure 3. This indicates that simple scaling could be assumed at this station instead of the more complex multi-scaling.

Similar scaling relationships were apparent in the data from the other gauges. This suggests that simple scaling may be appropriate in Thailand for the considered durations. Table 2 displays the findings of the scaling exponent factor H for the 37 stations in Thailand, with high coefficients of determination (R^2) ranging from 0.97 to 1.0 for each station. The results indicate a strong validity of the simple scaling property of the extreme rainfall in time series.

Estimation of the parameters at ungauged sites

The spatial distribution maps of the scaling exponent parameters H generated by the 34 stations are shown in Figure 4. By using statistical analysis based on the L-moment approach, it is possible to determine the location parameter μ_{24} and scale parameter σ_{24} of the EV1 distribution of the 24-h AMRI. The results are shown in Table 2. With the same technique, two maps of statistical parameters can be constructed, as shown in Figures 5 and 6. It is expected that those three maps are applicable for any ungauged locations within Thailand and that it is required to verify these maps for regional IDF relationships.

As a result of the hilly terrain in the north and east of Thailand, and there are not many observatories there, it is better to have information on the surrounding areas from neighboring countries that the IDW method will be more accurate to generate IDF curves at these locations. However, the IDW method outperforms multi-quadric interpolation and traditional kriging (Ware 2005).

Application and validation of the regional scaling model

The regional scaling model can be applied at any site in the study region for storm duration d equal to 0.25, 0.5, 0.75, 1, 2, 3, 6, 12, and 24 h. For each storm duration d and return period T, the design storm $I(d,T)$ can be evaluated as follows:

(1) Estimate the local scale exponent (H) value for the site of interest by interpolating from the map in Figure 4.

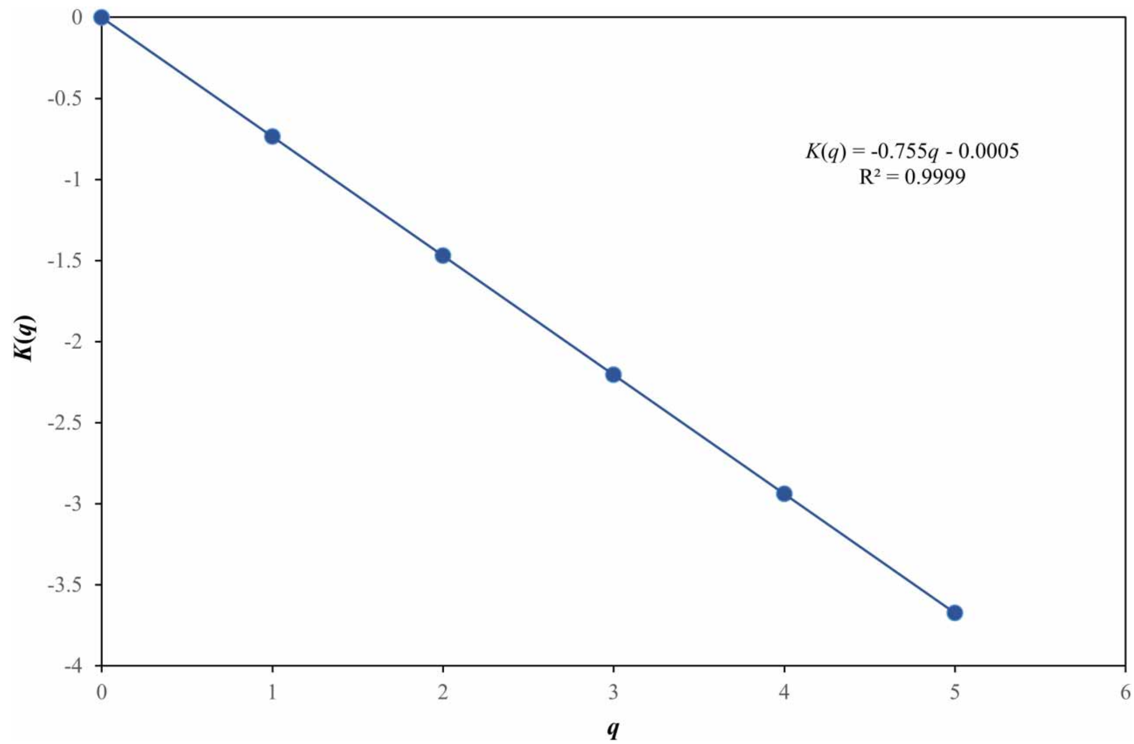

Figure 3 | Relationship between slope function $K(q)$ and the order moment q at the Bangkok station.

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Table 2 | The parameters at recording rain gauge

	Name of stations	Scale exponent (H)	Location parameter (μ_{24})	Scale parameter (σ_{24})
1	Narathiwat	0.554	5.996	2.518
2	Pattani	0.647	4.273	1.639
3	Songkhla	0.656	4.731	3.005
4	Trang	0.682	3.549	1.25
5	Kho Lanta	0.695	3.55	1.574
6	Phuket Airport	0.71	4.254	1.197
7	Nakhon Si Thammarat	0.546	6.685	3.048
8	Takua Pa	0.653	6.073	0.888
9	Surat Thani	0.748	3.018	2.058
10	Samui	0.71	5.75	1.225
11	Chumphon	0.709	3.792	1.749
12	Prachuap Khiri Khan	0.618	3.965	2.155
13	Hua Hin	0.756	2.698	1.193
14	Pattaya	0.728	2.717	1.142
15	Koh Sichang	0.812	2.976	0.994
16	Chon Buri	0.812	2.797	0.987
17	Bangkok	0.755	3.332	1.332
18	Kanchanaburi	0.821	2.979	0.92
19	Suphan Buri	0.793	2.169	1.458
20	Lop Buri	0.703	2.437	1.438
21	Nakhon Ratchasima	0.723	2.607	0.832
22	Ubon Ratchathani	0.715	3.253	1.274
23	Nakhon Sawan	0.75	1.372	1.443
24	Chaiyaphum	0.778	3.178	0.949
25	Roi Et	0.697	2.623	1.707
26	Phetchabun	0.748	1.615	1.462
27	Khon Kaen	0.699	1.968	1.947
28	Kamphaeng Phet	0.78	2.367	1.146
29	Mukdahan	0.729	2.662	1.213
30	Phitsanulok	0.758	2.737	1.175
31	Tak	0.783	2.738	1.216
32	Sakon Nakhon	0.698	3.213	1.861
33	Uttaradit	0.749	2.414	1.934
34	Nong Khai	0.67	2.718	1.226
35	Lampang	0.755	2.506	1.271
36	Lamphun	0.795	2.542	1.006
37	Chiang Rai	0.7	3.603	1.224
	Mean	0.720	3.293	1.477
	Standard Deviation	0.064	1.225	0.538

(2) Estimate the location and scale parameters (μ_{24} and σ_{24}) of 24-h duration from Figures 5 and 6, respectively.
(3) Calculate μ_d and σ_d of a specified duration, d, from Equations (8) and (9), respectively.
(4) Calculate the extreme rainfall intensity of specified duration and return period from Equation (7).

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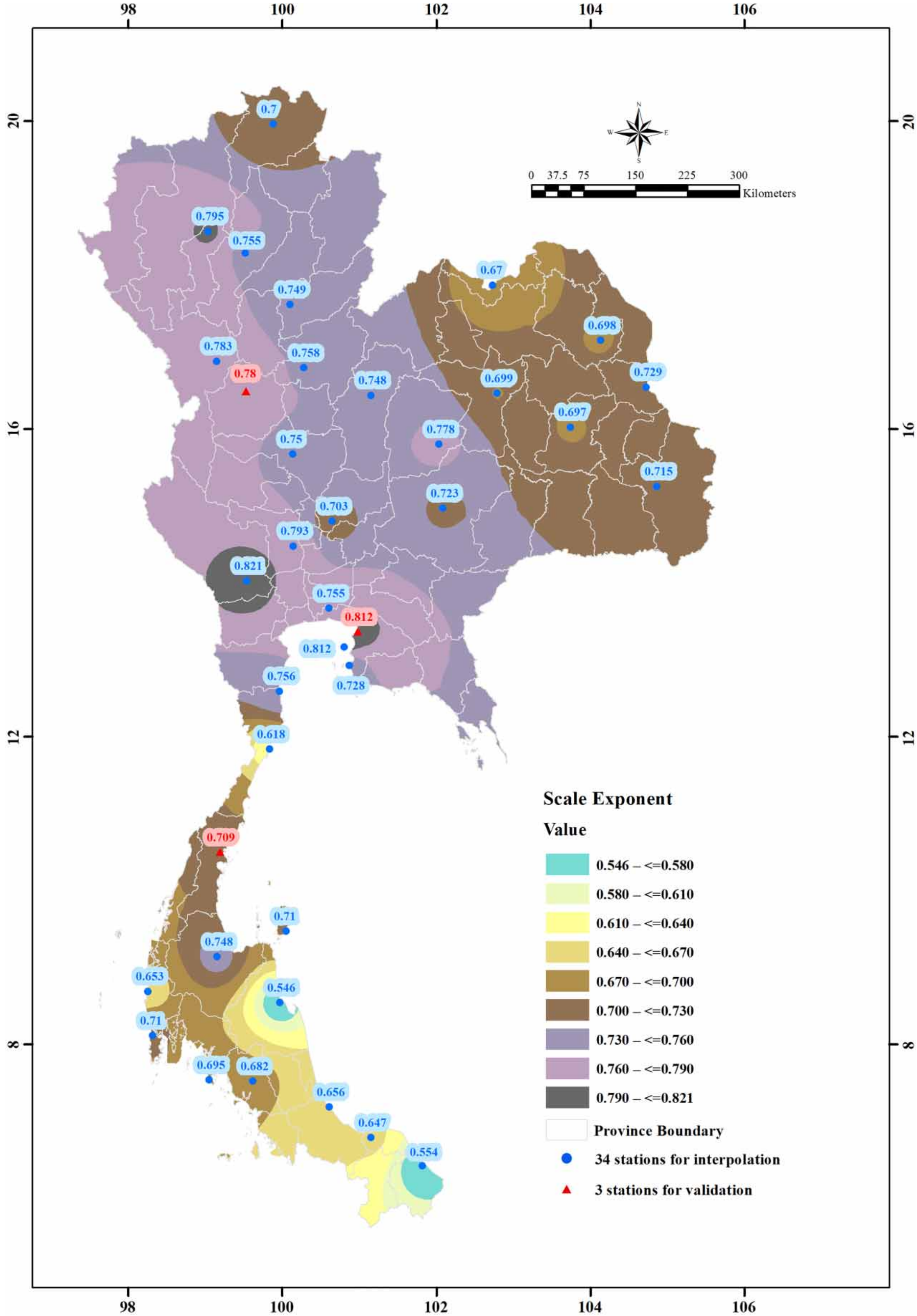

Figure 4 | Spatial distribution of the scaling exponent (*H*) of 24-h intensity. Remark: Dots are those stations used to develop relationships, and triangles are those used for validation.

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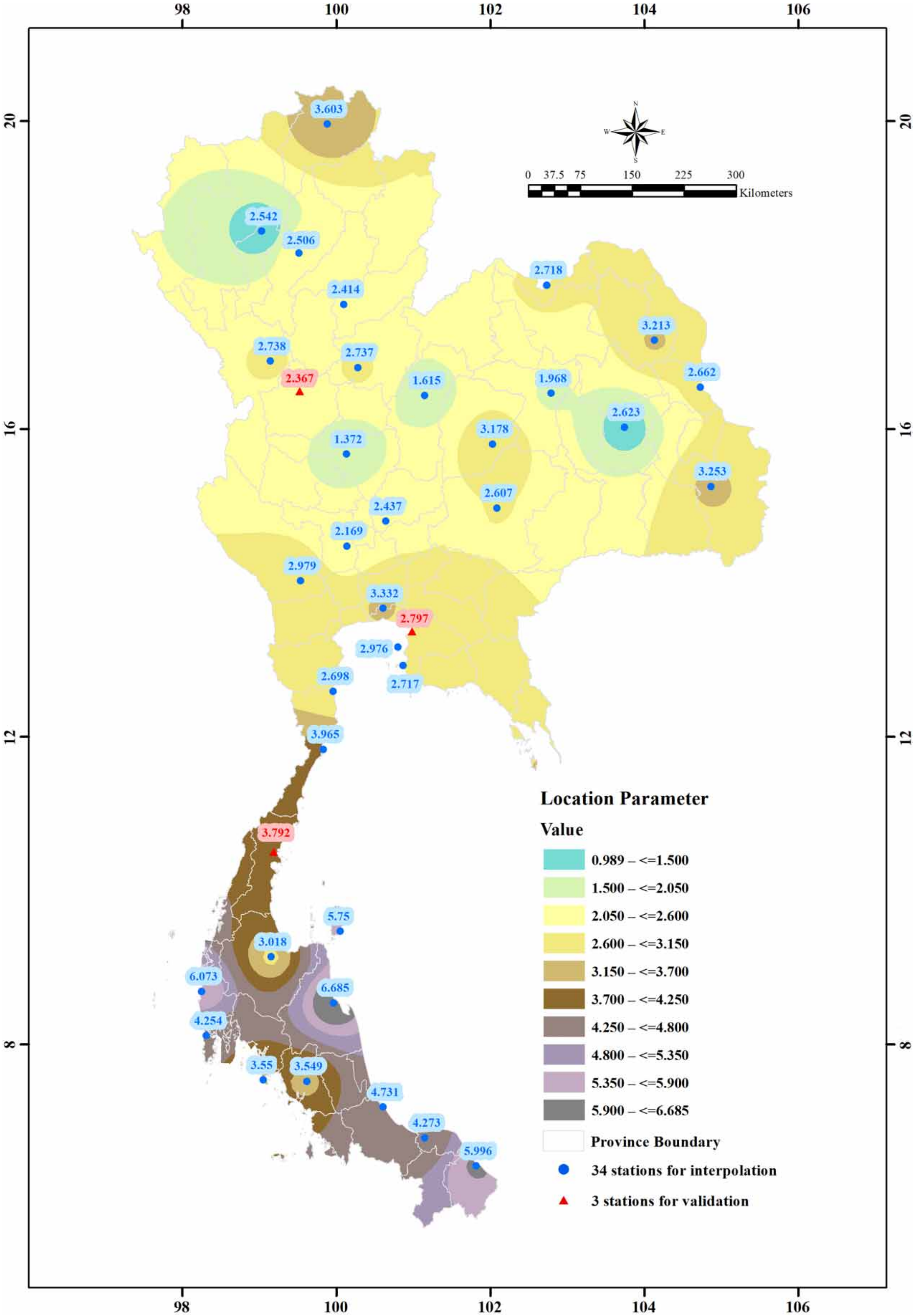

Figure 5 | Spatial distribution of the location parameter (μ_{24}) of 24-h intensity. Remark: Dots are those stations used to develop relationships, and triangles are those used for validation.

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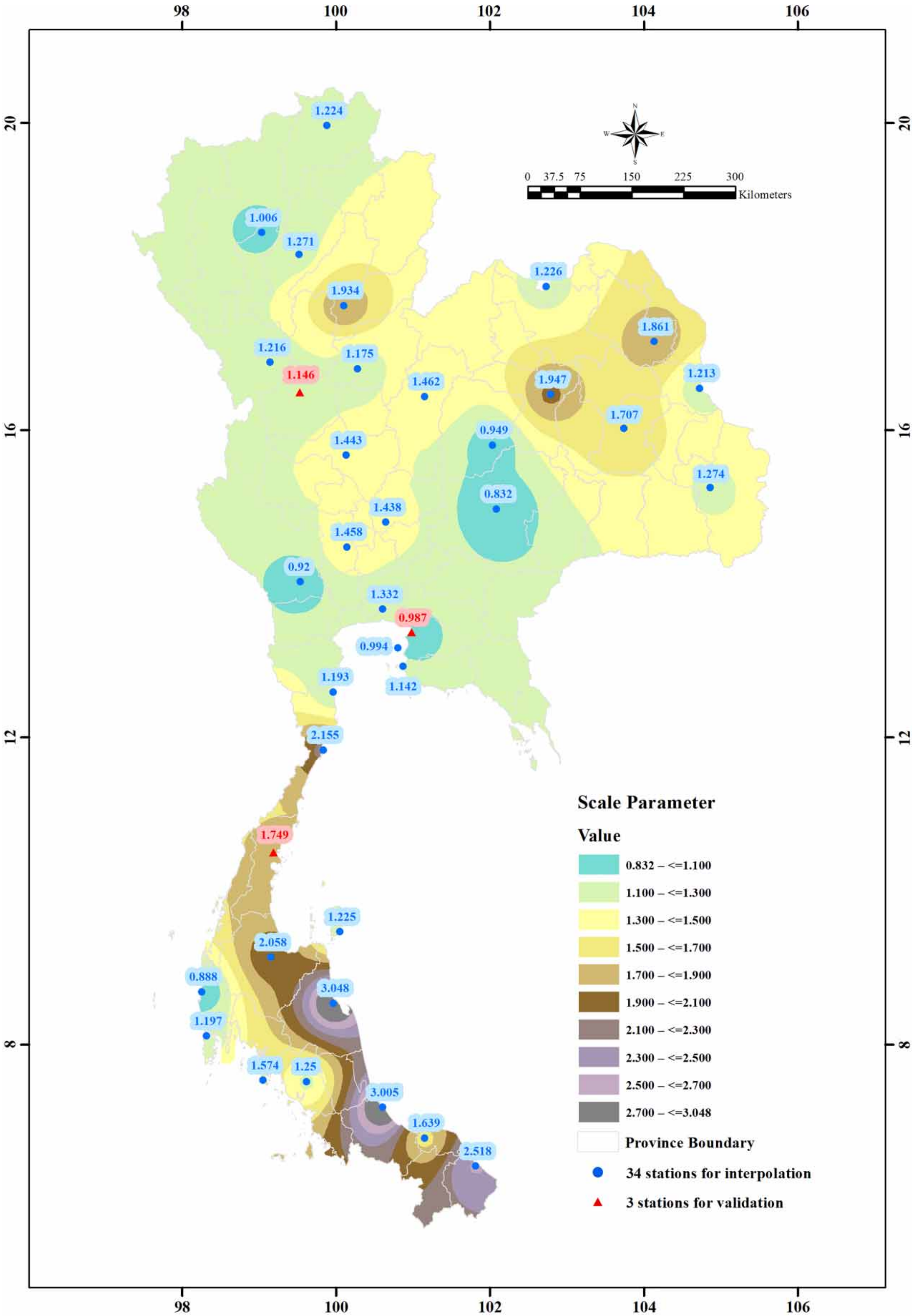

Figure 6 | Spatial distribution of the scale parameter (σ_{24}) of 24-h intensity. Remark: Dots are those stations used to develop relationships, and triangles are those used for validation.

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For demonstrating the performance of the regional IDF model, which is developed in this study; the calculated rainfall intensities of the nine return periods (2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years) and nine durations (0.25, 0.5, 0.75, 1, 2, 3, 6, 12, and 24 h) by using this model were compared with the design storm $I(d,T)$ values estimated by the conventional method, a frequency analysis based on the EV1 distribution, with the observed data. Three stations, namely Chon Buri, Chumphon, and Kamphaeng Phet, were chosen from the study area for validation. These validation gauges were considered as the ungauged sites (the regional scaling model did not use data from these stations). The results are shown in Figures 7–9.

Tables 3 and 4 show the RMSE and MRPE values that were obtained for nine return periods (2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years) and nine durations (0.25, 0.5, 0.75, 1, 2, 3, 6, 12, and 24 h) for three stations. According to the validation results for all three stations, the regional scaling model performed well for Thailand, with a mean relative percentage error that was less than 20%. They performed just as well as the studies in Singapore (Chang & Hiong 2013), Japan (Nhat *et al.* 2008), Greece (Galiatsatou & Iliadis 2022), Spain (Casas-Castillo *et al.* 2022), and Turkey (Yuksek *et al.* 2022).

Chon Buri station is in the east, and Kamphaeng Phet station is in the north; both have hilly terrain and are poorly gauged (see Figure 1). The study of Erazo (2020), on rainfall intensity interpolations in poorly gauged and mountainous areas of Ecuador, shows that the IDW method is the most efficient way to represent both the spatial pattern of precipitation throughout Ecuador and the daily volumes of areal precipitation at the catchment scale (Erazo 2020). Since Thailand is also a tropical country with some hilly areas like Ecuador, we conclude that the three simple scale parameters of the interpolation for Thailand could be evaluated by the IDW interpolation technique.

CONCLUSIONS

Flooding is always a big problem in Thailand as a result of insufficient drainage systems for both urban and rural areas. To mitigate this problem, an accurate IDF relationship for the site must be used for hydraulic infrastructure design. Because continuous rain records in the country are significantly fewer in number than daily records, we used simple scale theory to

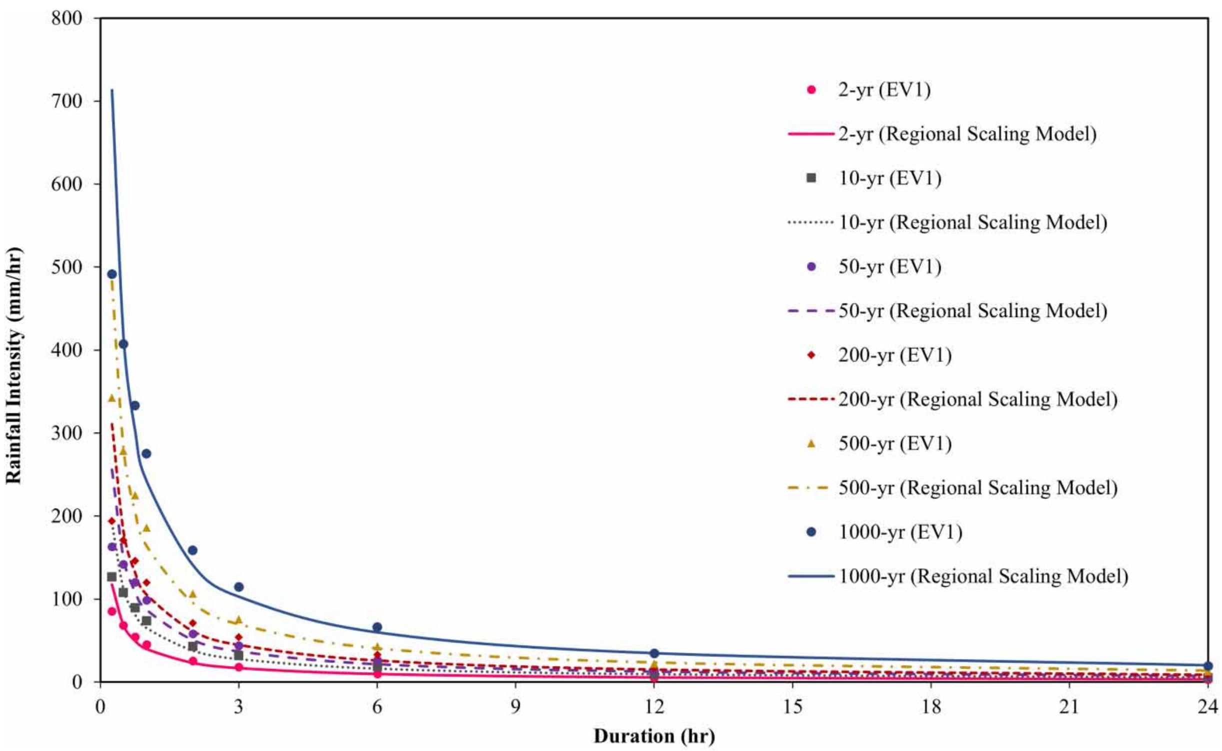

Figure 7 | Comparison of the IDF relationships derived from the regional scaling model and those with the conventional method (EV1) for the Chon Buri station.

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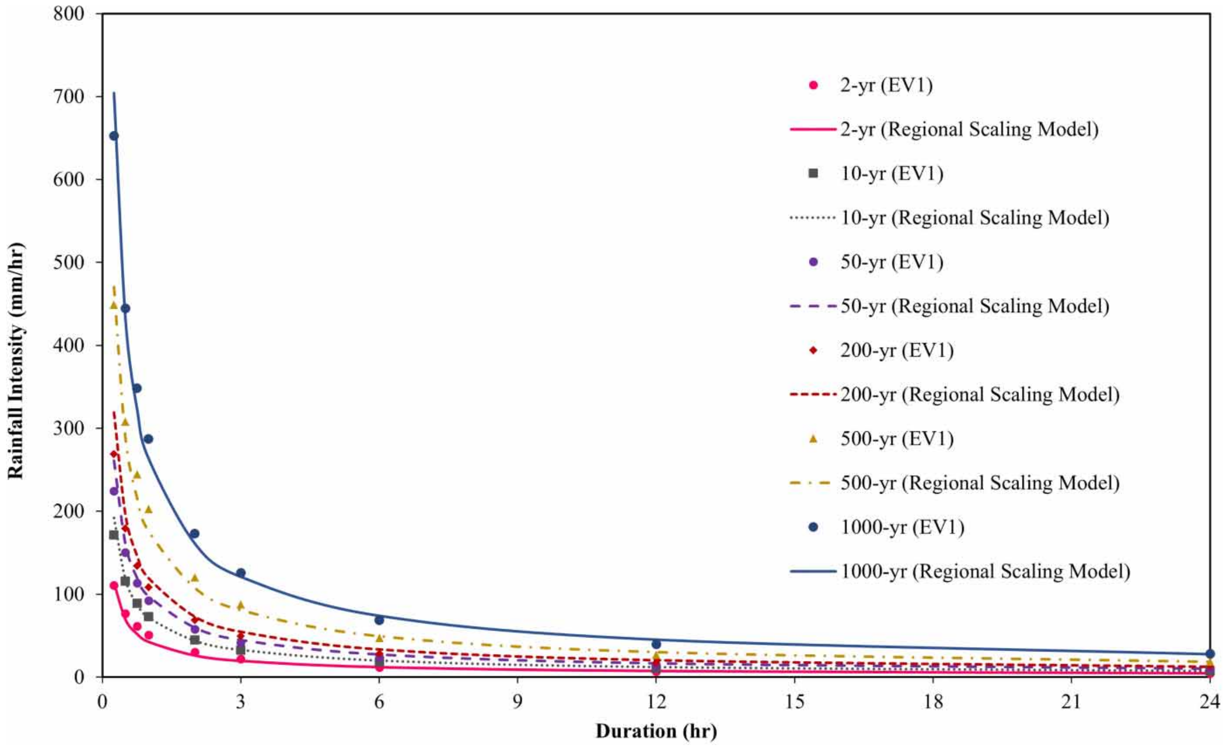

Figure 8 | Comparison of the IDF relationships derived from the regional scaling model and those with the conventional method (EV1) for the Chumphon station.

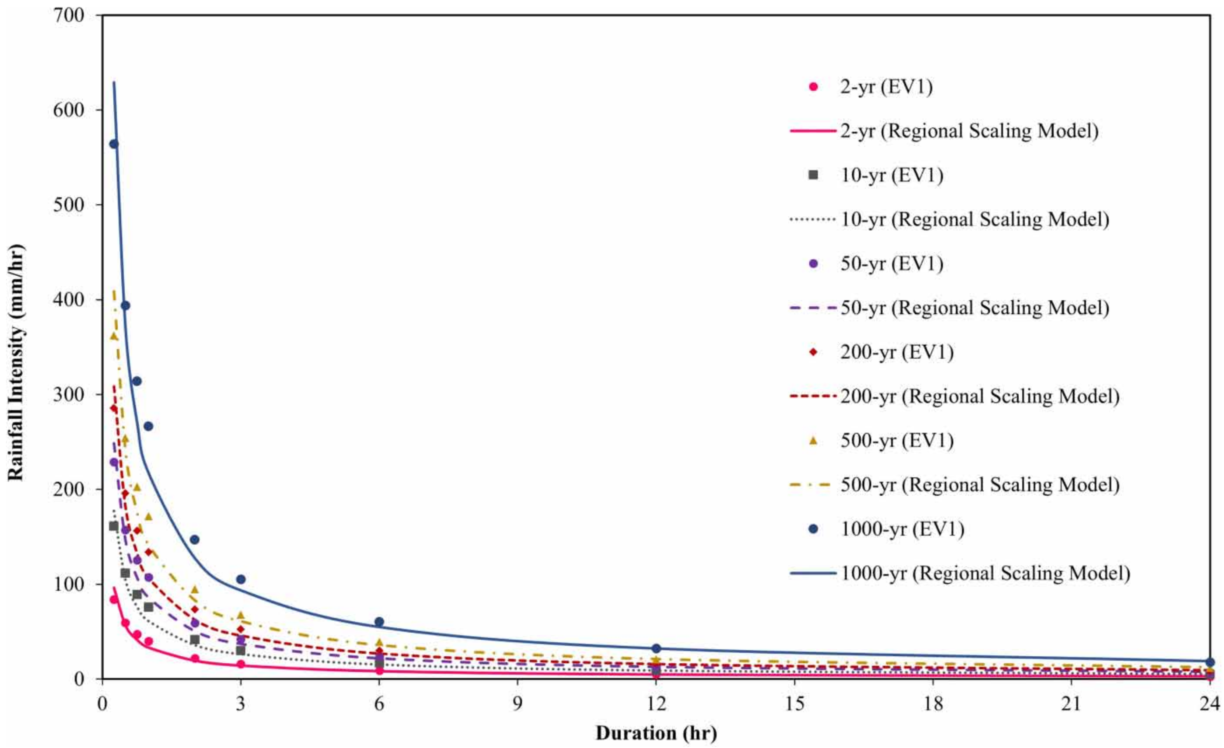

Figure 9 | Comparison of the IDF relationships derived from the regional scaling model and those with the conventional method (EV1) for the Kamphaeng Phet station.

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Table 3 | RMSE (mm/h) results of the validation stations

Return period (year)	Chon Buri	Chumphon	Kamphaeng Phet
2	5.50	5.16	5.21
5	8.80	5.03	7.48
10	11.00	6.99	9.05
25	13.78	10.32	11.08
50	15.85	13.01	12.60
100	17.90	15.76	14.12
200	19.94	18.55	15.64
500	23.96	17.06	21.64
1,000	37.88	21.89	32.64

Table 4 | MRPE (%) results of the validation stations

Return period (year)	Chon Buri	Chumphon	Kamphaeng Phet
2	10.05	9.19	9.43
5	12.04	6.27	10.11
10	13.38	5.66	10.46
25	14.68	7.49	10.76
50	15.39	9.16	10.91
100	15.96	10.52	11.04
200	16.42	11.67	11.13
500	10.80	8.08	9.67
1,000	11.71	6.77	9.96

calculate a scale exponent from each of the 37 AMS across the country. Regarding the 30-year records of daily rainfall, AMS of extreme daily rainfall intensity were extracted and used to obtain location and scale parameters. The interpolation values of the scale exponent and the parameters of location and scale were mapped and ready to be used. The IDF curves from three at-site records were used for validating the result. This showed that, by and large, the errors were less than 15%. The proposed maps can help generate an accurate IDF curve at any site in Thailand.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Bara, M., Kohnava, S., Gaal, L., Szolgay, J. & Hlavcova, K. 2009 Estimation of IDF curves of extreme rainfall by simple scaling in Slovakia. *Contributions to Geophysics and Geodesy* **39** (3), 187–206.

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Bumpenkit, P. 1999 *The Relationship of Rainfall Intensity Duration Frequency of Difference Regions in Thailand*. Report Royal Irrigation Department (RID), Thailand.

Casas-Castillo, M. d. C., Rodríguez-Solà, R., Llabrés-Brustenga, A., García-Marín, A. P., Estévez, J. & Navarro, X. 2022 A simple scaling analysis of rainfall in Andalusia (Spain) under different precipitation regimes. *Water* **14**, 1303. https://doi.org/10.3390/w14081303.

Chang, C. W. & Hiong, S. 2013 Estimation of sub-daily IDF curves in Singapore using simple scaling. In *Proceeding Paper in Impact World 2013, International Conference on Climate Change Effects*, May 27–28, 2013, Potsdam.

Erazo, B. 2020 *Representing Past and Future Hydro-Climatic Variability Over Multi-Decadal Periods in Poorly-Gauged Regions: The Case of Ecuador*. *Thesis*, Université Paul Sabatier, Toulouse, France.

ESRI 2008 *ArcGIS Desktop 9.3 User Manual*. Redlands, CA, USA.

Galiatsatou, P. & Iliadis, C. 2022 Intensity-duration-frequency curves at ungauged sites in a changing climate for sustainable stormwater networks. *Sustainability* **14** (3), 1229. https://doi.org/10.3390/su14031229.

Gupta, V. K. & Waymire, E. 1990 Multiscaling properties of spatial rainfall and river flow distributions. *Journal of Geophysical Research* **95** (3), 1999–2009.

IFRC 2023 *Thailand Monsoon Flood 2022 – Operational Update, Appeal no. MDRTH002*. International Federation of Red Cross and Red Crescent Societies.

Kuzuha, Y., Komatsu, Y., Tomosugi, K. & Kishii, T. 2005 Regional flood frequency analysis, scaling and PUB. *Journal of Japan Society of Hydrology and Water Resources* **18** (4), 441–458.

Menabde, M., Seed, A. & Pegram, G. 1999 A simple scaling model for extreme rainfall. *Water Resources Research* **35** (1), 335–339.

Mustonen, S. E. 1969 Rainfall-Intensity-Frequency Curves for Some Stations in Thailand. The Thai Meteorological Department, Bangkok, Thailand.

Nhat, L. M., Tachikawa, Y., Sayama, T. & Takara, K. 2008 Development of the regional rainfall intensity-duration-frequency curves based on scaling properties. *Annual Journal of Hydraulic Engineering* **52**, 85–90.

Poaponskorn, N. & Meethom, P. 2013 Impact of the 2011 floods, and flood management in Thailand. In: *ERIA Discussion Paper Series*.

Rittima, A., Piemfa, K., Uthai, N. & Jantaramana, A. 2013 An improvement of design rainfall analysis of the central basin of Thailand. *Research and Development Journal* **24** (4), 28–38.

Shrestha, A., Babel, M. S., Weesakul, S. & Vojinovic, Z. 2017 Developing Intensity–Duration–Frequency (IDF) curves under climate change uncertainty: the case of Bangkok, Thailand. *Water* **9**, 145.

Ware, E. C. 2005 *Correction to Radar-Estimated Precipitation Using Observed Rain Gauge Data*. *MS Thesis*, Cornell University, New York, USA.

Yamoat, N., Hanchoowong, R., Sriboonlue, S. & Kangrang, A. 2022 Temporal change of extreme precipitation intensity-duration-frequency relationships in Thailand. *Journal of Water and Climate Change* **13** (2), 839–852.

Yuksek, Ö., Anilan, T., Saka, F. & Örgun, E. 2022 Rainfall intensity-duration-frequency analysis in Turkey, with the emphasis of Eastern Black Sea basin. *Teknik Dergi* **33** (4), 12087–12103.

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