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HA XUAN ANH

DETERMINING RAINFALL INTENSITY FOR DESIGNING RAINWATER DRAINAGE SYSTEMS IN HANOI CITY

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INTRODUCTION

1. The essential of the research

Stormwater drainage in Hanoi, the capital of Vietnam, is a top priority for ensuring the stability and development of the country's technical infrastructure. Accurately determining the design rainfall intensity is crucial for calculating design runoff, which is essential to effectively plan and implement urban stormwater drainage systems, both for Hanoi and across Vietnam.

However, several challenges remain in determining design rainfall intensity, including: (i) Design rainfall intensity equations are typically based on the variables of return period (P) and rainfall duration (t). Although most meteorological and rain gauge stations now record data automatically, but the correction and synthesis of data on the maximum annual daily rainfall and the average maximum rainfall intensity of the periods at meteorological and rain gauge stations have not been implemented. (ii) The selection of probability distributions to derive the rainfall Intensity-Duration-Frequency (IDF) relationship in design equations often relies on commonly available distributions, which may not fully capture local rainfall patterns. (iii) The design rainfall intensity and runoff equation in TCVN 7957, Vietnam's national technical guideline on urban drainage system design, relies on the limit intensity method. This method, however, tends to produce significantly larger errors compared to actual conditions. Additionally, most existing equations used in research are based on methodologies developed in the former Soviet Union, with parameters derived from estimated rainfall data typically covering periods of less than 20 years, and in some cases fewer than 10 years. This limited data span is inadequate compared to the recommended baseline period of 20–30 years needed to accurately reflect rainfall characteristics. Furthermore, the climate constants in these rainfall intensity equations were derived from datasets from the 1980s, making them less suitable for current conditions, where short-duration, high-intensity rainfalls are increasingly frequent. Due to Hanoi's current fluctuations in infrastructure, basin surface, and rainfall patterns, there is a pressing need for studies on rainfall intensity that both build upon existing knowledge and incorporate updated data to enhance reliability, accuracy, and practical value. Such studies are essential to support the planning and design of urban rainwater drainage systems aligned with the infrastructure objectives outlined in the Capital Construction Master Plan approved by the Prime Minister. Based on this analysis, the doctoral thesis titled 'Determining Design Rainfall Intensity for Rainwater Drainage in Hanoi City' is both urgent and of high practical significance

2. Objectives

Overall objective: To develop equations of design rainfall intensity for enhancing the accuracy and reliability of design calculations for Hanoi's urban rainwater drainage system.

Main objectives:

- Analyze and identify the most suitable probability distribution function for rainfall datasets.
- Develop and create Intensity-Duration-Frequency (IDF) relationship curves.
- Determine climate constants for equations of design rainfall intensity.
- Assess the practical applicability of the proposed equations for real-world implementation.

3. Research subject and scope

- Subject: Design rainfall intensity
- Scope: Hanoi city

4. Methodology

This thesis selectively incorporates both domestic and international research findings, utilizing a combination of traditional and modern research methods, including investigation, data collection and evaluation, synthesis and analysis, mathematical approaches, numerical modeling, and expert consultation

5. Contents of the research

- Analyze and select a suitable probability distribution function for the latest rainfall dataset.

- Derive IDF relationship for Hanoi City area.
- Determine climate constants (A, C, b, n) in the rainfall intensity equation using mathematical regression method.
- Evaluate the possibility of applying the thesis equation in practice.

6. Research results

- Analye and comfirm the Gumbel probability distribution functions as the motst suitable probability distribution for the Hanoi city area.
- Derive a family of IDF curves for Hanoi city based on the rainfall data series updated to 2023.
- Establish a new set of climate sonstants (A, c, b,n) for the design rainfall intentisty equation.
- Assess the reliability of the climate constants using the Root Mean Square Error (RMSE) method and the correlation coefficient.
- Evaluate the practical applicability of the proposed rainfall intensity equation for urban drainage system design in Hanoi.

7. Finding and innovation

- Select an appropriate probability distribution function to develop a frequency curve that closely aligns with empirical rainfall data.
- Derive the Intensity-Duration-Frequency (IDF) relationship for Hanoi using the latest rainfall data updated through 2023.
- Identify the optimized parameter set for the proposed design rainfall intensity equation tailored to Hanoi City.

8. Scientific and practical implications of the research

- Enhance the scientific foundation for selecting an appropriate probability distribution function for short-duration rainfall, forming the basis for establishing the IDF relationship and developing the design rainfall intensity equation.
- Strengthen the methodology for determining parameters in the design rainfall intensity equation using the IDF relationship, thereby providing a solid scientific basis for calculating design rainfall intensity in rainwater drainage planning for Hanoi City.

- Apply the thesis findings in practical urban planning and drainage design for residential and urban areas in Hanoi City.
- Utilize the research outcomes as reference material for further professional studies and applications in related fields.

CHAPTER 1: OVERVIEW

1.1 Overview of equations of design rainfall intensity

1.1.1 Definition

Rainfall intensity is typically defined as the depth of rainfall over a given time period. Each rainstorm is characterized by two key values: the total rainfall measured and the duration of the storm. The maximum average rainfall intensity over a specified calculation period is determined by the ratio of maximum measured rainfall to the rain duration. Typically, interest focuses on the event's frequency or return period. Incorporating a frequency factor (p%p\%p%) in the design rainfall intensity equation allows for calculating rainfall intensity values that correspond to specific design frequencies, enhancing the utility of these values in practical applications.

1.1.2 Equations of design rainfall intensity

1.1.2.1 Equations of design rainfall intensity over the world

Equations for calculating design rainfall intensity vary widely across the world. This diversity arises from differences in meteorological considerations for sewer and stormwater drainage design, as well as the unique hydrometeorological conditions specific to each location. Commonly used design rainfall intensity equations include those developed by Gorbachev, the National Hydrological Institute of the former Soviet Union, and the Leningrad Academy of Sciences, along with equations utilized in countries such as the United States, United Kingdom, Japan, Germany, and China

1.1.2.2 Equations of design rainfall intensity in Vietnam

In Vietnam, design rainfall intensity equations are widely used due to the sparse rain gauge stations and the relatively short data length records, which restrict the application of other methods. Commonly applied equations include those specified in TCVN 7957, developed by the former Hydrology Department, created by the Design Institute under the Ministry of Transport, and formulated by Hanoi University of Civil Engineering. Analyzing these equations reveals that the parameters influencing rainfall intensity values are constantly changing. Furthermore, many researchers still employed the equations from the former Soviet Union, with parameters estimated from rainfall data spanning less than 20 years and, in some cases, less than 10 years. Additionally, climate constants derived from 1980s data are increasingly outdated, as short-duration and high-intensity rainfall events have become more frequent.

1.2 Overview of rainfall Intensity-Duration-Frequency (IDF) curves

1.2.1 Definition

IDF curves are used to represent the relationship between rainfall intensity, duration and frequency. It is an important characteristic used to determine rainfall intensity in a certain period (5 minutes, 10 minutes, 30 minutes, 45 minutes, ...) according to specific frequencies or return periods (2 years, 5 years, 10 years, ...) to serve the calculation of design flow for drainage works and urban planning.

1.2.2 Studies related to IDF curves

The concept of establishing an Intensity-Duration-Frequency relationship was first proposed by Bernard in 1932 and has been widely developed around the world [41]. Research on IDF contains three main stages: (1) Updating rainfall data over specific periods and calculating frequencies; (2) Developing a system of curves and mathematical relationships expressed by the IDF equation; (3) Analyzing the spatial distribution properties of IDF. The products of these studies are rainfall intensity maps for practical application, as well as textbooks and reference materials Chow, 1964; Linsley & Cs, 1975; Chow & Cs, 1988 [48], [49]; Viessman & Cs, 1989 [77]; Wanielista, 1990; Smith, 1993. In England và Ireland, Institute of Hydrology (NERC, 1975)

[79]; India (UNESCO, 1974; Subramanya, 1984) [71]; Sri Lanka (Baghirathan & Shaw, 1978); Italy (Pagliara and Viti, 1993); Koutsoyiannis & Cs (1998) [58]; Jakarta (Daniell T. Tabios G.Q, 2008) [51]; New York (Eagleson P.S, 1970) [53]; London (Escritt L.B, 1972) [54]; Benzeden E., Hacisuleyman H, 2003 [40]; Bougadis J., Adamowski K, 2006 [43]; Burlando P., Rosso R, 1996 [44]; Canterford, R.P.& Cs, 1987 [45]; Cheng L. AghaKouchak A, 2014 [47]; Cao C., Piga E., Saba A, 1993 [50]; Martel J.L.; Brissette F.P., Picher P.L., Troin M., Arsenault R., 2021 [65]; Miller J.F., Frederick R.H., Tracey R.J, 1973 [66]; Ologadien I, 2019 [68]; Sun Y., Wendi D., Kim D.E., Liong S.-Y, 2019 [72]. Recently, the spatial distribution of IDF has also been expressed through the geographical parameters of a mathematical function expressing the IDF relationship [60], [61], [62], [63], [73]. For regions with little or no rainfall data, studies often use approaches such as rainfall isosurface maps (Hershfield, 1961), [56].

In Vietnam, the IDF relationship has been widely applied in design calculations and studies on creating of the IDF relationship curves have been conducted for a long time. IDF relationship curves is widely introduced in books and textbooks of universities such as: "Hydrological Calculation" of the Thuy Loi University (1985) [24]; “Hydrological calculations for small water works” written by Prof. Ngô Đình Tuấn & Prof. Đỗ Cao Đàm (1986) [25]. the IDF relationship is also used in the calculation standards and regulations of the Ministry of Agriculture and Rural Development such as QPVN-08-76, QP-TL.C-6-77; Technical standard 22TCN 220 - 1995 of the Ministry of Transport; Vietnam national standard TCVN 7957:2008 on drainage and sewerage networks and other references.

1.3 Applications of design rainfall intensity equations

The Vietnamese standard TCVN 7957 remains widely used for designing urban rainwater drainage systems, but certain limitations exist when applying its empirical equations. Specifically, the design rainfall intensity equation in TCVN 7957 employs the Limit Intensity Method, which studies have shown to produce significantly larger errors than actual conditions. Additionally, many commonly used equations in Vietnam are adapted from models developed in the former Soviet Union, based on data sets covering less than 20 years, and in some cases, less than 10 years. Consequently, these equations do not fully reflect current hydrometeorological conditions, as climate constants derived from older datasets no longer align with today's climate patterns. Moreover, due to the impact of climate change, rainfall characteristics such as intensity, frequency, and duration have become increasingly variable, particularly in large cities like Hanoi.

Furthermore, an analysis of existing studies shows that most studies on design rainfall intensity employed sone common probability distribution functions, such as Pearson Type III, Log-Pearson Type III, Log-normal, and Gumbel. The choice of an appropriate probability distribution function significantly impacts the accuracy of rainfall intensity calculations. However, very few studies focus on systematically selecting the most suitable distribution function for specific locations by comparing distribution functions against testing criteria.

1.4 Studies related to empirial equations of design rainfall intensity

1.4.1 Studies conducted worldwide

Numerous studies on equations for calculating design rainfall intensity for urban stormwater drainage systems have been conducted by researchers worldwide [80], [46], [75], [69], [70]. These studies often focus on maximizing the use of available local rainfall data to develop equations, thereby increasing accuracy by basing calculations on regional rainfall and climate characteristics. Additionally, empirical IDF equations for areas lacking observation data are typically derived from IDF curves established at nearby stations or locations with long-term rainfall records.

1.4.2 Studies conducted in Vietnam

In the past two decades, several researchers have studied rainfall intensity equations for designing urban stormwater drainage systems in Vietnam [7],

[10], [8], [74]. owever, an analysis of these studies reveals that most have primarily focused on applying existing empirical equations rather than developing or refining these equations to better suit current conditions. Consequently, many of the empirical equations are based on older data sources, and the coefficients used are now outdated, underscoring the need for independent studies aimed at updating and improving these equations to reflect present-day hydrometeorological conditions.

1.5 General introduction to Hanoi City

1.5.1 Geographic location and natural conditions

Hanoi is geographically located between 20°53' to 21°23' North latitude and 105°44' to 106°02' East longitude, bordering Thai Nguyen and Vinh Phuc provinces to the north, Ha Nam and Hoa Binh to the south, Bac Giang, Bac Ninh, and Hung Yen to the east, and Hoa Binh and Phu Tho to the west. Situated in a tropical monsoon region, Hanoi's climate is characterized by hot, humid, and rainy summers, while winters are cooler and drier. On average, Hanoi experiences 145–180 rainy days annually, with rainfall ranging from 1,500 to 2,100 mm in lowland areas and 1,600 to 2,600 mm in highland areas. Rainfall patterns are influenced by atmospheric circulation systems, including storms, tropical depressions, monsoon activity from the southwest or southeast, as well as interactions between storms, cold air masses, and upper-level cyclones.

1.5.2 Current rainfall drainage system and inundated problems

There are many other rivers in Hanoi such as the Day River, the Duong River, the Cau River, the Ca Lo River, etc. Small rivers flowing in the inner city such as the To Lich River, the Set River, the Lu River and the Kim Nguu River can be considered natural drainage routes of the city. The primary drainage direction of the To Lich River basin flows naturally into the Nhue River through the Thanh Liet Dam, with a capacity of 80 m^3/s, as long as the Nhue River's water level remains below +3.5 m. When the Nhue River water level exceeds 3.5 m, the basin's flow is redirected to the Red River via the Yen So drainage and pumping station cluster [15]. n recent years, due to unusual weather patterns and prolonged heavy rainfall events exceeding design frequencies, large-scale flooding has occurred despite irrigation systems operating at full capacity and close coordination of flood prevention efforts.

1.5.3 Rainfall observation network and data collection

There are many stations measuring climate and rainfall factors in the system and surrounding areas such as Ba Vi, Soc Son, Kim Anh, Me Linh, Tien Phong, Dong Anh and Phuc Loc, Lang, Phu Ly, Dap Day, Ha Dong, Thuong Tin, Dong Quan, Phu Xuyen, Thanh Oai, Van Dinh (Figure 1.7). Most of the stations have date from 1960 to present (some stations have longer data from 1936 to present).

1.5.4 Social and economic characteristics

Hanoi is the largest centrally-governed city in Vietnam, and is also the second most populous city and has the second highest population density among the 63 provincial administrative units of Vietnam and is the political, economic, social and cultural center of the country.

1.6 Research problems

An analysis of the design rainfall intensity equations commonly used in Vietnam reveals that their parameters are closely tied to specific local characteristics, such as climate, geography, and rainfall patterns. Most of these equations include appendices with lookup tables listing parameter values for each locality. However, these parameters require periodic updates due to fluctuations in the underlying factors that influence them, as discussed above.

CHAPTER 2: SCIENTIFIC RATIONALE ON DETERMINING EMPIRICAL EQUATIONS FOR DESIGN RAINFALL INTENSITY

2.1 Legal basis

2.1.1 Laws correspoding to urban drainage systems

Urban Planning Law No.30/2009/QH12; Water Resources Law No. 28/2023/QH15; Environmental Protection Law No.72/2020/; Meteorology and Hydrology Law No.90/2015/QH13; Natural Disaster Prevention and Control No. 33/2013/QH13.

2.1.2 Decrees and techincal guides on urban drainage and enironment

Decree No.98/2019/NĐ-CP; Decree No.08/2022/NĐ-CP; Decree No.68/2022/NĐ-CP.

2.1.3 Policies and legcal documents of urban drainage and environment

Decision No.1259/QĐ-TTg of the Prime Minister on approving the master plan for construction of Hanoi Capital to 2030 towards 2050; Decision No. 725/QD-TTg of the Prime Minister issued on May 10, 2013 on approving the drainage plan of Hanoi Capital to 2030 towards 2050; Decision No. 589/QD-TTg issused April 6, 2016 of the Prime Minister approving the adjustment of the Orientation for the development of drainage in urban areas and industrial parks in Vietnam to 2025, vision to 2050; Decision No. 379/QD-TTg dated March 17, 2021 of the Prime Minister approving the National Strategy for Natural Disaster Prevention and Control to 2030 towards 2050.

2.2 Theoretical basis

2.2.1 Probability and statistical theory for hydrometeorology

The basic fundemental of probability and statistics applied in hydrometeorology includes concepts such as frequency, cumulative frequency, mean, sample variance, sample deviation, square root error, dispersion coefficient, bias coefficient. Next, the theory of empirical and theoretical frequency curves... are presented and analyzed in turn in the thesis.

2.2.2 Probability density funtions and Cummulative density functions

In mathematics, a probability density function (PDF) represents a probability distribution, providing a way to calculate probabilities over continuous intervals through integration. Informally, a PDF can be thought of as a smooth approximation of a histogram, illustrating how probability is distributed over possible values. Meanwhile, in probability theory, the cumulative distribution function (CDF) fully characterizes the probability distribution of a continuous random variable by showing the probability that the variable will take a value less than or equal to any given point.

2.2.3 Properties of radom variables

Some important characteristics of a random variable include: The expected value is a weighted average of all possible values of the variable, or the sum of the products of the probabilities of each possible value of the variable and that value. The variance measures the statistical dispersion of the variable, which implies how far the values of the variable tend to fall from the expected value. The standard deviation measures the dispersion of the values. Skewness measures the degree of asymmetry of the probability distribution of a random variable.

2.2.4 Selection of suitable probability density function

Due to the limited sample size in datasets, such as rainfall, theoretical distributions are used to approximate observed data, essentially idealizing the observed dataset, considering the observed data as the results of some mathematical formulas. Therefore, usually, after constructing the empirical distribution function, it is necessary to study, evaluate, consider, and select the theoretical distribution so that it best fits the empirical distribution. Some commonly used distribution functions are Normal, Log Normal, Exponential, Gamma, Pearson Type III, Log-Pearson III, Kritsky-Menken, Gumbel, etc.

2.2.5 Steps for determining empirical equations of design rainfall intensity

The method of determining design rainfall intensity is built based on 08 basic steps, including 05 steps of constructing IDF curve and 03 steps of determining the equation for calculating rainfall intensity. Figure 2.1 describes the process of constructing IDF curve and determining the equation for rainfall intensity in the thesis.

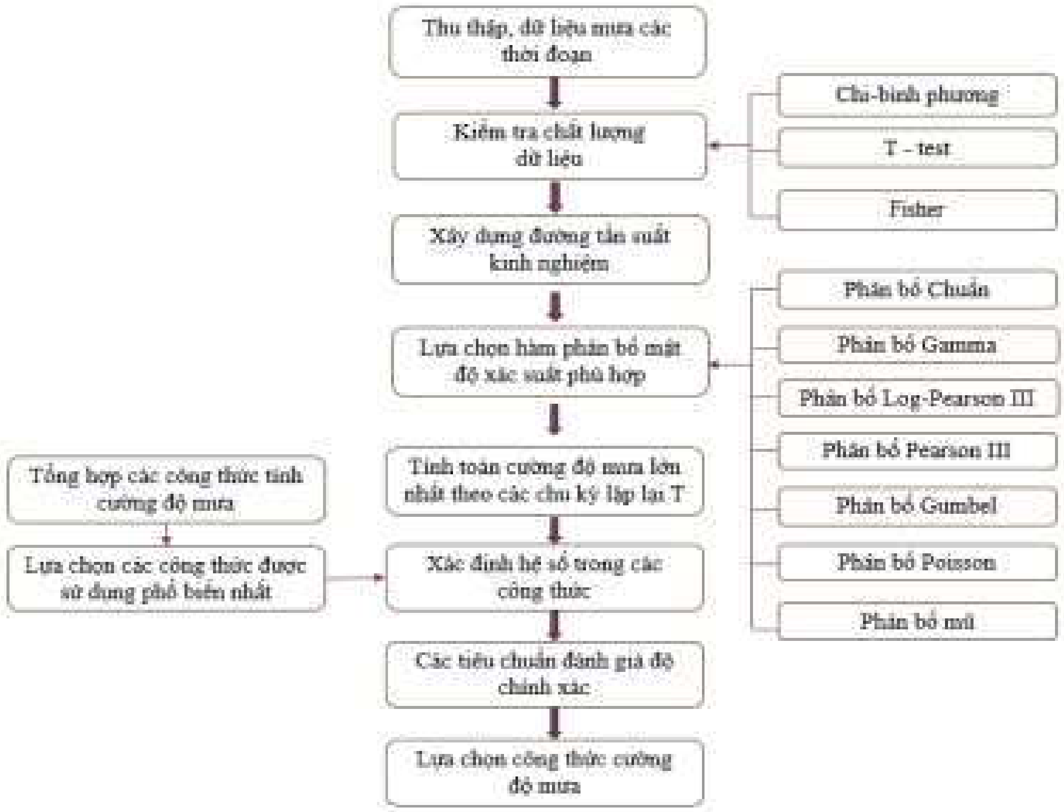

Figure 2.1. Steps of creating IDF curves and equations of design rainfall intensity

2.3 Practical basis

2.3.1 Application of IDF relationship in urban planning

The IDF relationship is widely applied in many disciplines, directly serving the hydrological calculation of civil works, irrigation, traffic, drainage, etc. The basic IDF relationship is expressed in 3 common forms: (1) IDF relationship curve; (2) rainfall intensity distribution map; (3) equations for determining design rainfall intensity. Most developed countries in the world nowadays recommend building IDF relationship curves to calculate runoff rates for design. Building the IDF relationship will contribute to increasing the accuracy when calculating design rainfall intensity. However, technical guidelines of countries also specify that this method is only suitable for areas and locations with short-duration rainfall and sufficient data length.

2.3.2 Application of empirical equations of design rainfall intensity in designing urban drainage system

The empirical equations for calculating design rainfall intensity are presented in technical guidelines for calculating urban stormwater drainage of many countries in the world. The use of these equations is still very popular in the world currently because they satisfy the requirements for documents and observed rainfall data. This proves that in practice, it is necessary to develop empirical equations to determine the design rainfall intensity with high reliability and accuracy.

CHAPTER 3: DETERMINING DESIGN RAINFALL INTENSITY FOR THE DRAINAGE SYSTEM DESIGN OF HANOI CITY

3.1 Selection of appropriate probability distributions

In this content, the thesis created the IDF curve from 5-minute rainfall data at Lang Station (Hanoi) using Pearson Type III, Log-Pearson Type III, and Gumbel distributions, as well as comparing and evaluating the results.

3.1.1 Empirical probability distributions

Using 5-minute rainfall data from Lang station spanning 1961 to 2023, the annual maximum rainfall values were extracted to construct the empirical frequency distribution. These values were then arranged in descending order, converted to equivalent 1-hour rainfall, and analyzed using the Weibull and Kritsky-Menken quadrature formulas.

3.1.2 Pearson Type III distribution

Using the Pearson Type III distribution on the rainfall data, the mean mẫu ($\bar{R}$), standard deviation (s), and skewness (C_s) were calculated, yielding values of 16.203 mm, 4.801 mm, and 0.414, respectively. Referring to the frequency coefficient and skewness coefficient tables, the K values were determined for return periods of 2, 5, 10, 25, 50, and 100 years.

3.1.3 Log-Pearson Type III distribution

To use the Log-Pearson Type III distribution, first calculate the log of the 5-minute rainfall data and obtain the characteristic numbers corresponding to the logarithmized data set consisting of sample mean $\overline{y}$=1.190, sample deviation s=0.134, and skewness Cs=-0.361. Then calculate the K values corresponding to the recurrence intervals and the skewness coefficient.

3.1.4 Gumbel distribution

The characteristic values of the Gumbel distribution include the mean $\mu = \beta - 0.5772\alpha$, standard deviation$\sigma = \alpha.\sqrt{1.645}$, skewness $C_s = 1.1396$. Based on 5-minute rain gauge data, sample average is calculated $\bar{R} = 16.203\ mm$, sample skewness $s = 4.801\ mm$. Applying the formula of Gumbel $R = \bar{R} + K.s$. The value of K is taken in the case where n is very large. This is not suitable because hydrometeorological data are usually small in volume. Therefore, it is important to take the value of K corresponding to the number of elements in the data series.

3.1.5 Comparison amongst selected probability distribution

Next, the rainfall intensity for a 5-minute duration, as estimated by the above distributions, was compared with empirical values. To assess the goodness of fit, a Chi-square (χ^2) test was conducted with 3 degrees of freedom ($\nu = 3$) at a 5% significance level. The results indicate that all three distributions approximate the empirical frequency reasonably well. The Chi-square values for the Gumbel, Pearson Type III, and Log-Pearson Type III distributions were 2.435, 5.111, and 4.306, respectively—all below the critical value of 7.815. Consequently, the Gumbel distribution, with the smallest test value, provided the best fit.

3.2 Determining the design rainfall intensity for Lang gauging station

3.2.1 Estimating rainfall intensity of various short duration

Rainfall intensities for durations of 5, 10, 15, 30, 45, 60, 90, 120, 180, 360, 720, and 1440 minutes, corresponding to return periods of 2, 5, 10, 25, 50, and 100 years, were calculated using the Pearson Type III, Log-Pearson III, and Gumbel probability distributions. A Chi-square goodness-of-fit test was conducted, revealing that the Gumbel distribution provided the best fit.

3.2.2 Deriving IDF curves for Lang gauging station

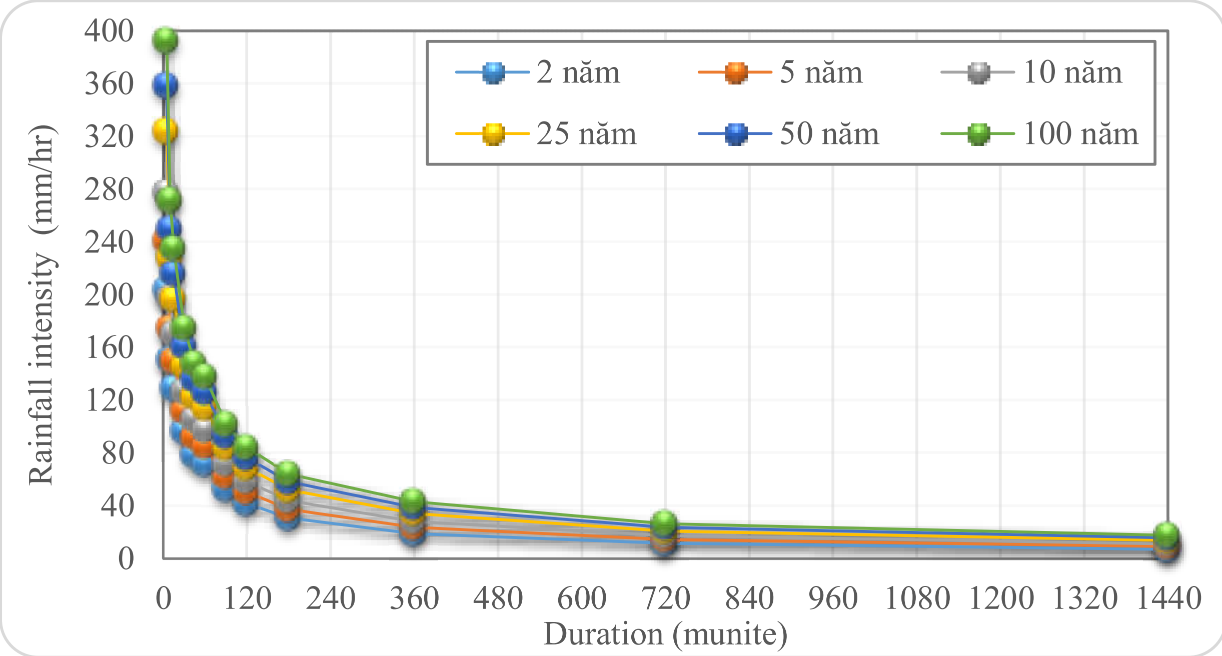

Figure 3.1. The IDF curves of Lang station

Using the calculated rainfall frequencies for the specified durations and return periods, this thesis developed an Intensity-Duration-Frequency (IDF) relationship for the Lang meteorological station in Hanoi, as illustrated in the figure above.

3.2.3 Deriving an empirical equation of rainfall intensity for Lang gauging station

Based on the short-duration rainfall intensities and their corresponding return periods from the IDF curve, along with the selected general rainfall intensity formula, this thesis developed a design rainfall intensity equation for Lang station. The parameters of the equation were determined using the least squares method and the Generalized Reduced Gradient Nonlinear approach. The resulting equation is as follows:

$$q = \frac{0.36 \times 2003 \times (1 + 0.598 \times \log P)}{(t_m + 5)^{0.602}} \tag{3.1}$$

After developing the equation, the thesis compared the proposed equation with some existing equations such as the equation in TCVN 7957 and the equation of the Institute of Hydrology and Meteorology Science and Climate Change, using root mean square error (RMSE) and correlation coefficient. The results showed that the proposed equation gave the smallest RMSE and the highest correlation coefficient.

3.3 Determining the design rainfall intensity for Ha Dong gauging station

3.3.1 1 Estimating rainfall intensity of various short duration

Similar to Ha Dong meteorological station in Hanoi, rainfall intensity of various durations of 5, 10, 15, 30, 45, 60, 90, 120, 180, 360, 720, 1440 minutes with return periods of 2, 5, 10, 25, 50, 100 years were determined respectively.

3.3.2 Deriving IDF curves for Ha Dong gauging station

Based on the calculated data, the IDF relationship for Ha Dong station was developed as shown in the below figure:

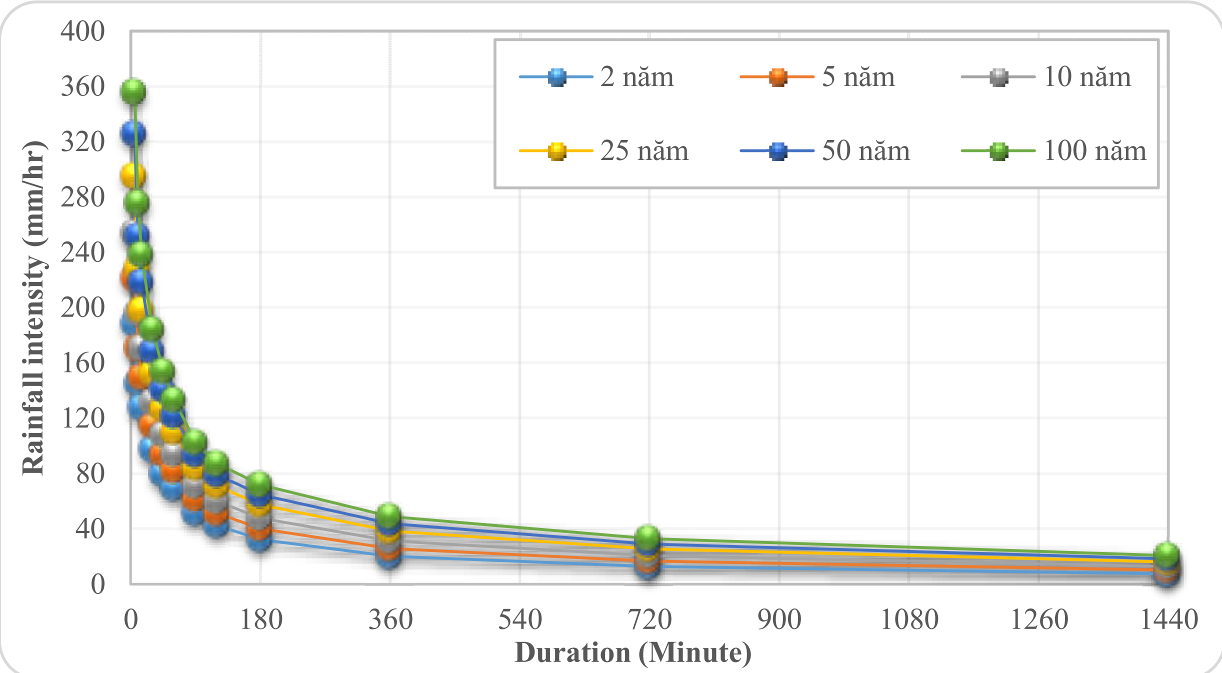

Figure 3.2. The IDF curves of Ha Dong station

3.3.3 Deriving an empirical equation of rainfall intensity for Ha Dong gauging station

Based on the IDF data constructed above and using the non-linear general gradient method, the equation for calculating design rainfall intensity for Ha Dong station was defined as follows:

$$q = \frac{0.36 \times 2320 \times (1 + 0.655 \times \log P)}{(t_m + 9)^{0.633}} . (3.2)$$

The equation was then compared and evaluated with other equations in TCVN 7957 and the equation of Institute of Hydrology and Meteorology Science and

Climate Change. The results showed that the proposed equation showed the smallest RMSE and the highest correlation coefficient.

3.4 The study results

The thesis developed an equation for calculating rainfall intensity based on the IDF relationship for the Hanoi city area to support rainwater drainage design. Key achievements include: (1) identifying the Gumbel probability distribution function as the most suitable for accurately reflecting the variability of short-duration rainfall data at the Lang and Ha Dong meteorological stations; (2) developing a design rainfall intensity equation for both stations by determining parameters from IDF relationship curves; and (3) comparing and evaluating the proposed equations against other models, showing that the thesis equation aligns more closely with the IDF curve data.

CHAPTER 4: APPLICABILITY OF THE PROPOSED DESIGN RAINFALL INTENSITY EQUATION

4.1 Numerical modelling method and the study area

4.1.1 Numerical modelling method

Numerical models can simulate and calculate processes and phenomena across scales, from regional to national or even global levels [26]. hese models offer several advantages over physical models, including high calculation accuracy, cost efficiency, flexibility, and versatility for research, planning, and scenario development. Advances in science and technology, particularly with high-speed computing, have led to the widespread application of hydrological numerical models in the planning, design, and efficient management of water resources in Vietnam and worldwide.

4.1.2 MIKE URBAN model

The two models SWMM and MIKE URBAN are being widely used in Vietnam in calculating urban stormwater drainage. In which, the MIKE URBAN model has been showing many outstanding advantages in terms of user interface, calculation capabilities including calculation speed, flexible simulation of one-way flow in canals and two-way surface overflow, flooding... This model has also proven its high applicability due to its wide use in large topics and projects. The MIKE URBAN model is a software package for simulating water supply, drainage and urban flooding developed by DHI company of the Danish Hydraulic Research Institute.

4.1.3 Overview of the study area

The To Lich River basin spans approximately 7,759 hectares and is divided into seven sub-basins: To Lich (2,000 ha), Lu (1,020 ha), Set (710 ha), Kim Nguu (1,730 ha), Hoang Liet (810 ha), Yen So (550 ha), and West Lake (930 ha). This basin encompasses the entirety of Hoan Kiem, Ba Dinh, Hai Ba Trung, and Dong Da districts, as well as portions of Thanh Xuan, Hoang Mai, and Cau Giay districts. The Kim Nguu River, approximately 4,640 meters in length, drains an area of 1,730 hectares. Its drainage network includes the Thanh Nhan, Hoang Mai, Mai Dong, Kim Nguu, and Linh Nam canals. The Kim Nguu River merges at the Dai Do junction and subsequently flows into the To Lich River, with its water level regulated by the To Lich River at their confluence.

4.2 Application method and evaluation metrics

4.2.1 Application method

The steps to apply the MIKE URBAN model to evaluate the applicability of the proposed equation to practical problems are as follows:

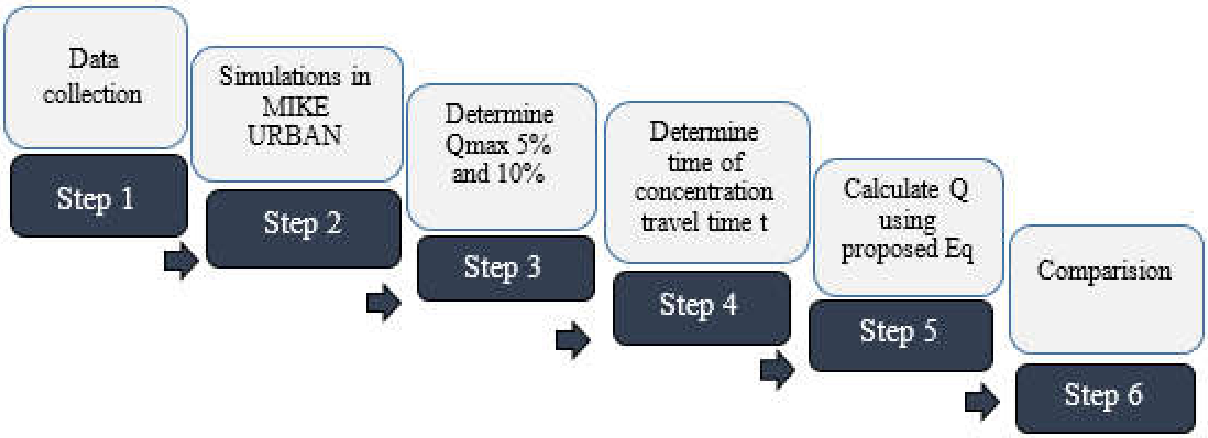

Figure 4.1. Steps to evaluate the effectiveness of applying new equation

4.2.2 Model evaluation metrics

To evaluate model efficiency and accuracy, commonly used criteria include the Nash-Sutcliffe Efficiency (NSE) index, absolute error, and timing error.

4.3 Setup, calibration, and validation of the MIKE URBAN model

4.3.1 Selection of the test area

As discussed in the previous section, this thesis focuses on drainage canal No. 300, a branch of the Tran Phu drainage canal located on the left bank of the Kim Nguu River in Hoang Mai District, Hanoi City. The drainage basin covers an area of 106 hectares and serves as the primary drainage channel for the Gamuda Gardens urban area. Analyzing the basin’s location and drainage system reveals that the 300 basin is of moderate size, with a relatively straightforward drainage structure, minimally impacted by other stormwater systems within Hanoi’s inner city, and conveniently located near meteorological monitoring stations. Furthermore, there are several water level monitoring stations in this basin, providing valuable data to support the model evaluation discussed in the following section. For these reasons, the 300 basin was selected as the thesis study area.

4.3.2 Data collection

To model the stormwater drainage system using the MIKE URBAN model for the test area, data types will be collected and used including documents and information on the surface drainage system such as sub-basins, routes and sizes of sewers, drainage cannals, manholes, etc. In addition, rainfall data and water level data of automatic monitoring stations within and surrouding the test area will also be collected.

4.3.3 Setup, calibration, and validation of the model

In this thesis, the model and the schematization of stormwater drainage system were adapted from the project "Developing a real-time flood warning system for Hanoi's inner city" funded by the Nordic Development Fund and implemented by the Ministry of Natural Resources and Environment. This MIKE URBAN model schematization includes a total drainage area of 1,730 hectares, encompassing 314 drainage basins, 314 water intakes or manholes, and 401 canals and drainage culverts with a combined length of approximately 75,816 meters (Figure 4.2).

To calibrate the model, rainfall and water level data from May 24 and 25, 2016, were used, while data from August 28, 2016, were employed to validate the parameters obtained during calibration. The calibration results, assessed through evaluation metrics, were evaluated acceptable, with a NASH coefficient of 0.75 (Figure 4.2).

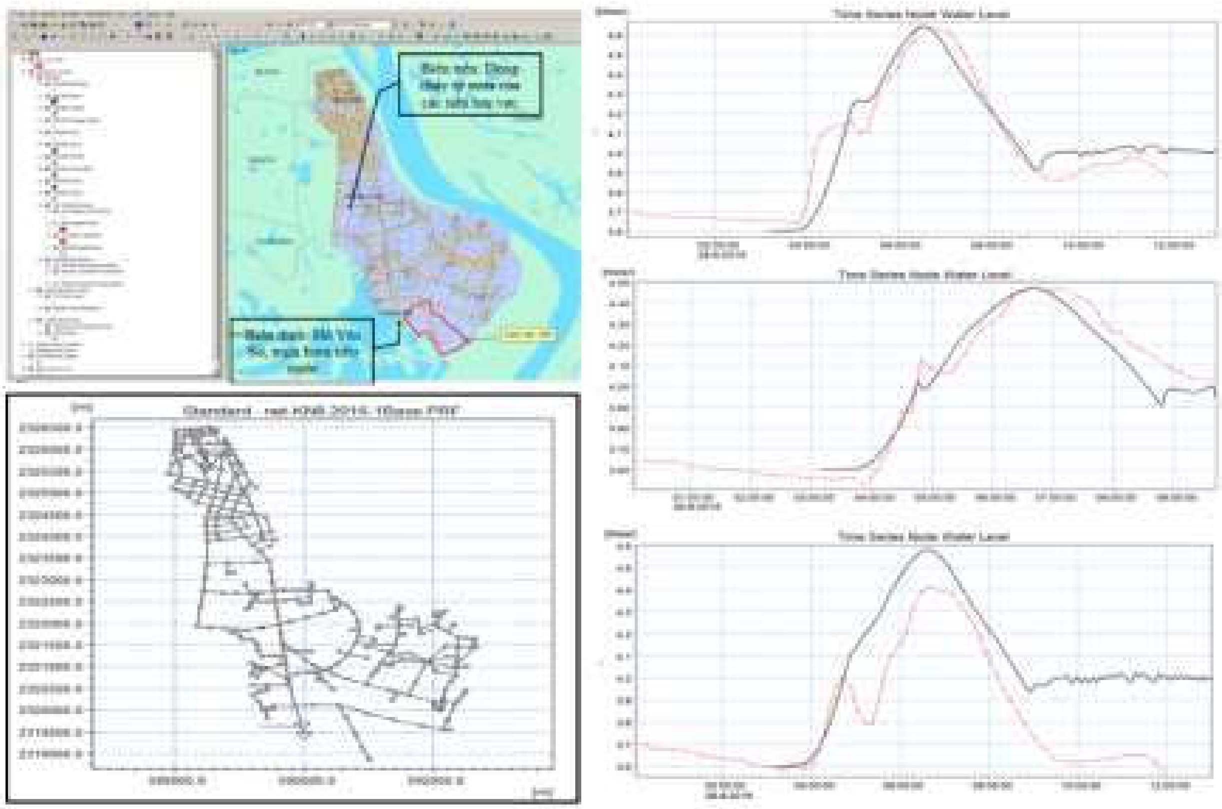

Figure 4.2. Model setup and model validation results

4.3.4 Simulation performances

Based on observed data from Lang Station over a 34-year period (1990-2023), each year's largest rain event, defined by the maximum 180-minute total rainfall in 10-minute increments, was identified. These rain events were then simulated using the MIKE URBAN model to determine the maximum runoff (Qmax) at the outlet of the selected basin for each event. All Qmax values recorded at this outlet were subsequently compiled to construct a theoretical frequency curve for maximum runoff. According to the frequency curve, the

Qmax corresponding to a 10% probability event (or a 1-in-10-year event) was determined to be 41.3 m^3/s.

4.4 Applicabability of the proposed equation

To assess the applicability of the proposed equation for designing rainwater drainage systems, the thesis compared the discharge results obtained from the proposed equation with those from the MIKE URBAN model and from calculations based on the TCVN 7957 standard equation. The results (Table 4.1) indicated that the design discharges from the three methods are approximately similar. Among them, the MIKE URBAN model produced the highest discharge value, followed by the proposed equation. It is noted that the MIKE URBAN model accurately reflects the actual discharge for the 10% frequency event in the study area, as it has been evaluated as highly reliable.

Therefore, the results from the thesis equation align more closely with observed data than those from the general formula in TCVN 7957. However, it should be noted that, to date, this comparison has only been conducted in one test area. For a more concrete conclusion, it is necessary to validate the thesis equation across multiple areas with diverse characteristics and more complex rainwater drainage systems. Overall, the thesis equation shows high potential for practical application in designing rainwater drainage systems for Hanoi City.

Table 4.1. Results of design discharge by three methods

No.	**Methods**	**Q (m^3/s)**	**Difference with the model performance (%)**
1	MIKE URBAN Model	36,70	0%
2	TCVN 7957	34,10	7,1%
3	Proposed equation	35,47	3,36%

4.5 Discussion

The thesis evaluates the applicability of the proposed design rainfall intensity equation to the practical challenge of designing a stormwater drainage system for Hanoi City. To achieve this objective, the thesis compared results from the proposed equation with two established methods: the MIKE URBAN model and the TCVN 7957 standard equation. Leveraging the MIKE URBAN stormwater drainage model, along with data and insights from previous projects, the thesis compiled the most recent input data for urban stormwater modeling to perform necessary simulations for the test area. Calibration and validation results, based on water level data collected at four monitoring stations, demonstrated that the model effectively simulated both peak flow magnitude and timing, with model performance indicators such as NASH (> 0.75), ΔH (< 0.16 m), and Δt (< 6 minutes) indicating strong reliability.

The model was evaluated reliable for conducting simulation steps. Using data from the largest 180-minute rainfall events observed over a 34-year period (1990–2023), a frequency analysis was conducted in the model, yielding a maximum discharge value of 36.7 m^3/s for a 10% probability event. The thesis then applied the proposed equation, alongside the TCVN 7957 equation, to calculate the corresponding discharge for a 10% frequency event. Comparative analysis of the values obtained from different methods showed that the thesis equation produced results closest to those from the urban drainage model. This outcome indicates that the thesis equation has high applicability for designing rainwater drainage systems in Hanoi City.

CONCLUSION AND RECOMMENDATION

1. Conclusion

In recent years, Hanoi has experienced rapid urbanization alongside increasingly frequent and intense extreme weather events, particularly unusual rainfall. This shift has exposed shortcomings in the current design rainfall intensity calculations used for planning the city's rainwater drainage system, which no longer meet actual performance needs. The existing short-duration rainfall data are insufficient to support accurate design methods across all areas, highlighting the need to enhance the precision and reliability of these equations. To address this issue, this thesis establishes a scientific foundation for determining design rainfall intensity specifically for Hanoi's rainwater drainage system, achieving the following outcomes:

(i) A review of relevant studies in Vietnam and over the world shows that parameters in design rainfall intensity equations largely depend on the unique characteristics of each location and need regular updates to account for changes in influencing factors. Developing these equations from the Intensity-Duration-Frequency (IDF) relationships, using observed rainfall data, has become a widely adopted approach worldwide.

(ii) Using updated rainfall data through 2023 from two key meteorological stations in Hanoi, Lang and Ha Dong, this thesis analyzed and compared distributions, ultimately selecting the Gumbel distribution to construct a rainfall frequency curve that best represents observed conditions.

(iii) Developing the Intensity-Duration-Frequency (IDF) relationships for self-recorded rain gauge stations in Hanoi using short-duration rainfall data intervals of 5, 10, 15, 30, 45, 60, 90, 120, 180, 360, 720, and 1440 minutes, with return periods of 2, 5, 10, 25, 50, and 100 years, based on the Gumbel distribution.

(iv) Develop an equation to calculate design rainfall intensity for Hanoi's stormwater drainage system using the Generalized Reduced Gradient (GRG)

Nonlinear method, incorporating climate parameters tailored to local conditions.

(v) Evaluate the applicability of the proposed equation in this thesis for calculating rainwater drainage in Hanoi by using the MIKE URBAN model. The results demonstrate that the proposed equation is highly feasible and effective for addressing design challenges in Hanoi's rainwater drainage system.

2. Recommendation

Further research is needed to increase the density of self-recording rain gauge stations in Hanoi, which will enhance data coverage and improve the accuracy of research outcomes.

This thesis has so far been limited to comparison within a single test area; therefore, to reach more robust conclusions, comparisons across multiple test areas with diverse characteristics and complex drainage systems are essential. assessing the impacts of climate change requires updating to the latest climate change scenarios and data specifically applied to Hanoi.

List of publications corresponding to the doctoral thesis

1. Son Tran Thanh, Anh Ha Xuan (2023), Deriving of Intensity–Duration–Frequency (IDF) curves for precipitation at Hanoi, Vietnam, *E3S Web of Conferences,* 403, 06002. eISSN: 2267-1242. (Scopus)
2. Ha Xuan Anh, Tran Thanh Son (2022), Some issues related to rainwater reatment and reuse in urban areas, *Journal of Construction,* 2022 (4), 64-69. ISSN 2734-9888.
3. Ha Xuan Anh (2023), Choose probability distribution to constructe IDF curve for calculation of rainwater drainage system in Hanoi area, *Journal of Construction*, 2023 (9), 82-89. ISSN 2734-9888.