RAINFALL INTENSITY-DURATION-FREQUENCY CURVES AT UNGAUGED LOCATIONS WITH UNCERTAINTIES DUE TO CLIMATE CHANGE

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DEDICATION

To my father Umar Din Kibzai who, despite several financial and social hurdles, successfully made it possible to educate all of my siblings

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ABSTRACT

Intensity duration frequency (IDF) curves are important in designing and managing urban hydraulic structures for mitigation of floods. The objective of the study was to develop IDF curves at ungauged locations with associated uncertainties due to climate change. Peninsular Malaysia was considered as the case study area. The novelty of the study was to propose a new methodology for reliable estimation of IDF curves at any location with consideration of non-stationary behaviour of rainfall due to climate change which can be used for robust designing of climate change resilient urban hydraulic structures. Hourly observed rainfall data at 80 locations distributed over Peninsular Malaysia and four remote-sensing rainfall datasets namely, GSMaP_NRT, GSMaP_GC, PERSIANN and TRMM_3B42V7 were used for this purpose. Four widely used probability distribution functions (PDFs) and four methods for estimation of PDF parameters were compared to determine the most suitable PDF and its parameter estimation method in the study area. Subsequently, the estimated parameters of the selected PDF were used to generate IDF curves at all the observed locations. The performance of four remote sensing rainfall datasets in construction of IDF curves at observed locations was compared to find the best product. The bias in the IDF curve of the best rainfall product was corrected to generate the IDF curves at ungauged locations. To update the IDF curves for future climate change scenarios, high-resolution rainfall projections data were generated through selection of suitable global climate models (GCMs) of Coupled Model Intercomparison Project Phase 5 (CMIP5) and their downscaling at remote sensing rainfall grid locations. Climate change factor at each grid location was estimated through comparison of PDF of historical and future simulations of GCMs for different radiative concentration pathways (RCP) scenarios. The factors were used to perturb the historical IDF curves to generate IDF curves with associated uncertainties for future climate change scenarios. Results revealed general extreme value (GEV) as the best-fitted PDF and maximum likelihood as the best parameter estimation method at 62% of the stations. Performance assessment of remote sensing rainfall datasets revealed all datasets underestimated rainfall intensities for different durations and return periods. Comparative performance of the products revealed GSMaP_GC as the most suitable product for developing IDF curves at ungauged locations with least biases (8% to 27%). BCC-CSM1.1 (M), CCSM4, CSIRO-Mk3.6.0 and HadGEM2-ES were found as the most suitable GCMs models for the projection of daily rainfall in Peninsular Malaysia. The ensemble mean of projected rainfall showed a maximum increase in annual rainfall by 15.72% and an increase in variability by 26.15% during 2070-2099 compared to the base period (1971-2000) under RCP 8.5. The assessment of IDF curves with uncertainty revealed a maximum change in rainfall intensity for different durations under RCP 8.5 and the minimum for RCP 2.6. The rainfall intensity for different durations was found to increase with time. The highest increase was observed up to 96.8% for the period 2070-2099. The assessment of uncertainty in rainfall IDF for different RCP scenarios revealed higher uncertainty for higher return periods and vice versa. The IDF curves generated in this study can suitably be used for designing hydraulic structures at locations where observed rainfall data is not available. It can also be used for designing hydraulic structure for adaptation to climate change induced rainfall extremes and mitigation of urban flood.

ABSTRAK

Lengkung frekuensi tempoh keamatan (IDF) penting dalam perancangan dan menguruskan sebarang struktur hidraulik bandar untuk tebatan banjir. Objektif kajian ini adalah untuk membangunkan lengkung IDF di lokasi tanpa tolok dengan ketidak pastian yang dipengaruhi oleh faktor perubahan iklim. Semenanjung Malaysia dipilih sebagai kawasan kajian kes. Sesuatu yang baru dari kajian ini adalah cadangan satu metodologi dalam menganggarkan lengkung IDF yang dapat dipercayai di mana-mana lokasi dengan mempertimbangkan tingkah laku hujan pegun kesan dari perubahan iklim yang dapat digunakan dalam rekabentuk struktur hidraulik bandar yang berdaya tahan serta sesuai dengan pengaruh perubahan iklim. Hujan jangka panjang berskala jam yang direkodkan di 80 lokasi di Semenanjung Malaysia dan empat set data hujan “remote sensing” iaitu, GSMaP_NRT, GSMaP_GC, PERSIANN dan TRMM_3B42V7 digunakan untuk tujuan ini. Empat fungsi taburan kebarangkalian (PDFs) pilihan yang kerap digunakan dan empat kaedah anggaran parameter PDF dibandingkan untuk memperolehi PDF dan kaedah anggaran parameter di kawasan kajian. Selepas itu, parameter anggaran PDF yang terpilih digunakan untuk menghasilkan lengkung IDF di semua lokasi tolok. Prestasi empat set data hujan penderiaan jauh dalam pembinaan lengkung IDF di lokasi tolok dibandingkan untuk mencari produk terbaik. Kepincangan dalam lengkung IDF dari produk hujan terbaik diperbetulkan untuk menghasilkan lengkung IDF di lokasi yang tidak bertolok. Untuk mengemaskini lengkung IDF bagi senario perubahan iklim masa depan, data unjuran hujan beresolusi tinggi dihasilkan melalui pemilihan Model Edaran Umum (GCMs) yang sesuai daripada “Coupled Model Intercomparison Project Phase 5 (CMIP5)” dan pengunjurannya di lokasi grid hujan penderiaan jauh. Faktor perubahan iklim di setiap lokasi grid dianggarkan melalui perbandingan simulasi PDF sejarah dan GCMs masa depan untuk senario jalur kepekatan radiatif (RCP) yang berbeza. Faktor-faktor tersebut digunakan untuk penghasilan lengkung sejarah IDF bagi senario perubahan iklim masa depan yang berkaitan dengan faktor ketidak pastian. Hasilnya menunjukkan nilai ekstrem umum (GEV) sebagai PDF yang paling sesuai dan kebarangkalian maksimum sebagai kaedah anggaran parameter terbaik di 62% stesen. Penilaian prestasi set data hujan penderiaan jauh menunjukkan keamatan yang dihasilkan dari semua set data hujan adalah di bawah jangkaan bagi tempoh hujan dan kala kembali yang berbeza. Perbandingan prestasi menunjukkan GSMaP_GC adalah produk penderiaan jauh yang paling sesuai untuk menghasilkan lengkung IDF di lokasi yang tidak ditolok dengan kepincangan paling rendah (8% -27%). BCC-CSM1.1 (M), CCSM4, CSIRO-Mk3.6.0 dan HadGEM2-ES pula didapati GCM yang paling sesuai untuk unjuran hujan harian di Semenanjung Malaysia. Purata hujan yang diunjur menunjukkan peningkatan maksimum dalam hujan tahunan sebanyak 15.72% dan peningkatan kebolehubahan sebanyak 26.15% bagi tempoh 2070-2099 berbanding tempoh asas (1971 – 2000) di bawah RCP 8.5. Penilaian lengkung IDF dengan ketidak pastian menunjukkan perubahan maksimum bagi keamatan hujan untuk jangka masa yang berbeza di bawah RCP 8.5 dan minimum untuk RCP 2.6. Keamatan hujan untuk jangka masa yang berlainan didapati meningkat seiring dengan masa. Kenaikan tertinggi sehingga 96.8% dihasilkan untuk tempoh 2070-2099. Penilaian ketidakpastian IDF hujan untuk senario RCP yang berbeza menunjukkan ketidak pastian yang lebih tinggi untuk tempoh kala kembali bagi keamatan hujan yang lebih tinggi dan sebaliknya. Lengkung IDF yang dihasilkan dalam kajian ini dapat digunakan bagi rekabentuk struktur hidraulik dan sistem saliran untuk lokasi yang tidak merekodkan data hujan. Ia juga dapat digunakan untuk merekabentuk struktur hidraulik dengan adaptasi kepada perubahan iklim yang terdorong dari hujan ekstrem dan struktur tebatan banjir di kawasan bandar.

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LIST OF ABBREVIATIONS

APHRODITE		Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation
AR4	-	Fourth Assessment Report
AR5	-	Fifth Assessment Report
CCF	-	Climate Change Factor
CDF	-	Cumulative Distribution Function
CHRS	-	Centre for Hydrometeorology and Remote Sensing
CMIP	-	Coupled Model Inter-comparison Project
DID	-	Department of Drainage and Irrigation
FSS	-	Fractional Skill Score
GCM	-	Global Climate Model/ General Circulation Model
GEV	-	Generalized Extreme Value Distribution
GHGs	-	Greenhouse Gases
GMLE	-	Generalized Maximum Likelihood Estimator
GP	-	Generalized Pareto Distribution
IDF	-	Intensity Duration Frequency
IDW	-	Inverse Distance Weighting
IPCC	-	Intergovernmental Panel on Climate Change
JAXA	-	Japan Aerospace Exploration Agency
md	-	Modified index of agreement
MLE	-	Maximum Likelihood Estimator
MME	-	Multi-Model Ensemble
MOS	-	Model Output Statistics
NEM	-	Northeast Monsoon
NRMSE	-	Normalized Root Mean Square Error
PBIAS	-	Percentage of Bias
PDF	-	Probability Distribution Function
PERSIANN	-	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
R^2	-	Coefficient of determination
RCPs	-	Representative Concentrations Pathways

RF - Random Forest
RMSE - Root Mean Square Error
rSD - Ratio of Standard Deviations
SWM - Southwest Monsoon
UCI - University of California, Irvine
WMO - World Meteorological Organization

LIST OF SYMBOLS

W/m^2	Watt per square meter
%	Percent
∞	Infinity
mm/hr	millimetre per hour
ln	Natural Logarithm
°	Spatial degree of resolution of latitude and longitude
k	Shape Parameter
μ	Location Parameter
σ	Scale Parameter
Δ	Climate Change Factor

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Rainfall intensity-duration-frequency (IDF) curves are globally used to incorporate rainfall information into water infrastructure design (Watt and Marsalek, 2013, Koutsoyiannis et al., 1998). The IDF curves are developed based on the mathematical relationship of frequency, intensity and, duration of rainfall data (Koutsoyiannis et al., 1998) through the use of probability distribution function (PDF) of maximum rainfall depth for a specific duration (Chow et al., 1988). These curves can be used for estimating probable extreme rainfall amounts of different durations and intensities to address climate extremes. Such information can be used for designing hydraulic structures for the protection of floods from probable maximum rainfall extremes for a particular return period (Koutsoyiannis, et al., 1998; Noor et al., 2018).

Development of IDF curves requires long-term observed hourly or sub-hourly rainfall records which are not available in many regions of the globe. In such a case, hydraulic structures are designed based on IDF curves developed using rainfall data of nearby gauge locations. The nature of IDF curves varies widely over space due to variations in rainfall intensity and durations (Kidd et al., 2017, Sorooshian et al., 2011). Therefore, nearby station data is usually employed in generating IDF often not reliable for designing water infrastructures. Besides, the accuracy of IDF curves decreases significantly with distance from rain gauge locations (Marra et al., 2017). Therefore, the lack of sufficiently long good quality rainfall records can lead to error in IDF and improper designs of urban drainages and stormwater infrastructure systems. To overcome the difficulty associated with sparse observational records and scarcity of long-term record, alternative data source at the location of interest is suggested (Courty et al., 2019). A range of gridded precipitation products are now available globally which may be categorized as gauge-based, remote sensing-based, reanalysis or combination of these three (Belo-Pereira et al., 2011, Herrera et al., 2012, Schiemann et al., 2010, Yatagai et al., 2009, Nashwan and Shahid, 2019b, Faiz et al., 2018, Laiti et al., 2018, Huang et al., 2018, Yao et al., 2020, Palomino-Ángel et al., 2019, Almazroui and Saeed, 2020). Such data are recently used for developing IDF curves at ungauged or data scarce locations (Noor et al., 2018).

IDF curves are generally developed based on historical rainfall data considering a stationary climate where changes in mean and variability of rainfall over time are considered insignificant. However, the changing nature of the earth’s climate is now widely recognised. One result of this climate change is that the water holding capacity of the atmosphere is likely to increase (Trenberth, 2011). This has serious implications for the distribution of global precipitation (IPCC, 2014). Changes in extreme rainfall events will occur due to increased evaporation and atmospheric moisture content (Wang and Chen, 2014, Abbaspour et al., 2015, Pour et al., 2020b). Since rainfall is the major element of the hydrological cycle, any additional change in its distribution and volume may result in large scale flooding (Hajani et al., 2017, Pour et al., 2020a, Pour et al., 2014). The urban stormwater management infrastructure based on IDF curves developed using the observed data can become insufficient to deal with the unexpected increase in runoff (Tfwala et al., 2017, Willems, 2013, Watt and Marsalek, 2013; Shahid et al., 2017a, Almazroui et al., 2019).

Estimation of adaption investment proportional to climate-related risks is one of the vital challenges in infrastructure planning and management (Hall et al., 2015). Development of an optimized and secure water resources management system is even more significant (Giuliani et al., 2015). Analysis of cost and adaption investment due to impacts of climate change is of prime importance in the planning of water management infrastructure system (Hughes et al., 2010). Significant cost-effective steps should be taken for identification of water resources investments that can reduce the risks (Borgomeo et al., 2018, Shahid et al., 2017b). For such analysis, it is very important to quantify the impacts of climate change on urban water management infrastructure.

To minimize the losses due to the plausible extreme events, the designs for urban infrastructures need to be revised and updated by considering the effects of changing climate. A complete analysis of climate events requires an analysis of both their spatial and temporal extent (Shahid, 2010, Shahid, 2009). Global climate models (GCMs) are the main tools used by the scientific community to reproduce the current climate and project future changes of extreme precipitation events. Utilization of GCM projections to review and update the current procedures of designing and construction of water management infrastructure for the adaptation and mitigation to climate change is important (Batisani and Yarnal, 2010, Wang et al., 2016a).

1.2 Statement of Problem

The use of the best PDF and its parameter estimation technique is vital for the development of IDF curves (Rahman et al., 2013). Selection of most suitable PDF from a large number of PDFs and the selection of the most suitable method for the estimation of PDF parameters is important for the development of reliable IDF curves (Srivastav et al., 2014). However, the best-fit PDF and suitable parameter estimation method vary widely in space and time. It is a major challenge to identify the most suitable PDF and parameter estimation method for a large area covered by many stations.

Lack of long-term hourly or sub-hourly rainfall record and the spatial sparseness of weather stations are major barriers in generating IDF curves at any point of interest (Nashwan and Shahid, 2019a, Prein and Gobiet, 2017, Nashwan et al., 2018). Moreover, still no reliable method is available for development of IDF curves at ungauged locations. Therefore, the establishment of a justifiable mechanism for developing IDF curves at ungauged locations is indispensable. Remote sensing precipitation data can assimilate variability and dynamics of extreme rainfall events at ungauged locations and thus, has potential to be used for the development of IDF curves (Chen et al., 2013, Marra et al., 2016, Panziera et al., 2016). However, the performance of remote sensing precipitation varies widely with time and space. Selection of suitable remote sensing precipitation product based on its ability to generate IDF curve is a major challenge in generating reliable IDF curves.

GCMs are generally used for the projection of future climate. Several assumptions are made in GCM development due to lack of complete information about atmospheric processes, which cause a large uncertainty in GCM simulations. A suitable set of GCMs is generally selected to reduce the uncertainty in climate projections Samadi et al. (2010). Besides, the projections of GCMs are required to downscale to a fine resolution for impact assessment at the local scale (Pour et al., 2014, Ahmed et al., 2015a, Khan et al., 2018). Selection of a suitable set of GCMs and appropriate downscaling method are the most challenging tasks in reliable climate projections (Ahmed et al., 2015b, Nourani et al., 2018, Sachindra and Perera, 2016).

The expected increase in precipitation intensity and frequency due to climate change would certainly alter the existing IDF curves (Rodríguez et al., 2014, Mailhot and Duchesne, 2009). This emphasizes the need of revising the urban standards of civil engineering designing practices based IDF curves that are estimated from the projected intensity and frequency of extreme rainfall under climate change scenarios to develop climate-resilient urban infrastructures (He et al., 2006, Grum et al., 2006, Papa et al., 2004). Incorporation of climate uncertainty in IDF curves can help better decision making in urban hydraulic infrastructure planning and management (Papa et al., 2004, He et al., 2006, Grum et al., 2006, Shrestha et al., 2017). However, deriving robust technique for the development of IDF curves with uncertainties due to climate change remain a challenge for hydrologists.

1.3 Objectives of the Study

The major objective of the proposed research is the estimation of IDF curves at ungauged locations with associated uncertainties due to climate change to aid in climate-resilient hydraulic infrastructure designing. The specific objectives are:

i. To develop a framework for the generation of rainfall IDF curves through the selection of best probability distribution function and parameter estimation method.
ii. To estimate IDF curves at ungauged locations using bias correction of high-resolution gridded remote sensing-based rainfall data.
iii. To generate high-resolution rainfall projections for climate change scenarios through the selection of a suitable set of GCMs and robust statistical downscaling method.
iv. To develop rainfall IDF curves at ungauged locations with associated uncertainties for different climate change scenarios.

1.4 Scope of the Study

Development of IDF curves at ungauged locations under climate change scenarios is the main focus of this study. Peninsular Malaysia was considered as the case study area for the study. Therefore, data collection and analysis were limited to Peninsular Malaysia only. The IDF curves were developed by fitting PDFs to the annual maximum rainfall series. Performance of four PDFs and four methods for parameter estimation was evaluated to select the best-fit PDF and most suitable parameter estimation method.

For developing IDF curves at ungauged locations, the performance of four remote sensing-based rainfall data namely, GSMaP_GC, GSMaP_NRT, PERSIANN and TRMM were evaluated. Although several remote sensing data products are available for use in hydrological studies, the temporal resolution and short period of availability have restricted their application. The hourly rainfall data for longer periods were available only for these four products. Therefore, only the performance of these products in developing of IDF curve was assessed in this study.

Several GCMs are available in CMIP5 suit used in the latest projection of climate change by IPCC (2013). Based on APHRODITE rainfall data past performance approach was used for the selection of the most suitable set of CIMP5 GCMs under four representative concentration pathways (RCPs) scenarios. The IDF curves under changing climate were developed using downscaled outputs of selected GCMs.

The four bias corrections methods were used for developing MOS downscaling model are power transformation (PT), Generalized Quantile Mapping, (Gen QM), Gamma Quantile Mapping (Gamma QM) and Linear Scaling (LS) method. The performance of four bias correction methods was compared to select the best downscaling method for Peninsular Malaysia. The most suitable downscaling method was finally used for downscaling of selected GCMs at the spatial resolution of remote sensing data.

An ensemble of the downscaled outputs of the selected GCMs was used for assessment of the spatial and temporal variation of rainfall and rainfall extreme indices. A climate change factor (CCF) was used for updating the existing IDF curves (at ungauged locations) with associated uncertainties under four climate changes scenarios namely, RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 for two future periods, 2020-2059 and 2060-2099. The CCF was developed by estimating the difference between the PDF parameters of GCMs' projected future and historical annual maximum rainfall distributions.

1.5 Significance of the Research

A novel approach is proposed for developing rainfall IDF curves with associated uncertainties at ungauged locations by using remote sensing rainfall data, gauged rainfall data and GCMs projections. The approaches used for developing IDF curves at ungauged sites and incorporating the impacts of climate change in rainfall IDF curves is a novel contribution to the knowledge of the design of urban water management infrastructure. The proposed study will help in the improvement of knowledge in the use of PDFs for development of IDF curves, development of IDF curves at ungauged locations and incorporation the impacts of changing climate in rainfall IDF curves. IDF curves for ungauged sites under future climate change scenario is essential in the development of climate-resilient urban hydraulic infrastructures in Peninsular Malaysia. This study will help in analysing and evaluation of remote sensing rainfall products for development rainfall IDF curves and other hydrological studies in ungauged or data-scarce regions. It will help in understanding the impacts of changing climate on rainfall IDF curves, future changes in rainfall extremes and changes in precipitation pattern in Peninsular Malaysia.

The study proposes a novel procedure for selection of a suitable set of GCMs out of a larger pool of GCMs for use in any hydrological and climatological study. It will help in downscaling and projection of rainfall under various climate change scenarios. The study provides a novel method for developing an ensemble projection of future climate. It can also be useful for other impact assessment studies.

Information on possible changes in IDF curves will help different urban stakeholders and decision-makers to improve their knowledge on changes in precipitation pattern and the nature of IDF, which in turn will help in long-term climate change adaptation and mitigation planning. The study will help engineers and practitioners to incorporate climate change information for efficient designing and planning of urban stormwater management infrastructure and other hydraulic structures. The research framework developed in this study can be used for replication of the method in other regions for reliable estimation of IDF curves for development of climate-resilient urban structures, in the absence of long-term observe rainfall record.

1.6 Thesis Outline

This thesis consists of five chapters. Descriptions of the chapters are given below in brief.

Chapter 1 provides a general background of the study, problem statement, hypothesis, objectives, scope, and significance of the study.

Chapter 2 describes a general review of the literature. It covers a review of the methods used for the development of IDF curves, development of IDF curves at ungauged locations, remote sensing rainfall data, climate change, impacts of climate change on rainfall extremes and rainfall IDF curves, use of GCMs for the projection of future climate, selection of GCMs, downscaling and projection of rainfall under climate change scenarios and development of IDF curves for ungauged locations under climate change scenarios.

Chapter 3 explains the data and methodology used in the present study. It broadly discusses data and their sources, geography and climate of the study area, selection of PDF and distribution parameter estimation methods for the development of IDF curves, methods for the development of IDF curves at ungauged locations through the selection of suitable remote sensing rainfall data set, selection of GCMs, development of downscaling models, downscaling and projection of rainfall and rainfall extremes and rainfall IDF curves under climate change scenarios.

Chapter 4 presents the results obtained in the study. Best fit probability distribution, development of IDF curves, evaluation of remote sensing rainfall products, development of IDF curves at ungauged locations, selection of a suitable set of GCMs, downscaling and projection of rainfall, projection of rainfall extreme indices and updating existing IDF curves at ungauged locations with uncertainty levels are presented in this chapter.

Chapter 5 provides the conclusions made from the results presented in Chapter 4. Future research recommendations related to current research work are also provided at the end of this chapter.

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