DETERMINATION OF WATER QUALITY DEPTH FOR STORMWATER FACILITIES IN PENINSULAR MALAYSIA

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DETERMINATION OF WATER QUALITY DEPTH FOR STORMWATER FACILITIES IN PENINSULAR MALAYSIA

by

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C	Runoff coefficient
C_i	Means inlet concentration
C_o	Means outlet concentration
C_v	Area-weighted volumetric runoff coefficient for the landuse
IA	The fraction of impervious area
N	Total number of event
N_o	Total number of overflow event
ns	Total number of observed point
P	Probability of non-exceedance
P_d	Rainfall depth for water quality design storm
r	Rank number
R	Runoff capture ratio
Zg	Interpolated value
Zs_1	Observed value at point I
z_0	Estimated value in point 0
z_i	z value at known point i,
$z_{i,act}$	Known value of point i
$z_{i,est}$	Known value of point i.
λ	Lambda

LIST OF ABBREVIATIONS

AN	Ammoniacal Nitrogen
APHA	American Public Health Association
ARC	Atlanta Regional Commission
ARI	Average recurrence interval
ASCE	American Society of Civil Engineers
BIOECODS	Bio-ecological Drainage System
BMPs	Best Management Practices
BOD	Biochemical Oxygen Demand
CC	Columbia County
CDFs	Cumulative Probability Density Functions
COD	Chemical Oxygen Demand
DDF	Depth–Duration–Frequency
DID	Department of Irrigation and Drainage
DO	Dissolved Oxygen
DOE	Department of Environment
FWS	Free Water Surface
GIS	Geographical Information System
IDW	Inverse Distance Weighting
IDF	Intensity Duration frequency
IDNR	Iowa Department of Natural Resources
IEDT	Inter-Event Time Definition
IPCC	International Governmental Panel on Climate Change
LID	Low Impact Development
MAE	Mean Absolute Error

MBE	Mean Bias Error
MDE	Maryland Department of the Environment
MIT	Minimum Inter Event Time
MK	Mann Kendall
MSMA	Manual Saliran Mesra Alam Malaysia
NJDEP	New Jersey Department of Environmental Department
NO_3^-	Nitrate
NO_2^-	Nitrite
NT	Northeast Tennessee
NYSDEC	New York State Department of Environmental Conservation
OK	Ordinary Kriging
POT	Peaks-Over-Threshold
RCMs	Regional Climate Models
REDAC	River Engineering and Urban Drainage Research Centre
RMSE	Root Mean Square Error
SNHT	Standard Normal Homogeneity test
SSF	Subsurface Flow
SUDS	Sustainable Urban Drainage Systems
TIDEDA	Time Dependent Data
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UDFCD	Urban Drainage Flood Control District
UPRCT	Upper Parramatta River Catchment Trust
USEPA	United States Environmental Protection Agency

USM	Universiti Sains Malaysia
WEF	Water Environment Federation
WQD	Water Quality Depth
WQI	Water Quality Index
WQV	Water Quality Volume
WSUD	Water Sensitive Urban Design

PENENTUAN KEDALAMAN KUALITI AIR UNTUK KEMUDAHAN RIBUT HUJAN DI SEMENANJUNG MALAYSIA

ABSTRAK

Urbanisasi meningkatkan jumlah pencemaran ke saluran hiliran. Amalan Pengurusan Terbaik (BMPs) telah dikenalpasti sebagai pendekatan untuk menyelesaikan masalah ini. Keberkesanan BMPs bergantung kepada jumlah air larian yang boleh dikumpul dan dirawat yang disebut sebagai "Isipadu Kualiti Air" (WQV) dan memerlukan kedalaman larian yang disebut "Kedalaman Kualiti Air" (WQD). Nilai WQD yang disyorkan untuk Malaysia adalah 40 mm dan ianya dijana daripada data yang terhad. Kajian ini bertujuan untuk menentukan nilai WQD dengan menggunakan data hujan tempatan dan membangunkan peta taburan WQD untuk Semenanjung Malaysia. Pada 90^{th} persentil, WQD didapati berada dalam julat 33 - 57 mm. Walau bagaimanapun, WQD pada 95^{th} persentil adalah lebih tinggi iaitu di antara 44 - 90 mm. Oleh itu, nilai WQD 40 mm adalah tidak sesuai untuk Semenanjung Malaysia dan disarankan agar WQD ini dikaji semula. Penemuan kajian ini boleh digunakan untuk tujuan sedemikian. Kajian ini juga menunjukkan bahawa disebabkan oleh hanya sedikit peningkatan trend terhadap nilai ekstrim, maka nilai extrim tidak perlu dimasukkan dalam penentuan nilai WQD untuk mengelakkan reka bentuk berlebihan pada kemudahan BMPs. Untuk peta taburan WQD, Inverse Distance Weighting (IDW) dipilih sebagai kaedah interpolasi WQD yang paling sesuai pada 90^{th} persentil sementara Ordinary Kriging pada 95^{th} persentil. Satu kajian lapangan yang melibatkan tanah bencah telah dijalankan untuk menentukan hubungan antara nilai WQD dan prestasi rawatan kemudahan BMPs. TSS mencatatkan prestasi yang lebih

tinggi apabila kedalaman hujan berada di bawah nilai WQD. Walau bagaimanapun, BOD, COD, TN, TP dan AN mencatatkan prestasi yang lebih tinggi apabila kedalaman hujan melebihi nilai WQD.

DETERMINATION OF WATER QUALITY DEPTH FOR STORMWATER FACILITIES IN PENINSULAR MALAYSIA

ABSTRACT

Urbanization increases the amount of pollution carried out to downstream waterways. Best Management Practises (BMPs) have been identified as an approach to solve the problems. The effectiveness of BMPs depends on the volume of storm runoff that can be captured and treated by them, which is referred as water quality volume (WQV) and requires a fixed depth of runoff which is referred to as "Water Quality Depth" (WQD). The recommended WQD value for Malaysia stands at 40 mm and generated from limited data. This research aims to determine WQD by using local rainfall data and develop WQD distribution map for Peninsular Malaysia. It shows that 90th percentile is an optimum rainfall depth value for Northern and Central regions of Peninsular Malaysia while 95th percentile for Southern and East Coast regions. At 90th percentile, WQD was found to be in the range of 33 - 57 mm. However, WQD at 95th percentile was much higher which is in the range of 44 - 90 mm. Therefore, WQD of 40 mm was insufficient for Peninsular Malaysia and it is suggested that the WQD be reviewed. Findings of this study can be used for such a purpose. This study also shows that, due to the small number of significant increasing trends in extreme value identified, it was unnecessary to include extreme value in WQD estimation to avoid over design in BMPs facilities. For WQD distribution map, Inverse Distance Weighting (IDW) was chosen as the most reliable method for WQD interpolation at 90th percentile while Ordinary Kriging at 95th percentile. A field study at a constructed wetland was carried out to ascertain the relationship between WQD and BMPs facilities treatment performance. TSS recorded higher performance when rainfall depth was below than WQD value. However, BOD, COD, TN, TP and AN recorded higher performance when rainfall depth exceeded WQD value.

CHAPTER ONE

INTRODUCTION

1.1 Background Study

Urbanization is a common phenomenon which has culminated in a myriad of environmental impacts. Rapid urbanization increases expansion of urban land uses, yet it correlates with increasing stormwater runoff. Urban stormwater runoff transports pollutants to receiving waters thereby leading to the degradation of water quality (Huang et al., 2010). In addition, stormwater runoff has become a major problem as the condition is poorly managed (Barbosa et al., 2012). To alleviate such a situation, sustainable stormwater management which complies with legislation requirements has been applied to ease the concern for environmental protection. In their research, Barbosa et al. (2012) suggested that sustainable stormwater management should be flexible, based on local characteristics, and consider issues including temporal, spatial and administrative factors and legislation.

The concepts of sustainable strategies in stormwater management vary according to the focus and country where they were initially developed. The most common concepts include the Best Management Practices (BMPs), Low Impact Development (LID), Water Sensitive Urban Design (WSUD), as well as Sustainable Urban Drainage Systems (SUDS). In this research, the BMPs concept which is used in Malaysia has been adopted. BMPs which deals with stormwater takes into account both protection of natural resources and the future needs (Hvitved-Jacobsen et al., 2010). Additionally, BMPs has been proven to be effective in removing pollutant and reducing runoff. BMPs are capable to reducing runoff via canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration (Battiata et al., 2010). When using bioretention as BMPs facilities, Li and Davis (2009) claim that runoff volume reduction and water quality benefits are intrinsically linked. Therefore, it is apparent that BMPs facilities should be implemented because it can solve a remedy hydrology and water quality impairment from urban development.

In BMPs facilities system, storage capture volume is implemented to mitigate impacts of stormwater pollutant on receiving waters. To ensure pollutant load is treated, BMPs should be designed to capture certain volume of runoff. Sharifi et al. (2011) concluded that the effectiveness of BMPs depends on the volume of runoff which is captured and treated. Lack of storage capacity, on the other hand, will affect removal efficiency of BMPs. As such, Wang et al. (2017) found that insufficient storage capacity affect removal efficiency of BMPs in Singapore. Overall, the design of BMPs facilities need to ensure balance between runoff capture capabilities and effectiveness in protecting receiving waters. Hence, getting the required capture volume of runoff will reduce pollutants and simultaneously improve water quality. The design capture volume to be treated in BMPs facilities is termed “Water Quality Volume” (WQV) and requires a fixed depth of runoff which is referred to as "Water Quality Depth" (WQD). There are various methods to estimate WQV, which are all based on capturing runoff volume from the more frequent storm events (Atlanta Regional Commission, 2001). Figure 1.1 illustrates the WQV requirements in BMPs facilities.

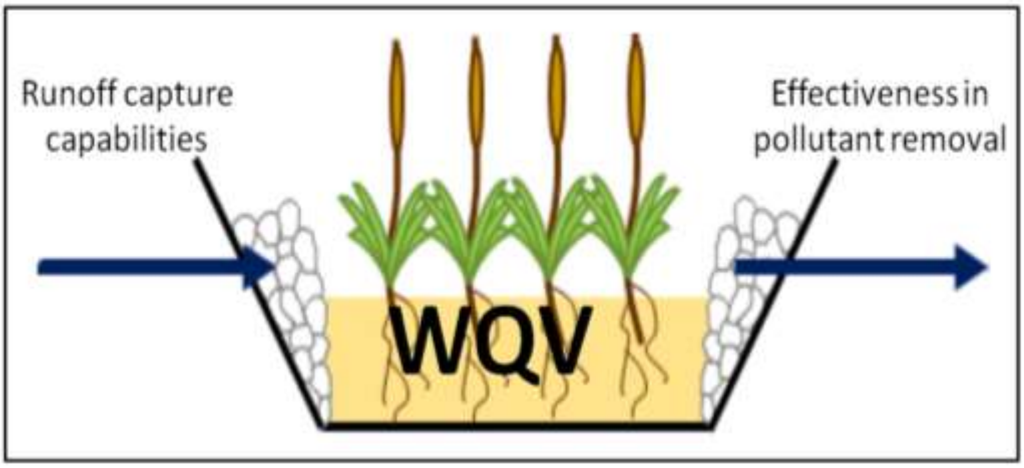

Figure 1.1: WQV requirements in BMPs facilities.

Both WQV and WQD concepts have originated from countries with temperate climate including United States (US) and Australia. In most states in the US, WQD corresponds to the first half an inch of runoff (Massachusetts Department of Environmental Protection, 2008; New Hampshire Department of Environmental Services, 2008; and Minnesota Pollution Control Agency, 2008). In Australia, WQD and average recurrence interval (ARI) are both included in stormwater guideline for treated stormwater runoff. Queensland in Australia, on the other hand, proclaims that WQV must be designed within one year ARI while Upper Parramatta River Catchment Trust recommends retaining a WQD of 15 to 20 mm to capture 60% of the average yearly rainfall (UPRCT, 2004). In tropical climate, Wang et al. (2017) reported that WQD is a better parameter in determining the size of BMPs and they recommended a WQD range of 10 to 30 mm. Such a value was obtained from hydrological analysis of 80 events in Singapore. Given these facts, it is clear that both WQV and WQD values vary depending on rainfall variability in the country. Therefore, estimation of WQV should be made according to local rainfall conditions to ensure BMPs facilities meet the required targets.

BMPs performance is also impacted by climate change especially when extreme events become a norm (Chan et al., 2012). The increasing of extreme rainfall events may exacerbate flood magnitudes and lead to increased sediment and nutrient loadings (Wang et al., 2013). With regard to this matter, Hvitved-Jacobsen et al. (2010) suggested considering extreme event value in rainfall data analysis as it indicates a potential risk to large pollutant concentrations. For tropical countries, Lim and Lu (2016) believed the design features of a water program need to be modified under more extreme rainfall conditions. Such an idea is supported in a study by Beck et al. (2015), which reported that total rainfall, hourly and daily extreme in Singapore had increased. In addition, the study indicated that the increase in daily extremes was the fastest, changing the temporal scaling of the extremes. Therefore, adaptation should be made in WQV estimation especially when considering extreme events that might occur regularly under future climate change conditions. More importantly, intense rainfall will overwhelm the drainage system and BMPs facilities should be back up by extreme event adaptation.

1.2 Problem Statements

WQV has become a key factor when designing the size of BMPs. At present, the BMPs design guideline for both Singapore and Malaysia is drawn from temperate areas especially Australia (Payne et al., 2015). Nevertheless, such design guideline and sizing curves cannot simply be adopted by tropical regions. Since rainfall-runoff characteristics typically vary from one place to another, the practice in temperate regions may not be applicable to tropical climate. Therefore, it is appropriate for Malaysia to develop its own BMPs design and performance target based on local climate. Furthermore, the WQV estimation has to be based on local rainfall condition to avoid undersized and oversizing of BMPs structure (Payne et al., 2015).

To date, the recommended WQD value in Urban Stormwater Management Manual for Malaysia stands at 40 mm (DID, 2012). Such a value is generated from limited data and applies across Peninsular Malaysia. Because of the variation of rainfall distribution, a single WQD might not be adequate over an entire peninsula. Suhaila et al., (2011) highlighted that each area in Peninsular Malaysia has its unique rainfall pattern due to topographical and geographical factors as well as influence of the monsoon. Moreover, Mohd Noor (2014) highlighted that most rainfall depth in Malaysia measure below 40 mm. Hence thorough study should be done to determine an accurate WQD for Peninsular Malaysia. This is also important as WQD has a direct influence on the size and cost of BMPs.

In the past, extreme events have been left out from WQV analysis to avoid a few large events from dominating the results. However, climate change has led to extreme rainfall events becoming a norm. Thus, WQV cannot solely be analysed based on local rainfall data but must consider extreme rainfall data especially in light of the anticipated extreme rainfall intensity. Yet, there is a lack of studies on WQV in tropical countries especially with regard to extreme event conditions. It is imperative for adaptation of extreme rainfall event in BMPs facilities be considered as it can assist in future design flows.

Moreover, Wang et al. (2017) suggested the exact value of WQD require further analysis to meet removal targets, especially in tropical countries. Thus, a field study is needed to evaluate the relationship between observed removal rates and WQD in order to treat the intense but common rainfall events in a tropical region.

1.3 Objectives of the Study

This research aims to fulfill four objectives, namely:

i. To determine WQD by using local rainfall data for Peninsular Malaysia;
ii. To evaluate the effect of extreme rainfall events in WQD estimation;
iii. To develop WQD distribution map for Peninsular Malaysia using spatial interpolation methods; and
iv. To determine relationship between WQD and treatment performance of BMPs facilities.

1.4 Significance of the Study

WQD has been widely used in the design guidelines of many countries. However, the reliable value of WQD for Peninsular Malaysia has yet to be identified. This study will provide an estimation of WQD based on local rainfall data and WQD distribution map available at the end of the study. It is hoped that engineers and decision makers will be able to use the WQD value from the study in designing future BMPs facilities. This will not only facilitate design process but can avoid the problem of undersized or oversized BMPs structures.

Previous studies have often excluded extreme rainfall value in WQV estimation. Analyses of this research will, therefore be focused on the effects of including extreme value in WQV estimation. Additionally, this research will provide an in-depth understanding of the relationship between WQD and BMPs facilities treatment performance. This can also become a reference for a country experiencing a lot of rainfall, especially in Asia.

1.5 Scope of Works

The scope of this study is as follows:

i. Only rainfall stations with rainfall records exceeding 20 years are considered for WQV estimation.
ii. For trend analysis, this research is confined to investigating only extreme data in absolute indices. Other indices such as percentile based, threshold and duration indices were excluded.
iii. The research study focuses only on constructed wetlands. Other BMPs facilities such as bioretention and swales were not investigated.
iv. The stormwater quality parameters investigated included solids and nutrients. Other stormwater quality parameters such as microbiological parameters, hydrocarbons and heavy metals were excluded.

1.6 Thesis Outline

This thesis is divided into five chapters. Chapter One provides introduction on BMPs and Chapter Two describe the impacts of urbanization to hydrology and water quality, which necessitate the need for water quality volume in BMPs facilities design. Besides comparing the water quality volume method, rainfall characteristics shall also be extensively discussed in order to support WQV estimation. Toward the end, a review of constructed wetland and performance of constructed wetland shall be presented. Chapter Three discusses the types of data used in the study, methodology of research process and data analysis, description about the study area, WQV estimation, trend analysis, interpolation method and cross validation, field data collection, performance of stormwater constructed wetland as well as statistical analysis. Chapter Four discusses the result of water quality depth in 90th and 95th percentile, trend analysis for extreme value, spatial interpolation method using Inverse Distance Weighting (IDW) and Ordinary Kriging (OK) method, as well as performance of constructed wetland. The final chapter, Chapter Five provides the conclusions gathered from the study and recommendations for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Impacts of Urbanization

Urbanization results in the growth of an impervious area. Such a situation brings impact to hydrology and water quality. The hydrologic impact results in an increase of runoff volume and peak runoff; in addition to a decrease in the time peak. Increasing runoff volume and peak runoff is due to an increased proportion of impervious surfaces which reduces infiltration losses and depression storage. Nelson and Booth (2002) reported that increasing peak runoff culminates in an upsurge of flood risks, damages to property and land degradation. In Shenzen, China, Shi et al. (2007) found that runoff peak has risen by 12% on average due to urbanization. In addition, urbanization also elevates runoff volume due to growing proportion of impervious surfaces (Barron et al., 2011). Franczyk and Chang (2009) predicted the runoff volume and estimated a 2.7% increase in annual runoff mean by 2040. Figure 2.1 illustrates the hydrologic changes as a result of urbanization.

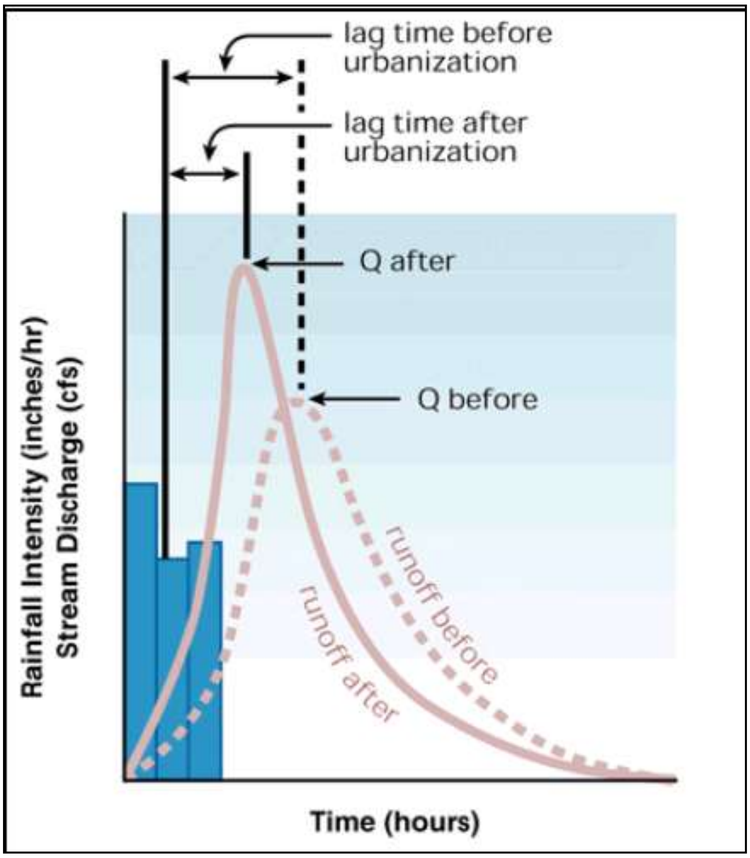

Figure 2.1: Hydrologic changes due to urbanization
(Adapted from https://cfpub.epa.gov/watertrain/moduleFrame)
(Accessed 30 May 2018)

Urbanization also results in water contaminants carried out to downstream waterways. Mandelker (1989) reported that 65% to 75% of pollution originates from non-point source from urban area. Stormwater runoff from urban areas consists of sediments, nutrients, heavy metals, bacteria, oils and grease. According to Sonzogni1 et al. (1980), suspended solids and nutrient loads from urban area are found to be between 10 to 100 time higher compared to non urbanised area. Furthermore, Line et al. (2002) also found 10-fold increases in solid loads and doubling in nutrient load in urbanised area.

Rainfall characteristics play an important role in urban stormwater quantity and quality control (Shikagi et al., 2007; Liu et al., 2012; Sandoval et al., 2013).

Shikagi et al. (2007) found that the total concentration of phosphorus was significantly higher in rainfall intensity of 75 mm/hour compared to 25 mm/hour. In a research conducted by Liu et al. (2012), high intensity in short duration and high intensity in long duration generated higher event mean concentration value in stormwater runoff. The researchers also confirmed that smaller ARI rainfall event with high intensity-short duration generated a major portion of the annual pollutant load and should be used as threshold for treatment system design (Liu et al., 2012). Therefore, stormwater treatment design should be based on the small and frequent rainfall events rather than larger rainfall events because the former produce a major portion of pollutant loads.

Being a rapidly developing country, Malaysia has also experienced the impacts of urbanization. Moreover, Malaysia has a tropical climate and receives higher annual rainfall amount. Therefore, it is important to improve the design of urban stormwater management. For this purpose, the relation between rainfall characteristics and water quality needs to be studied in more detail.

2.2 Rainfall

Rainfall, which occurs as a series of continuous event characterized by different depth, amount, duration, intensity and inter event time, is an input parameter for hydrology analysis and stormwater models. As such, understanding of rainfall characteristics is important for the development of effective stormwater management system.

2.2.1 Data Consistency

Accuracy and reliability of a rainfall analysis relies on the quality of long-term rainfall record. For this reason, rainfall data should be tested and checked for reliability and homogeneity. Factors such as location of the station, tool and method of data recording, measuring and observing techniques as well as collection and observation quality affect the homogeneity of rainfall records (Peterson et al., 1998). Furthermore, poorly distributed or equipped rainfall observation system leads to additional potential errors in long-term rainfall records (Che Ros et al., 2016). Inhomogeneous rainfall data may also be due to increasing climate and rainfall variability in an area. Førland and Hanssen-Bauer (2003) suggested that inhomogeneity of rainfall series should be adjusted when used in long-term climate variation studies.

There are various methods to detect inhomogeneity. They are classified into two groups, namely the ‘absolute method’ and the ‘relative method’ (Karabörk et al., 2007). In the 'absolute method', a test is applied for each station individually while in the 'relative method’, neighbouring stations are used in the testing process (Wijngaard et al., 2003). According to Peterson et al. (1998), it is easier to detect inhomogeneity using the relative method because of climate variations. However, this method is unable to show how real changes can be distinguished from purely random fluctuations (Buishand 1982). A neighbouring station must also have similar surrounding area and climate environment with the studied station and this is quite impossible to find.

The ‘absolute method’ uses statistical analysis to check inhomogeneity of the rainfall series. A lot of methods have been proposed for testing homogeneity in statistical analysis. Among them, Standard Normal Homogeneity Test (SNHT) and Pettitt tests have been found to be more sensitive in determining inhomogeneity of gauging stations (Firat et al. 2010). Karabork et al. (2007) used these two methods to detect inhomogeneity of precipitation in Turkey and considered stations as inhomogeneous if at least one of the tests rejects the homogeneity. On the other hand, Wijngaard et al. (2003) used the SNHT method, Buishand test, Pettitt test and Von Neumann test for testing homogeneity and the results of these different tests were condensed into three classes, namely ‘useful’, ‘doubtful’ and ‘suspect’. It was concluded that such a hybrid test method was a good choice to detect inhomogeneity due to the fact that detected inhomogeneity was mostly caused by simultaneous changes in the observation network. Furthermore, different methods have different sensitivity to break. The hybrid test method, however, uses many options thus resulting in a more accurate answer.

Table 2.1 shows the methods utilised, as well as variable and purpose of homogeneity tests by various researchers. In Malaysia, most researchers used the method proposed by Wijngaard et al. (2003) to ascertain homogeneity of data. However, different researchers used different variables to detect inhomogeneity, thus resulting in varying results. Suhaila et al. (2008) used two testing variables in detecting inhomogeneity of rainfall series in Peninsular Malaysia. They detected a different result in the list of inhomogeneous stations between wet days series and rainfall amount series. Suhaila et al. (2008) also concluded that the choice of testing variable depended on the study objectives. Therefore, it is imperative to check long-term rainfall data series for consistency and homogeneity. In addition, the choice of testing variables is also important as it affects the result.

Table 2.1: Methods and variables used for homogeneity tests

Researcher	Method	Variable	Purpose
Suhaila et al. (2008)	SNHT, Buishand range test, Pettitt test, and von Neumann ratio	Rainfall amount, wet day series	Detect inhomogeneity of rainfall series
Che Ros et al. (2016)	SNHT, Buishand range test, Pettitt test, and von Neumann ratio	Annual total rainfall	Homogeneity of the daily rainfall series
Kang and Yusof (2012)	SNHT, Buishand range test, Pettitt test, and von Neumann ratio	annual mean, annual maximum and annual median.	Homogeneity of the daily rainfall series
Firat et al. (2010)	SNHT, (SwedEisenhart) Runs Test and Pettitt homogeneity	the monthly and annual total precipitation records	Missing value analysis and homogeneity tests for 267 precipitation stations throughout Turkey.

2.2.2 Rainfall Events

Rainfall characteristics including depth, duration and intensity influence the pollutant loading in urban stormwater (Goonetilleke and Thomas, 2003; Shigaki et al, 2007; Alias et al. 2014). Because of intermittent rainfall, many research on hydrology employ the concept of rainfall events. Appropriate rainfall events may differ between systems, catchments or water quality and quantity objectives of receiving water bodies.

In a research conducted by Liu et al. (2012), it was found that rainfall events with high intensity in short duration and high intensity in long duration generate higher pollutant event mean concentration in stormwater runoff. Guo and Baetz (2007) reported that rainfall event has an influence on the required size of rainwater storage units for green building application. On the other hand, Ahn et al. (2014) used event–based model to overcome the limitations of conventional-design storm methodology and continuous simulation method in flood frequency analysis.

Rainfall event was also used in designing stormwater treatment system based on water quality and runoff volume. Liu et al. (2016) found that small and frequent rainfall events were more appropriate for stormwater treatment performance efficiency. This was due to the fact that smaller rainfall events with high intensity in short duration generate a major portion of annual pollutant load. This highlights the need for prudent selection of rainfall events for stormwater treatment design based on stormwater quality and appropriate runoff volume.

2.2.3 Minimum Inter Event Time (MIT)

Separation of rainfall event typically depends on the time chosen in Minimum Inter Event Time (MIT) (Shamsudin et al., 2010) or Inter-Event Time Definition (IETD) (Joo et al., 2013) - which is also referred to as antecedent dry period (Tian, 2009). MIT is defined as the minimum dry period between two rainfall pulses, and is the length of 'no rain' or 'dry period' that make two events independent on each other. Three methods have been used to determine the IETD, namely autocorrelation analysis, average annual number of events analysis, and coefficient of variation analysis. These three methods use meteorological characteristics and does not consider basin characteristics.

Adams et al. (1986) showed that rainfall event characteristics such as volume, intensity and duration varied according to different MIT. Shamsudin et al. (2010) claimed that different MIT provided varying number of rainfall events and shorter MIT have more varied duration and depth compared to rainfall separated by longer MIT. Furthermore, Asquith et al. (2006) identified that an increase of MIT will increase rainfall event depth and have significant impact on the derivation of an Intensity Duration Frequency curve. Based on several studies, MIT used for separation of rainfall event ranges from 6 to 8 hours and are widely adopted by many published studies. Driscoll et al. (1989) found that a 6-hour separation time produced the most consistent statistical results when attempting to define individual rainfall event from continuous records. Park et al. (2011) also used 6 hour interval to study the effects of seasonal rainfall distribution on water quality captured volume. Several researchers also used MIT over 8 hours in their research. Guo and Urbonas (2009) used three different MIT, namely 6 hour, 12 hour and 24 hour in delimiting individual storm events from continuous rainfall records. Shrestha (2013) recommended 6 to 72 hours of minimum inter event dry period for separated storm event in the study of percentile analysis. Nojumuddin et al. (2016) examined suitable MIT for Johor Malaysia and found that 8 hours was the chosen MIT for the study area. When considering basin characteristics, MIT values between 1 and 6 hours were suggested for most urban areas (Joo et al. 2013). For flood frequency study, Ahn et al. (2014) claimed that MIT of 3 hour was determined as the rule for rainfall event separation.

Clearly, MIT plays an important role in identifying independent rainfall event especially in the study related to water quality. This is because long rainfall duration (long MIT) has dilution effect and can lead to relatively low pollutant concentration (Liu et al. 2016). For the design of stormwater runoff control structures, the MIT used to develop rainfall statistics is related to drawdown time, infiltration time, or treatment time for a given BMPs structure. Therefore, shorter MIT would provide too short a time for BPMs to dry and be ready for the next event.

2.2.4 Extreme Rainfall Event

Extreme event is an event that is rare at a particular place and time of the year and differs from one region to another (Parry et al., 2007). The rainfall thresholds on which a rainfall event can be characterized as extreme vary among country. The different definitions of what is or is not an extreme event are due to the varieties in local features and interaction with the atmospheric circulation. Rainfall depth exceeding 124.4 mm is referred to as extreme rainfall events in India (Pattanaik and Rajeevan, 2010). In the European region, an extreme rainfall threshold differs from region to region and is in the range of 20 mm to 45 mm (Anagnostopoulou and Tolika, 2012).

There is no international standard for selecting extreme rainfall thresholds. This uncertainty leads to researchers often using a method that meets their own unique requirements. Extreme rainfall thresholds are usually determined by parametric and non-parametric methods. There are five (5) categories of extreme event indices regularly used in both methods, namely absolute indices, percentile based indices, threshold indices, duration indices and others, which have significant societal impacts. The absolute critical value method and the percentile-based method are commonly used in non-parametric test. Although both methods are easy to use, the absolute critical value method is unable to reflect spatial differences of rainfall distribution while the percentile method is influenced by the size of rainfall data series (Liu et al. 2013).

The parametric method is popular in current studies and is widely used in the distribution fitting methods. Specifically for rainfall data, the appropriate index is the threshold model which isolates events exceeding a specified threshold value. This index is also referred to as Peaks-Over-Threshold (POT) approach and is commonly used in hydrology analysis (Pandey et al. 2001). Liu et al. (2013) reported that the accuracy in determining extreme value threshold by using parametric statistical method relies on the size of rainfall series and fitting probability distribution function. Consequently, Anagnostopoulou and Tolika (2012) claimed that the determination of extreme rainfall threshold should be used in different methodologies and indices and the POT method and 99th percentiles indices have been proven to be more efficient in the European region.

Evidently, the threshold for extreme rainfall is difficult to set as extreme events are rare and occur on a relatively small and local scale. Nevertheless, identification of extreme rainfall events of certain magnitude is important due to the impacts on human society as well as ecological systems. Despite many studies on this subject being conducted in Malaysia, a large knowledge gap still exists with regard to extreme rainfall threshold and indices. Thus, research on such matters is strongly encouraged.

Climate change has been shown to affect many natural systems including extreme rainfall events. The International Governmental Panel on Climate Change (IPCC) reported that extreme event is among the impacts of global warming caused by the increase in anthropogenic greenhouse gas concentration. Figure 2.2 depicts the effect of climate change on future precipitation regimes. It shows a shift in the distribution toward the right, which implies an increase in the frequency and intensity of extreme events due to climate change. Loo et al. (2015) established the link between global warming and monsoon rainfall in Southeast Asia and their study proved that monsoon rainfall distribution is influenced by weather systems, such as the Arctic Oscillation, Siberian High and Western Pacific Subtropical High, as well as the complex Asian topography. Dore (2005) and Wang et al. (2013), in addition, stated that for areas with mean total precipitation increase, heavy and extreme precipitation events also increase in a large percentage. In Bangladesh, future increases of mean precipitation may lead to more frequent extreme events (Shahid 2011). Wang et al. (2013) indicated that extreme rainfall intensity and frequency are projected to increase by most models used in the study of climate change impact in the Apalachicola River Basin, Florida. Future increase of annual maximum rainfall also would affect the analysed drainage system which could trigger more frequent surcharge episodes (Notaro et al. 2015). The shortest duration (10 min) appeared to be the most critical situation and hydraulics structure design should consider this scenario (Jung et al. 2015).

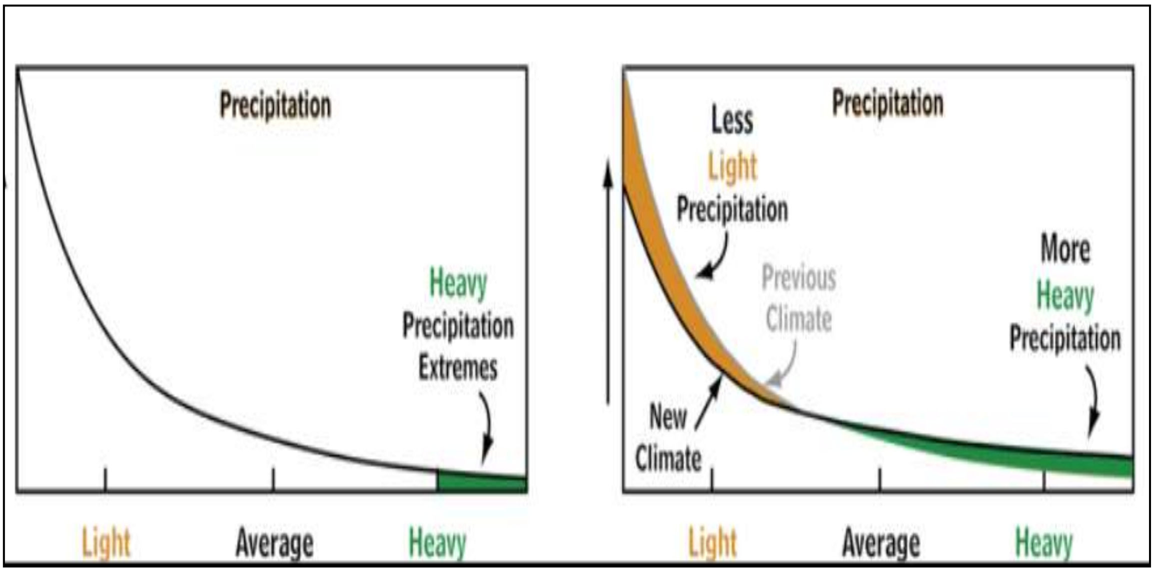

Figure 2.2: Effect of climate change on future temperature and precipitation regimes (Adapted from Karl et al., 2008)

With the increasing trend of extreme events, an issue that must be addressed is how can size and capacity of the BMPs facilities respond to such phenomenon. Because the BMPs design is based on analysis of past rainfall events data, variations in the intensity and frequency of extreme rainfall becomes a critical issue. Furthermore, Park et al. (2010) found that changes in rainfall amount and the frequency of extreme rainfall events affected surface water quality. Although standard design practice for urban infrastructure assumes stationarity of rainfall time series, Hirsch (2011) recommended that designers must also include non-stationarity considerations into water planning and management decisions. Arnbjerg (2006) suggested that the current Depth–Duration–Frequency (DDF) and Intensity-Duration-Frequency (IDF) curve require an adjustment due to variation of extreme event characteristics. A number of studies have demonstrated the need to revise existing IDF related to climate change impacts. By using a group of Regional Climate Models (RCMs), Wang et al. (2013) assessed climate change impact on IDF curves at the Apalachicola River Basin, Florida. Notaro et al. (2015) updated DDF curves for five year return period upon detecting statistically significant trends in annual maximum rainfall trends in Paceco urban area. Al Mamoon et al. (2016) found that significant changes were predicted at the end of century (2080 - 2099) in Qatar and increasing 24-hour design rainfall for ARIs of 10 - 20 years was in the range of 43% to 54%.

Trend analysis has been used to ascertain changes in the recent extreme rainfall data, and whether these changes can be considered statistically significant or otherwise. Non-parametric Mann Kendall test has proven as a useful method in determining existence of statistically significant trends (Shahid 2010; Babar and Ramesh, 2014). For urban drainage, Arnbjerg-Nielsen et al. (2013) recommended using an average of 30 years of rainfall records and 99.9 percentile and higher for quantiles methods to study about extreme rainfalls. Babar and Ramesh (2014) analysed rainfall data for a period from 1971–2010 (39 years) to compare suitable methods to study extreme rainfall trend analysis in Nethravathi basin, India.

Though faced with the climate change issue, adaptation of extreme rainfall has only focused on IDF curve. We need a better understanding of the storage capacity and performance of BMPs under more extreme rainfall conditions. The design criteria of BMPs should also take into account past trends as well as future climate changes projections. BMPs facilities need to resist the impact of increasing extreme rainfall events. Adaptation of it must be considered because it can convey future design flows. Moreover, such an action can reduce the extent of structural damage caused by extremes, in addition to elevating the performance of BMPs facilities.

2.3 Water Quality Volume

A BMPs facility is a structure used to treat stormwater. Not only can it reduce and delay the volume of stormwater entering a drainage system, BMPs facilities can also improve water quality before it is discharged into receiving waters. Estimating design volume is necessary before any assessment can be made in relation to pollutant loading in BMPs facilities. If the design volume is too small, this can lead to a large number of rainfall events exceeding the BMPs facilities capacity. Alternately, if the design volume is too large, this will increase the cost (Guo and Urbonas, 1996) and possibly lead to excessive land use. Therefore, BMPs facilities are required to have WQV, a storage that captures and treat stormwater runoff from the small and frequently occurring storm events. The employment of WQV overcomes the variation in flow rate and pollutant concentration in BMPs facilities (Niu et al, 2016). In practice, WQV is calculated based on rainfall depth because runoff volume is related to rainfall depth. It is evaluated based on rainfall historical records whilst considering local condition factors. WQV design method has been suggested by American Society of Civil Engineers (ASCE) and Water Environment Federation (WEF) and included in General Consideration in United States Environmental Protection Agency (USEPA) - Stormwater Management Practice Design Guideline. Since 2002, WQV estimation approach has been applied to BMP storage designs in many areas of the United States, particularly in the Urban Drainage Flood Control District (UDFCD) in Denver, Colorado.

Recommended WQV should be approximately the 75% to 90 % of storms and such volumes would capture the majority of pollutants from the site (Collins et al. 2010). The 85th and 90th percentile rainfall depths are also commonly used by various states, countries, and local agencies (WEF and ASCE, 1998; UDFCD 2001; Guo and Urbonas, 2002; Williardson and Walden, 2004). Table 2.2 presents a number of manuals and guidelines pertaining to information of design capture volume in various countries, states and cities including Malaysia.

Table 2.2: Guideline/manuals for WQV from a different country.

Country/state/city	Design capture volume/ WQV	References
Singapore	10 to 30 mm	Wang et al., (2017)
Malaysia	40 mm	DID (2012)
Portland	90% average annual runoff	Portland (2009)
Maryland	90% annual rainfall event (25.40 mm)	MDE (2000)
New York state	25.40 mm (90% rainfall event)	NYSDEC, 2010
Columbia County, Georgia	30.48 mm (85% rainfall annual event)	CC, 2009

Because of its importance in estimating the size of BMPs facilities within a reasonable cost, many researchers have looked at effective methods to determine WQV. There are a number of WQV estimation methods, including TP_{10} WQV method, maximized detention volume, rainfall capture rule, Pitt method, Half inch (first –flush) rule and One inch rule.

2.3.1 TP_{10} WQV Method

TP_{10} WQV method was proposed by the Auckland Regional Council, Technical Publication (Council 1999). In TP_{10}, WQV is calculated as 1/3 of the design rainfall depth defined as the at-site 2-year ARI 24-hour rainfall. This assumption was derived using data from a rainfall gauging station located in the

Botanic Gardens. TP_{10} stipulates is unable to capture and treat 80% runoff volume. TSS is used as an indicator pollutant and the water quality control goal of Total Suspended Solid (TSS) is 75%. The choice of this goal is also based on data from Botanic Gardens. Therefore, estimating WQV using this method may be device-dependent and different devices may produce different data.

2.3.2 Maximized Detention Volume

Maximized detention volume was introduced to determine stormwater quality detention volume (Ben Urbonas et al. 1989; Guo and Urbonas, 1996). Guo and Urbonas (1996) found that further increase in detention volume does not produce significant increase in the number of events or the runoff volume captured. They also found that designing stormwater quality control from rare and infrequent storms does not ensure the facilities provide enough detention time storage. Furthermore, Guo and Urbonas (1996) noted that 2 years of storm produce runoff larger than 95% event. They also claimed that smaller events may flow faster through facilities if the storage volume was too large. However, if the storage was too small, large storm may exceed the facility capacity. Therefore, this method estimates the storage volume based on finding the point of diminishing return as shown in Figure 2.3.