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A THESIS
FOR THE DEGREE OF MASTER OF ENGINEERING

Assessment of rainfall-runoff characteristics considering temporal variability in Hancheon watershed of Jeju Island

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2016. 02

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Assessment of rainfall-runoff characteristics considering temporal variability in Hancheon watershed of Jeju Island

Kanak Kanti Kar

(Supervised by Professor Sung-Kee Yang)

A thesis submitted in partial fulfillment of the requirement for the degree of
Master of Engineering

2015. 12.

This thesis has been examined and approved.

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This thesis is dedicated to

My Beloved Father, Mother and Brother

For their endless love, continuous support and encouragement

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Nomenclature

AMC	Antecedent Moisture Condition
ARF	Areal Reduction Factor
ANOVA	Analysis of Variance
ACF	Auto-correlation Function
AWS	Automatic Weather Station
CN	Curve Number
CV	Covariance
DEM	Digital Elevation Model
ESRI	Environmental System Research Institute
GEV	Generalized Extreme Value
GIS	Geographical Information System
HEC-HMS	Hydrologic Engineering Center- Hydrologic Modeling System
HSG	Hydrological Soil Group
HSPF	Hydrological Simulation Program - FORTRAN
HSIMHYD	Hydrologic Simulation Model
IDF	Intensity-Duration-Frequency
IHMM	Integrated Hydro Meteorological Model
KMA	Korean Meteorological Administration
lmomRFA	L-moments Regional Frequency Analysis
NRCS	Natural Resources Conservation Service
NERC	Natural Environmental Research Council
NSE	Nash-Sutcliffe Efficiency
RMSE	Root Mean Square Error
RFA	Regional Frequency Analysis
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
SCS	Soil Conservation Service
TRSM	Threshold Runoff Simulation Method
USACE	United States Army Corps of Engineers
USDA	U.S. Department of Agriculture

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Summary

Increasing the average rainfall and number of heavy rainfall events created the demand of rainfall-runoff characteristics estimation in Hancheon watershed of Jeju Island. This thesis paper considered the NRCS CN (Natural Resources Conservation Service-curve number), unit hydrograph method for understanding the runoff and developed L-moments method for rainfall frequency analysis.

Firstly, the NRCS CN method application result of five years rainfall showed 18% to 44% runoff variation from the total annual rainfall and the 2012 year received maximum rainfall-runoff volume. After that, unit hydrograph method was applied for estimation of peak runoff and peak time. To analyze observed rainfall-runoff and time, four storm events from 2012 were selected for calibration and typhoon Nakri of 2014 was used for validation. The HEC-hydrologic modeling system (HMS) simulation results showed the peak runoff varies from 151 to 546 m^3/sec and peak runoff time varies 8 to 27 hour. Meantime, a comprehensive relationship between Clark unit hydrograph parameters (time of concentration and storage coefficient) was also derived. The optimized values of hydrograph parameter were statistically verified by the analysis of variance (ANOVA) and the runoff comparisons were performed by r-square, root mean square error (RMSE) and Nash-Sutcliffe efficiency (NSE) method. The statistical performances of NSE, RMSE and r-square were found as 0.88, 37.52 and 0.76, respectively. The analysis results provide a decision for selecting rainfall-runoff event.

Final analysis was on rainfall frequency estimation considering spatio-temporal variability. As a result, L-moments based statistical analysis techniques were shown the dependable results. In the study, the recorded hourly rainfall data series of five rainfall stations were sorted by

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maximum consecutive hour rainfall (6-, 12-, 24-hour). Then, independence and stationary test of rainfall stations were analyzed using Mann-Kendal and autocorrelation function (ACF) analysis. Hereafter, cluster analysis and discordancy measure showed that the Hancheon watershed is belonging in three regions. Then, L-moments based heterogeneity measure identified that Gumbel and generalized extreme value (GEV) distribution as robust distribution for the study area. Afterwards, Monte Carlo simulation was applied to evaluate the accuracy of frequency estimation and the root mean square error (RMSE). In contrast, the RMSE values for watershed were seen as 0.014 to 0.237 for Gumbel and 0.115 to 0.301 for GEV distribution. The linear regression analysis of the frequency r-square value showed a variation of 0.842 to 0.974.

In essence, the assessment of rainfall-runoff characteristics following the above methods can be provided reliable and accurate results. Thus, these study findings are being suggested for water resources planning of Hancheon watershed as well as for Jeju Island.

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Chapter I: Introduction

1.1 Estimation of surface rainfall-runoff

Rainfall-runoff linkage is one of the most important relationships in hydrologic analysis. Runoff needs to be estimated for assessment of water availability and functions, to underscore the modalities for efficient utilization of water. Rainfall, on the other hand, is a primary input for watershed level runoff computation. The estimation of rainfall-runoff plays a pivotal role in water resource management and feasibility level planning for resources distribution, as well as hydrologic and hydraulic design of structures. In term of importance, a prominent stream which contains most its rain has been considered. There are some lumped (HEC-HMS, HSIMHYD, IHMM, etc.) and distributed (SWAT, GIS, SWMM, HSPF, NRCS CN, etc.) models are available for calculating watershed runoff after a rainfall event. Among of them, NRCS curve number (CN) method using GIS tool have been chosen for watershed of Jeju Island due to the models flexibility, efficiency, accuracy and parametric availability (SCS 1972).

The curve number (CN) is a combination of rainfall, land use and soil class. In hydrology, CN is used to determine the infiltration of water into soil and the amount of water becomes surface runoff. A high runoff means the area contains of high CN value in urban areas and a low runoff means the low CN value in dry soil. In this study, geographical extent had confined within the watershed. A watersheds runoff for daily rainfall events represents its overall response, and is therefore, an effective way to determine its total water availability (runoff volume). Thus, the approach has implicated for planning of several conservative measures in South Korea (Hawkins 1993; Kim et al. 2010).

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1. 2 Assessment of unit hydrograph parameters and runoff responses

Estimation of peak flood runoff and its timing is a fundamental issue for developing the design and controlling the functions of various flood protection and other hydrologic structures (Pegram and Parak 2004). The assessment of peak runoff depends on rainfall-runoff intensity, as well as the geomorphologic and climatic characteristics of a watershed. If the watershed area contains long temporal soaked rain, soil becomes saturated with water, for which no excess rainfall can enter it. Such cases are usually followed by the eventual draining out of excess rainfall into adjacent streams, resulting large amount of flow. These spatio-temporal variation of runoff largely constraints the pragmatic yet accurate estimation of peak flow, for which the concept of unique unit hydrograph is predominantly used. Unit hydrograph method is accepted procedure for transforming rainfall access to obtain runoff time distribution.

The very first unit hydrograph introduced by Sherman (1932), which considers the physiographic factors of watershed to predict hydrograph. A similar effort has been made in this study, which attempts to use the unit hydrograph concept to simulate a peak flood runoff of a typical water-soaked watershed area, by analyzing the historical information on rainfall-runoff of multiple storm rainfall events. A typical watershed named *Hancheon watershed* from Jeju Island has been chosen in this regard. Over the years, Jeju Island has been hit by heavy rainfall events as well as tropical storms and the study area also contains small patches with mountainous characteristics.

A total number of five rational models for determining the unit hydrograph have been inspected during this case study, the first of which was derived by Clark (1945). Clark unit hydrograph model works as a significant tool for rainfall-runoff simulation, where watersheds

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are assumed to have large length-width ratios and a relatively complex geomorphology (Sabol 1988). The model implies rainfall-runoff estimations using two major empirical parameters: time of concentration (Tc) and storage coefficient (R). The relationship between Tc and R was proposed by Johnstone et al. (1949), using major stream length and slope factor. The second rational method, developed by Snyder (1938), relates the time from centroid of the rainfall to the peak of unit hydrograph. The basic assumption of this method is that different watershed area having similar geometrical characteristics will have identical values of peak flood runoff and onset time. These regional parameters i.e. excess rainfall duration and area's storage coefficients are determined using the watershed lag time. The method also allows for un-gauged watersheds of similar patterns rainfall. The third method is known as the soil conservation service (SCS 1964) triangular unit hydrograph method, which developed a dimensionless hydrograph assumed by the relationship between accumulated total rainfall-runoff, infiltration and initial abstraction. However, implication of this method for high water levels is relatively difficult and the various antecedent moisture conditions (I, II and III) cannot handle rainfall-runoff problems accurately (Capece et al. 1988). The fourth method was the kinematic wave method (Wooding 1965) which investigated overland flow and created a stream hydrograph assuming gravity force. This is a physics based approach similar to the conventional hydrograph concept. The method requires the use of numerical methods in order to account for non-uniform rainfall and variable of watershed characteristics. The last method is Mod-Clark method, which inspected a computer aided model to incorporate grid cell data into detail hydrograph modeling (USACE 1995). This method is popular in rainfall-runoff modeling as it can very closely represent the torrential rainfall patterns and support to separate regression analysis using appropriate equations.

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To understand the storm rainfall-runoff characteristics of Hancheon watershed, several significant recent articles had been studied. Kim et al. (2014) investigated the flood runoff characteristics using surface image velocimetry method by disaster monitoring technology and considering 2012 years' storm rainfall events. The study gives an idea about observed runoff data measurement by Kalesto meter. Another study inferred that the Hancheon stream watershed runoff can be affected by the upstream reservoir operation (Moon et al. 2014). This study estimated peak runoff 'with' and 'without' reservoir operation scenarios, by considering typhoon Dianmu and typhoon Nari. Chung et al. (2011) developed threshold runoff simulation method (TRSM) to overcome the limitation of SWAT application for Jeju Island based on 2008-2010 daily limit rainfall-runoffs. The study provides the calibration method techniques and NRCS curve number (CN) idea for Hancheon watershed. Another study has been carried out based on the process of unit hydrograph parameters' estimation using stream water velocity, as developed by Jung et al. (2014), where the time of concentration and storage coefficient were estimated using Kraven II and Sabol formula respectively. The limitation of this study was unit hydrographs parameters range which could not be derived. Therefore, this study will present the parameters range along with peak runoff and time.

1. 3 Spatial interpolation of rainfall by areal reduction factor (ARF) analysis

Generally, design rainfall values are expressed from the fixed point rainfall, which is depth at a specific location. These require knowledge about spatial variability over a specified area. Concurrently, determine the amount of areal rainfall is also very important. Therefore, a spatial rainfall interpolation (point rainfall convert to areal rainfall) can be solved by areal reduction factor (ARF) estimation (Bell 1976; Coles and Tawn 1996; Michele 1999).

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Areal reduction factor (ARF) is define as the factors when applied to point values for a specific return period and duration provide the areal rainfall for the same durations and return period (NERC 1975). The ARF concepts give spatial variability framework of various hydrological processes. In mainland of South Korea, for dam design and operation, public safety and other surface water projects has been ARF for extreme hydrological events. In spite of the long term average rainfall and increasing extreme rainfall events, ARF estimation is also essential for Jeju Island's water control structures.

1.4 Development of L-moments approach by regional frequency analysis

In addition of gusty wind, typhoon wrought from heavy rainfall considered as a fundamental component of water cycle which has a wide range of application in hydrological engineering. The coastal part of East Asia is extensively and continuously hit by climatic disaster that has a substantial affect on large extent to the social and economic condition of the country (Jun 1989; Shabri et al. 2011; Chang 2012; Cai et al. 2014). As such, extreme hydro-meteorological occurrences are currently the lead research topics for its potentially dangerous phenomena (Bruce 1994; Obasi 1994). Attempts are therefore made to reliable estimation of extreme rainfall occurrence and corresponding frequency information accuracy to control the hydrologic systems design for Jeju Island.

A typical watershed of Jeju Island (Hancheon watershed), South Korea has been considered as study area for developing regional frequency distribution using L-moments approach. The study area usually experiences by several typhoon events per decade. Specially, over past ten years (2005-2014), a number of typhoons (e.g. Typhoon Nari, Khanun, Dembin, Sanba, Nakri) hit to the Island due its tropical calamity and more than 11 people were died, 2

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people were missing and 1.41 million USD property were looses. Due to short duration of data records, complex geographic and hydro-meteorological characteristics, a study need on regional frequency analysis (RFA) to improve the estimation process of extreme rainfall over the island. RFA approaches were widely applied for various spatial conditions. The idea was continuously developing and new approaches were further investigated by other researcher and hydrologists.

Many researchers published paper on regional frequency analysis and they used L-moments approach to determine regions as similar category rainfall and viewed as a modification of the probability moments (e.g. Bradley 1998; Parida et al. 1998; Fowler and Kilsby 2003; Kumar et al. 2005; Noto et al. 2009; Saf 2009; Shahzadi et al. 2013; Devi and Choudhury 2013; Liu et al. 2015). Previously, Um et al. (2010) studied on extreme rainfall in Jeju Island with respect to influential parameters including: elevation, latitude, longitude and five distribution models. They also proposed for the multiple non-linear forms, linear regression and established an intensity-duration-frequency (IDF) relationship curve that increased the model accuracy as 18.31-86.27%. Up to now, the working methods explored and published on regionalization for the estimation of rainfall includes: cluster analysis (Easterling 1989; Venkatesh and Jose 2007), L-moments analysis (Hosking 1990), L-moments associated with cluster analysis (Guttman 1993; Schaefer 1990; Satyanarayana and Srinivas 2008; Wallis et al. 2007), spatial correlation analysis (Gadgil et al. 1993), homogeneity test (Wiltshire 1986) and regional frequency analysis techniques (Eslamian and Feizi 2007; Ngongondo et al. 2011; Hossein and Arash 2014).

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1.5 Objectives and scope of thesis

To assess the rainfall-runoff characteristics and develop technique for rainfall frequency of Hancheon watershed, NRCS CN method, unit hydrograph method and L-moments approach has been addressed. The runoff volume, runoff intensity and rainfall return period analysis are the main objectives of this study. In addition, to design and prepare useful application from the limited observed data and distinct geomorphologic condition, the specific study activities are intent to:

- Estimate rainfall-runoff volume by NRCS CN method using the semi distributed model. The watershed runoff for daily rainfall events represents its overall response and is therefore, NRCS CN method an effective way to determine yearly total amount of water availability.
- Preliminarily investigate the temporal variations of peak runoff and hence establish Clark unit hydrograph parameters (Tc, R) range.
- Assess the statistical relationship by ARF techniques for the 6-, 12-, 24-hour design storm. Furthermore, graphical representation of ARF will provide an outline for Jeju Island.
- Develop an economical frequency estimation procedure for the extreme rainfall characteristics by the Hosking and Wallis (1997) method. The specific aim is to carry out the regional frequency analysis (RFA) method for 6-, 12-, 24-hour maximum consecutive rainfall series using L-moments approach. This information is expected to provide a suitable idea on the extreme rainfall probability distribution.

The results of this thesis may provide valuable suggestion for rainfall-runoff characteristics assessment considering the temporal variability.

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1.6 Structure of this thesis

The thesis organized into five chapters as follows:

Chapter I gives a brief introduction about the surface rainfall-runoff, unit hydrograph, spatial interpolation of rainfall by ARF, unit hydrograph and L-moments based frequency estimation with comprehensive literature review on rainfall assessment principles.

Chapter II provides details about the selected study area and basic rainfall data information. Also, the land use and soil class properties for further analysis are presented.

Chapter III describes the fundamentals of rainfall assessment techniques and equations used are presented. Specifically rainfall-runoff estimation by NRCS CN, unit hydrograph by Clark method, ARF ratio and L-moments approach for regional frequency analysis are obtained.

Chapter IV represents the results and related discussion on rainfall-runoff volume, peak runoff and time along with the unit hydrographs parameters range, peak runoff, areal reduction factor (ARF) ratios and rainfall design estimation by L-moments. Also, the study showed the frequency analysis results for different returns periods in terms of regions.

Finally, **Chapter V** summarizes the salient features of this present study, provides probable suggestion for study area and outlined with the future study directions.

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Chapter II: Study Area and Data Selection

2.1 Description of the watershed area and topography

The Hancheon watershed shows the dynamic and distinct hydrological characteristics with an area of 37.39 sq. km, located in Jeju Island of South Korea **(Figure 2.1)**. The watershed area is bounded by the north at latitude $32^{o}54'$ to $33^{o}31'$ and east longitude bounded at $126^{o}30'$ to $126^{o}33'$. Although the study area covers 2.02% of the total area of Jeju Island, but the orographic condition significantly influences the variability of the rainfall amounts. The major stream of watershed is Hancheon stream, originated at Halla Mountain flows from south to north and directly enter into the ocean. The stream is most important due to wideness and prototypical significant which control the runoff after a continuous rainfall.

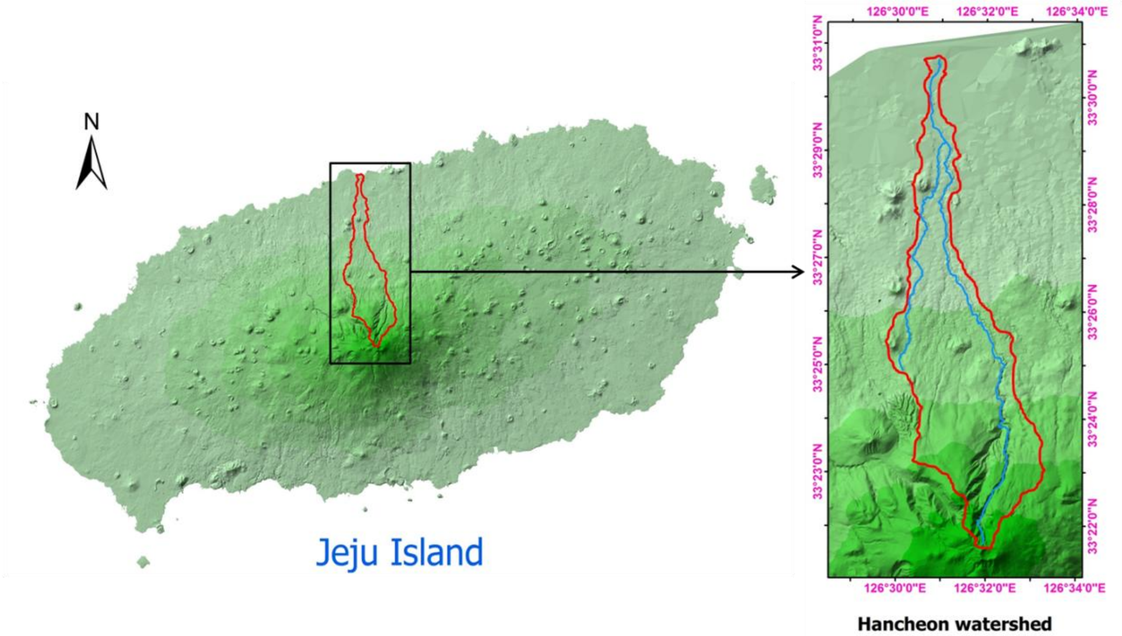

Figure 2.1 Hancheon watershed in Jeju Island.

The topography of study area has been generated in the form of a 30-meter resolution digital elevation model (DEM) using ArcGIS 10.3.1 software (which is available from

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environmental system research institute, ESRI). Topographical characteristics, average width of stream and watershed shape calculated using 1/250,000 spatial digitize map of the Jeju Island. After analyzing in GIS, the stream length, watershed average width and form factor are seen as 20.05 km, 1.86 km and 0.09. **Table 2.1** carried out the basic topographical information of the watershed.

Table 2.1 Watershed characteristics

Area (sq. km)	**Stream length (km)**	**Mean elevation (km)**	**Average width (A/L), km**	**Form factor (A/L^2)**
37.393	20.052	0.688	1.860	0.088

Considering the proto-typical significance of these study outputs, simplicity of the calculation methods, temporal variability and the overall appropriateness in connection with other uniform watershed, this study area is chosen.

2.1.1 Elevation and slope analysis

Watershed elevation considered as vital factor that affecting rainfall infiltration, runoff determination and evapo-transpiration of the area. Consequently, slope which effects on surface water velocity, flow and erosion features. The Hancheon watershed has an elevation of 10 m to 1,950 m from the mean above sea level **(Figure 2.2)**. The 0-600 m elevation with an area of 18.68 sq. km (50%) falls on urban area. Meantime, 601-900 m covers 18.1 % area, 901-1,100 m elevation accounted in 10.1% area, 1,101-1,400 m elevation covers 15.09% area and 1,401-1,950 m altitude covers 6.79% area of total watershed **(Table 2.2)**.

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Table 2.2 Elevation analysis result

Elevation (m)	Area (sq. km)	Percentage (%)	Cumulative area (sq. km)	Cumulative percentage (%)
0-300	8.113	21.694	8.113	21.694
301-600	10.563	28.244	18.676	49.938
601-900	6.767	18.096	25.444	68.033
901-1100	3.764	10.079	29.213	78.112
1101-1400	5.644	15.093	34.857	93.204
1401-1950	2.541	6.796	37.393	100

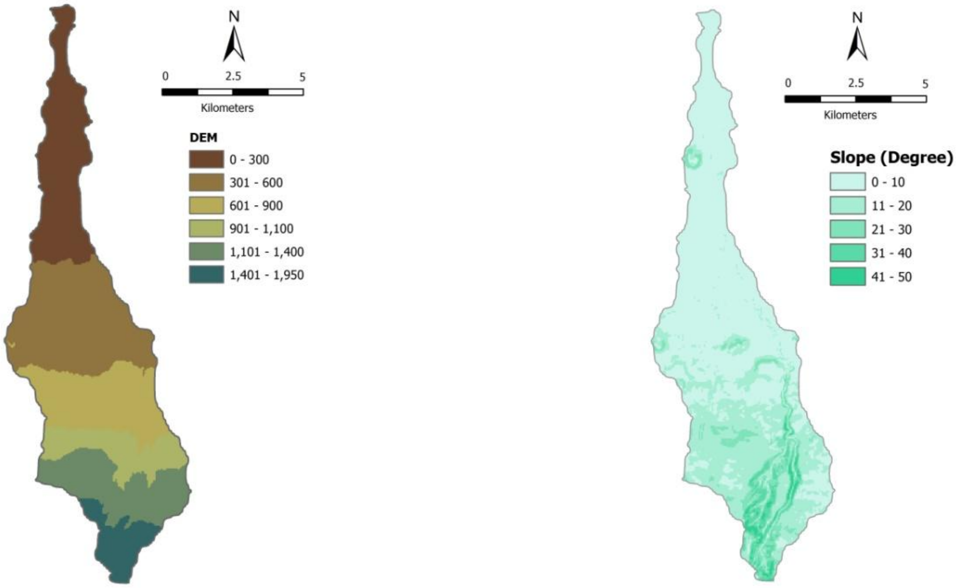

Figure 2.2 Digital elevation model (DEM) and slope analysis of the watershed.

On the other hand, slope is very effective parameter for the study due to its steep characteristics. Average slope of Hancheon watershed is 10.8 degree. Slope analysis results shows that 0 to 20 degree covers 87.72% area and rest of 12.28% area covering 20.01 to 50 degree slope **(Figure 2.2 and Table 2.3)**.

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Table 2.3 Slope analysis result

Slope (degree)	Area (sq. km)	Percentage (%)	Cumulative area (sq. km)	Cumulative percentage (%)
0-10	21.871	58.489	21.871	58.489
10.01-20	10.931	29.233	32.802	87.722
20.01-30	2.680	7.166	35.482	94.888
30.01-40	1.495	3.999	36.977	98.887
40.01-50	0.416	1.113	37.393	100

2.1.2 Land use classification

Land surface and its effective fineness are very important to estimate runoff of the study area. The land use classification of watershed shows that an area of 24.28 sq. km situated in forest and near to mountain that covers the 65% area. The northern part of the study area identified as urban area which covers 14.19% of total watershed has significance for analysis event rainfall and stream analysis.

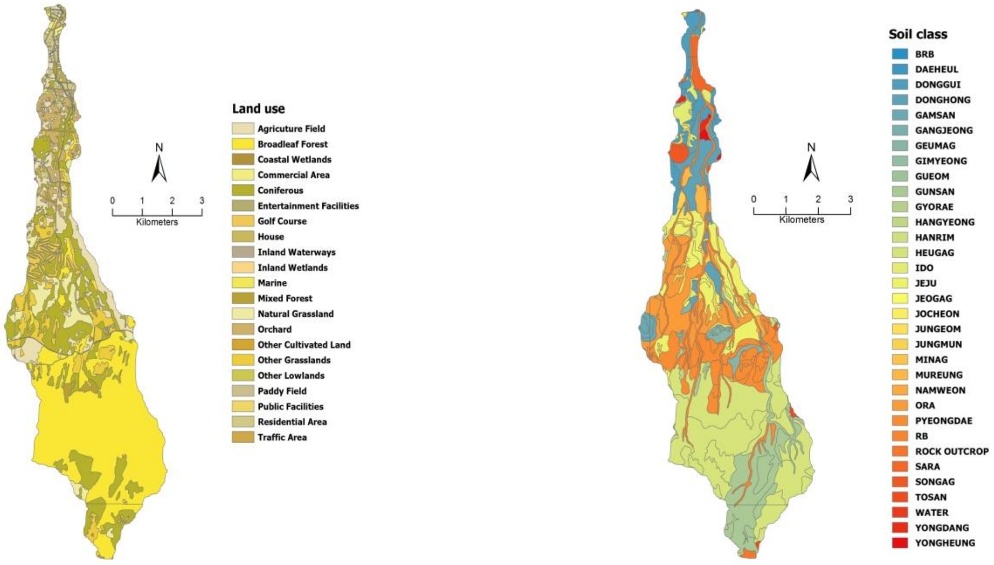

Figure 2.3 Land use and soil class map.

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Table 2.4 Land use analysis result over the watershed

Code	Land use name	Area (sq. km)	Percentage (%)
110	Residential area	0.754	2.017
130	Commercial area	0.189	0.504
140	Entertainment facilities	0.154	0.412
150	Traffic area	0.508	1.359
160	Public facilities	0.126	0.336
210	Paddy field	0.004	0.011
220	Agriculture field	3.429	9.171
230	House	0.025	0.067
240	Orchard	1.676	4.481
250	Other cultivated land	0.017	0.047
310	Broadleaf forests	15.694	41.970
320	Coniferous	8.583	22.954
330	Mixed forest	0.369	0.986
410	Natural grasslands	1.898	5.075
420	Golf course	0.819	2.189
430	Other grassland	2.769	7.405
510	Inland wetlands	0.004	0.011
520	Coastal wetlands	0.007	0.019
620	Others lowland	0.260	0.695
710	Inland waterways	0.103	0.275
720	Marine	0.006	0.015
	Total	**37.393**	**100**

2.1.3 Soil classification

The effective of soil, infiltration characteristics, permeability and average clay content are influenced the hydrology of any watershed. Based upon the soil classification analysis of Hancheon watershed **(Table 2.5)** HEUGAG, GUNSAN, PYEONGDAE and Jeju appears as

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28.89%, 12.09%, 10% and 9% area. This soil class data were collected from Korean society of agriculture engineering (1977) database.

Table 2.5 Soil class and HSG analysis result in the watershed

Soil class name	Area (sq. km)	Percentage (%)	Hydrologic soil group (HSG)
BRB	0.012	0.031	C
DAEHEUL	0.025	0.067	A
DONGGUI	1.651	4.416	C
DONGHONG	1.964	5.251	C
GAMSAN	0.387	1.035	A
GANGJEONG	0.019	0.051	D
GEUMAG	0.673	1.799	A
GIMYEONG	0.074	0.197	B
GUEOM	0.073	0.196	C
GUNSAN	4.521	12.091	B
GYORAE	0.066	0.177	C
HANGYEONG	0.081	0.217	B
HANRIM	0.140	0.375	A
HEUGAG	10.801	28.886	A
IDO	0.566	1.512	C
JEJU	3.481	9.308	C
JEOGAG	0.042	0.112	A
JOCHEON	0.025	0.067	B
JUNGEOM	0.105	0.281	B
JUNGMUN	0.789	2.109	C
MINAG	0.010	0.026	A
MUREUNG	0.444	1.187	D
NAMWEON	0.097	0.261	B
ORA	3.787	10.127	C
PYEONGDAE	4.017	10.743	C

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Soil class name	Area (sq. km)	Percentage (%)	Hydrologic soil group (HSG)
RB	2.371	6.340	C
Rock outcrop	0.098	0.263	B
SARA	0.440	1.177	B
SONGAG	0.345	0.923	C
TOSAN	0.066	0.176	C
Water	0.004	0.011	D
YONGDANG	0.114	0.306	B
YONGHEUNG	0.106	0.283	D
Total	**37.393**	**100**	

2.1.4 Hydrological soil group (HSG) analysis

The analysis of hydrological soil group (HSG) of Hancheon watershed is classified into four categories (A, B, C and D) based on the infiltration characteristics **(Figure 2.4)**. Infiltration characteristics influenced by the soil class and effective depth of soil. Group A having high infiltration that indicates the low runoff potentiality of soil, group B shows the moderately low runoff potential, group C having moderately high runoff potential and group D clarifies the high runoff potential of soil. Classification of HSG category shows that group A, B, C and D values are 12.08, 5.56, 19.19 and 0.573 sq. km **(Table 2.6)**. Therefore, 51.31% of total area showed moderately low infiltration. These soil classes have moderate rates of water transmission.

Table 2.6 Hydrological soil group (HSG) classification

HSG category	Area (sq. km)	Percentage (%)
A	12.077	32.298
B	5.556	14.859
C	19.186	51.310
D	0.573	1.532
Total	**37.393**	**100**

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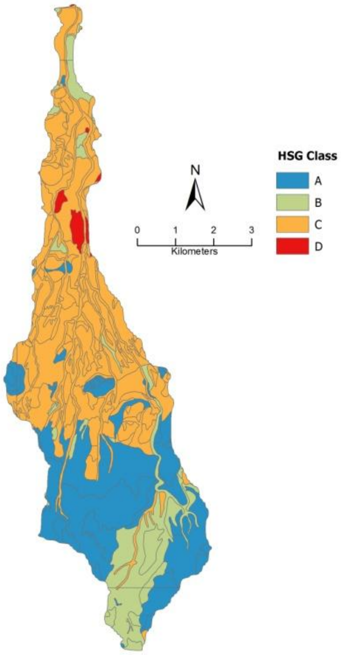

Figure 2.4 Hydrological soil group (HSG) category.

2.2 Rainfall data

Generally, weather of Jeju Island shows seasonal variation due to monsoon climate. About 43% of the total annual rainfall occurs in summer (June to August) and autumn (September to November). Every year, typhoon events are resulting from extreme consecutive hour rainfall and tropical wind to cause of flash flood. Due to the spatial and temporal variability of rainfalls, the Korean Meteorological Administration (KMA) of Jeju province collects hind casting meteorological data across the Hancheon watershed by tipping bucket system. In this study, we have used hourly rainfall data of five gauge station near the watershed which compiled by the automatic weather station (AWS) of Jeju regional meteorological administration. The data record length varies between 11 and 50 years. The annual average rainfall near coastal region shows 1,560 mm and the rest of the watershed area shows about 2,061 mm rainfall (Jung et al. 2014).

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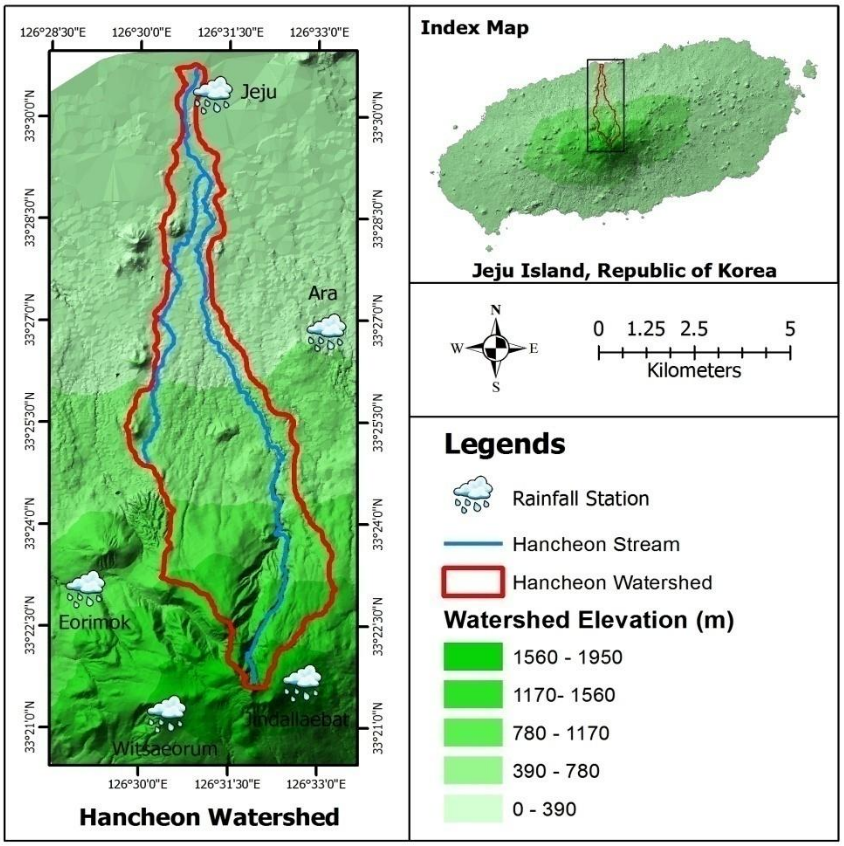

Figure 2.5 Location of rainfall stations near Hancheon watershed in Jeju Island.

2.2.1 Selection of rainfall station and available data

The substantial differences in elevation and geographical location have created considerable variation in daily rainfall patterns over different place of the island. Prior to the availability of above mention high-quality data, there were found very few rainfall recording stations in Hancheon watershed. Among five rainfall stations, Witsaeorum station (near to the highest peak of the Jeju Island) receives the maximum daily rainfall of 1,396.5 mm **(Table 2.7)** in a single calendar day since AWS began tracking rainfall data. **Figure 2.6** showing the daily maximum and annual total rainfall of each station which has the temporal and station-wise fluctuations. The maximum daily rainfall for Jeju station exists 615.6 mm, meanwhile total

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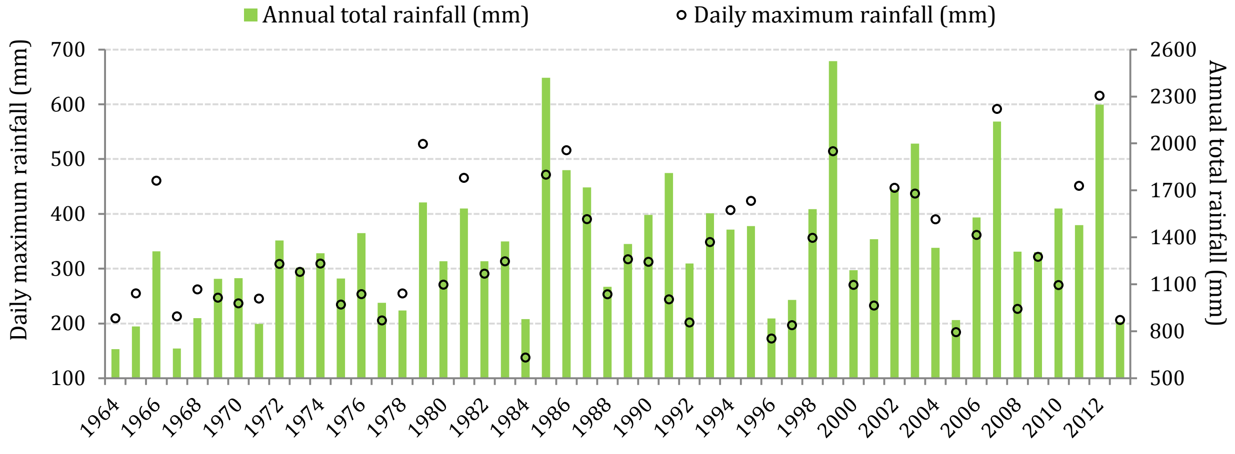
annual rainfall shows 2,526.0 mm in 2012. Accordingly, in the case of Ara, Eorimok, Witsaeorum and Jindallaebat rainfall station maximum daily rainfall are 838.5 mm, 909.5 mm, 1,396.5 mm and 1,183.5 mm for the year of 2012, total annual rainfall obtained as 3,461.5 mm, 4,459.0 mm, 6,514.5 mm and 7,317.0 mm. In comparison with the other rainfall years, highest number of extreme rainfall events occurred in 2012. The potential reason could be the orographic rainfall effects with mountainous topography.

Table 2.7 List and type of the five rainfall stations' utilized for analysis

Rainfall station	GPS point	Region	Elevation (m)	Period of data	Record length	1-day maximum rainfall (mm)
Jeju	33°31′ N 126°31′ E	Northern	20	1964-2013	50	615.6
Ara	33°27′ N 126°33′ E	North-Eastern	379	2001-2013	13	838.5
Eorimok	33°22′ N 126°32′ E	Mountain	972	1995-2013	19	909.5
Witsaeorum	33°23′ N 126°29′ E	Mountain	1673	2002-2013	12	1396.5
Jindallaebat	33°21′ N 126°30′ E	Mountain	1490	2003-2013	11	1183.5



Jeju station (1964-2013)

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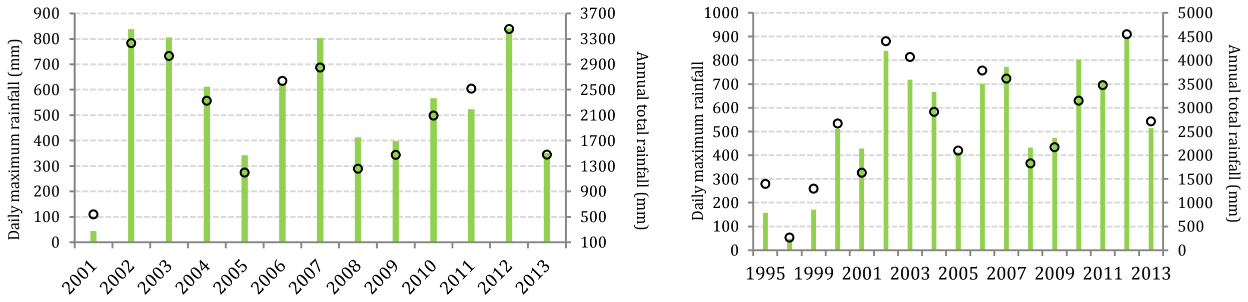
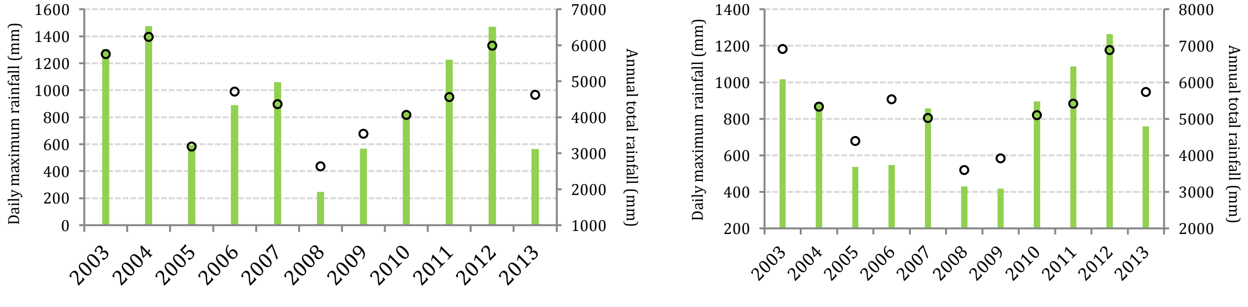


Ara station (2001-2013)

Eorimok station (1995-2013)



Witsaeorum station (2003-2013)

Jindallaebat station (2003-2013)

Figure 2.6 Rainfall time series data availability over five rainfall stations.

2.2.2 Thiessen polygon area analysis

To establish any basic water resources plan and adopt with watershed area, the rainfall observatory station convert into the spatial rainfall is very useful tool. Thiessen polygon ratio was developed around the rainfall stations to take account of the close proximity of average rainfall at each station. The analysis results Ara station covering maximum 31% area wherever Jeju, Eorimok, Witsaeorum and Jindallaebat shows 26%, 20%, 14% and 9% **(Figure 2.7 and Table 2.8)**. In Jeju Island, thiessen polygon ratio method shows the accurate spatial rainfall with compare to other method, which clarify that regional rainfall increases with the elevation. This analysis has done due to develop temporal runoff by NRCS CN method.

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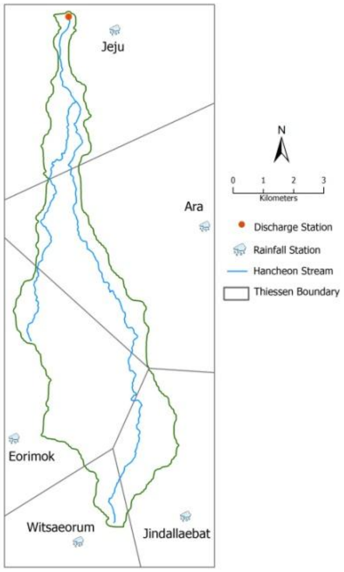

Figure 2.7 Thiessen polygon area for the Hancheon watershed.

Table 2.8 Thiessen polygon area and their percentage

Station name	**Area (sq. km)**	**Percentage (%)**
Jeju	9.725	26
Ara	11.590	31
Eorimok	7.478	20
Witsaeorum	5.235	14
Jindallaebat	3.365	9
Total	**37.393**	**100**

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Chapter III: Methodology

3.1 Rainfall-runoff relation

3.1.1 National resources conservation service (NRCS) method

Rainfall-runoff relationship was firstly developed (1972) among a watershed region by the U.S. Department of Agriculture (USDA) national resources conservation service (NRCS). For rainfall event, the excess rainfall P_e is always less than or same to the rainfall depth P (**Figure 3.1**). If there have some initial abstraction of rainfall for which runoff will not occur, then the potential rainfall is $P-I_a$.

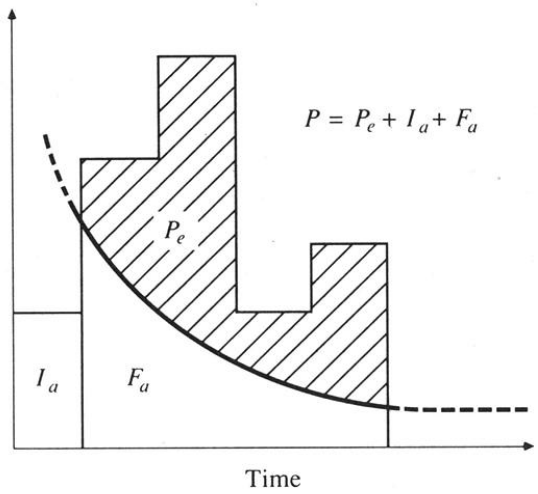

Figure 3.1 Variables of the NRCS method of rainfall abstractions: P is total rainfall, P_e is rainfall excess, I_a denote the initial abstraction and F_a is continuing abstraction. *(Source: Chow 1964)*

The NRCS methods assumes that the ratios of two actual and potential quantities are equal, which is,

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{3.1}$$

From continuity,

$$P = P_e + I_a + F_a \tag{3.2}$$

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From the combination of equation **3.1** and **3.2**, we found the P_e values as,

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad (3.3)$$

Which consider as basic equation for the excess rainfall depth computation by the NRCS method. For small watershed like Jeju Island, initial abstraction (I_a) is empirically assume as 0.4S, here S is the potential maximum retention.

3.1.2 Curve number (CN) estimation

Curve number (CN) is a function of land use, soil class (antecedent soil moisture) and others factor affecting runoff in watershed after a rainfall event occurred. In terms of dimensionless parameter CN defined as,

$$\mathrm{CN} = \frac{25400}{\mathrm{S} + \mathrm{CN}} \qquad (3.4)$$

Here, CN = 100 for impervious water surface and CN < 100 for natural surface.

Consequently, another important analysis is antecedent moisture conditions (AMC) that refers to presence of moisture content into the soil (**Table 3.1**). For practical application of AMC, three categories were grouped by NRCS:

AMC-I: Low moisture (dry condition)

AMC-II: Average moisture condition (normal condition)

AMC-III: High moisture, sufficient rainfall occurred over the preceding few days (wet condition)

For AMC-I and AMC-III condition following equations can be computed using,

$$\mathrm{CN(I)} = \frac{4.2\ \mathrm{CN(II)}}{10 - 0.058\ \mathrm{CN(II)}} \qquad (3.5)$$

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$$\mathrm{CN(III)} = \frac{23\ \mathrm{CN(II)}}{10 + 0.13\ \mathrm{CN(II)}} \qquad (3.6)$$

Table 3.1 AMC classification for the NRCS method of rainfall abstraction *(Sources: Mays 2012)*

AMC type	**Total five day antecedent rain (mm)**	
	Dormant season	**Growing season**
I	Less than 13	Less than 35
II	13 to 28	35 to 53
III	More than 28	More than 53

3.1.3 Runoff estimation by NRCS method

Five rainfall stations observed data, soil class and land use data has been used to determine the rainfall-runoff characteristics. The conventional land use/land cover map and soil map of watershed digitized by GIS and the attributed tables were linked accordingly. Afterwards, soil and land cover data have been intersected in GIS to determine the CN. As the watershed is positioned in the urban, semi urban and mountainous area of the Island, therefore a variation was seen. Among of them, lower elevation area (urban area) is contained a high curve number, indicating high runoff and low infiltration. Consequently, low curve number indicates the high infiltration and low runoff.

The NRCS CN method (SCS 1972) developed a rainfall-runoff relation for watershed. As defined by NRCS soil scientists, soils are classified into four hydrologic groups i.e. A, B, C and D (SCS 1986), depending on infiltration, soil classification and other criteria. Land use classifications are used in the preparation of hydrological soil-cover content, which in turn are used in estimating runoff. Antecedent moisture condition (AMC) is an indicator that refers to the moisture content present in the beginning of the rainfall-runoff event and can have a significant effect on runoff volume. Recognizing its significance, NRCS developed a guide for adjusting CN

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according to AMC based on the equation **3.5** and **3.6**.

3.2 Unit hydrograph analysis

This study employs to develop the consistency of surface runoff hydrograph according to Clark unit hydrograph method. The following steps were carried out during the process.

3.2.1 Storm events selection

Viessman et al. (1989) described three characteristics of heavy rainfall events from a well-defined unit hydrograph which are; the simple hydrograph structure with distinct peak, extended duration of rainfall and uniform spatial distribution. Following the above criterion, five independent heavy rainfall events **(Table 3.2)** from 2012 to 2014 have been clustered to be used in model calibration and validation. A study was carried out by Yang et al. (2014) which also considered heavy rainfall events for Hancheon watershed. In this study, without antecedent, the rainfall average lag time was found as around 1.5 hr, which increased notably by more than 45% following an antecedent rainfall event. The resulting temporal distribution of rainfall at five stations and consequent runoff was then assembled in HEC-HMS 2.2.2 version program (USACE 2000).

Table 3.2 Summary of selected five storm rainfall events

Storm events	**Data availability**	**Average rainfall (mm)**
Heavy rainfall	21-22 April, 2012	314.96
Typhoon Khanun	18-19 July, 2012	293.12
Typhoon Dembin	22-23August, 2012	961.89
Typhoon Sanba	16-17 September, 2012	659.38
Typhoon Nakri	1-2 August, 2014	678.94

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3.2.2 Initial value selection of Clark parameters

In order to apply the Clark method in HEC-HMS model, it is necessary to estimate the time-area relationship between runoff travel times and watersheds contributed area. Travel time is the only independent variable in this case, which time is required from the most remote part of watershed outlet. Generally, it is assumed that travel time is proportional to the stream length from the watershed's outlet point. A time-area relationship of watershed, which contributes runoff to the watershed outlet as a function of time is measured from the onset of rainfall excess.

Initial time of concentration and storage coefficient has been computed with the following empirical formula of Kirpich (1940) and Clark:

$$\text{Time of concentration, Tc} = 0.0663 \times \frac{L^{0.77}}{S^{0.385}} \quad (3.7)$$

$$\text{Storage coefficient, R} = \frac{\alpha L}{\sqrt{S}} \quad (3.8)$$

Here, L is the length of stream in km, S represents the land slope of watershed and α is coefficient (value varies from 0.4 to 1.4).

3.2.3 Calibration of Clark parameters

Consequential results of the Clark's two parameters (Tc and R) were examined by sensitivity analysis. The sensitivity was performed based on trial-and-error method. Meantime, the numerical values (Tc and R) were always assumed in between 0.1 to 3. The optimal values of the parameters were also derived. Afterwards, an optimum pair (Tc, R) was used to compare between observed and simulated peak runoff information. Meanwhile, the rainfall loss was also investigated. When the peak runoff values start to change by an extremely minor quantity

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following slight alterations of Tc and R (within 0.1 to 3), the values for Tc and R were acknowledged. The effort was also made to reduce the uncertainty of parameters.

3.2.4 Model performance

The calibrated parameters of four selected storm rainfall events were projected by trial-and-error approach. These parameter values were firstly adjusted by analysis of variance (ANOVA) method (e.g. Gophen 2012). After calibration of parameters, Nash-Sutcliffe efficiency (NSE) model (Nash and Sutcliffe 1970) and peak weighted root mean square error (RMSE) (USACE HEC-HMS 1995, 1998) were used for testing the performance of runoff model results.

$$\mathrm{NSE} = \left[1 - \frac{\sum_{i=1}^{i=n}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{i=n}(Q_{oi} - \bar{Q}_o)^2}\right] \times 100 \qquad (3.9)$$

$$\mathrm{RMSE} = \left[\frac{1}{n}\left\{\sum_{1}^{n}(Q_{oi} - Q_{si})^2\left(\frac{Q_{oi} + \bar{Q}_o}{2\bar{Q}_o}\right)\right\}\right]^{1/2} \qquad (3.10)$$

Here, *n* is ordinate number, *i* is varying from 1 to *n*, Q_{oi} is *i*-th ordinate observed runoff, Q_{si} is *i*-th ordinate simulated runoff and $\bar{Q}_o$ is average observed runoff of the hydrograph.

3.3 Areal reduction factors (ARF) fundamentals

ARF factor is defined as, point rainfall values when which applied for a particular duration and return period provide areal rainfall for the same duration and return period. There are two types of ARF, which are geographically fixed and storm centered relationship (Miller et al. 1973; Srikanthan 1995). Geographically fixed ARFs are related to rainfall at any random point. The method estimated from average frequency based quantile estimates using annual maxima rainfall series observed in a fixed point (Osborn et al. 1980). These ARFs only originate from rainfall

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statistics but not from any individual storms so as to refer as statistical reduction factors. The empirical equation can be represented as:

$$\mathrm{ARF} = \frac{\text{mean of annual maximum rainfall}}{\text{weighted mean of annual maximum point rainfall}} \qquad (3.11)$$

Storm centered ARF's are connected with the effective depth calculation for the discrete storm events. Following this method, the individual event ratio represents of contour lines depth and storms maximum depth. Due to the difficulty of implementation on multi centered storms, this ARF method is not widely used this kind of approach is very difficult to implement but can be used only for individual storms.

This study has conducted by the Asquith and Famiglietti (2000) method considering the effective depths for watershed area. The ARF results are always between 0 and 1. The RFA's are calculated upon the watershed characteristics, like as watershed shape and storm recurrence interval. The approach has a best fit line that provides expected ratio. It does not require spatial averaging of rainfall. So, this technique could be applied there. The empirical equation is follows as:

$$\mathrm{ARF} = \frac{\sum_{i=1}^{k}\left(\mathrm{w_i}\breve{\mathrm{R}}_{\mathrm{ij}}\right)_{\mathrm{r}}}{\sum_{i=1}^{k}\left(\mathrm{w_i}\mathrm{R}_{\mathrm{ij}}\right)_{\mathrm{r}}} \qquad (3.12)$$

Here, $\breve{\mathrm{R}}_{\mathrm{ij}}$ is station rainfall i for the annual maximum areal rainfall occurred in year j, R_{ij} is the annual maximum point rainfall, k is number of stations into the study area. From this method, 6-, 12-, 24-hr ARF ratios are determined. Later, this estimated result can be applied into the frequency analysis of spatial rainfall.

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3.4 L-moments based regional rainfall frequency analysis

3.4.1 L-moments method: theoretical background

The L-moments approach was firstly introduced by Hosking (1990) which is the suitable statistical modeling and facilitates the estimation process of probability distribution and frequency analysis. Recent years, rainfall extreme studies on statistical analysis are followed by method-of-moments estimator for annual maximum (viz. hourly, daily, monthly) time series, particularly in regional analysis. The L-moment provides a reasonable efficient estimation characteristic of hydrological data and distributions parameters. In practical, advantages of using L-moments includes: can be estimated from limited data samples, provide dispersion, skewness and kurtosis which have less bias than other ordinary moments of probability distributions. Hosking (1990) characterized the L-moments based on probability weighted moments (PWMs) and can be shown as:

$$\lambda_r = \frac{1}{r}\sum_{k=0}^{r-1}(-1)^k\binom{r-1}{k}E\{X_{r-k:r}\} \qquad (3.13)$$

Here, λ_r is a linear function of r-th L-moment of a X distribution and r = 1, 2, 3,… is a non-negative integer. From equation (1), the first four resulting L-moment can be written as:

$$\lambda_1 = EX \qquad (3.14)$$

$$\lambda_2 = \left(\frac{1}{2}\right)E(X_{2:2} - X_{1:2}) \qquad (3.15)$$

$$\lambda_3 = \left(\frac{1}{3}\right)E(X_{3:3} - 2X_{2:3} + X_{1:3}) \qquad (3.16)$$

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$$\lambda_4 = \left(\frac{1}{4}\right) E(X_{4:4} - 3X_{3:4} + \ 3X_{2:4} - X_{1:4}) \quad (3.17)$$

Hosking (1990) describes the utility of ratio estimators based on the L-moments ratios in hydrological extreme analysis and can be followed as:

$$\tau_2 = L - C_v = \ {}^{\lambda_2}\!/_{\lambda_1} \qquad (3.18)$$

$$\tau_3 = L - Skewness = \ {}^{\lambda_3}\!/_{\lambda_2} \qquad (3.19)$$

$$\tau_4 = L - Kurtosis = \ {}^{\lambda_4}\!/_{\lambda_2} \qquad (3.20)$$

Where, τ_2 is the measure of covariance (scale), τ_3 is the measure of skewness (shape) and τ_4 is the measure of kurtosis (peakedness). The value of τ_3 is constrained by 0 to 1 range. Notable, these ratio estimator equations and their graphical diagrams are particularly good to identify the distributional properties of highly skewed data. Thus, following the above equations rainfall of 6-, 12-, 24-hr L-moments ratio for each regions has shown in this study.

3.4.2 Data screening by discordancy measure

A discordancy measure, D_i, which is used to screen out the data from unusual sites and to check the appropriate data for regionalization. Let, a vector as $u_i = \left[t^{(i)},\ t_3^{(i)},\ t_4^{(i)}\right]^T$ which restrained the L-moments ratios for site *i* (Hosking and Wallis 1993), than discordancy measure defined as:

$$D_i = \frac{1}{3}\,(u_i - \bar{u})^T S^{-1}(u_i - \bar{u}) \qquad (3.21)$$

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Where, u_i = vector of L-CV, L-Skewness and L-Kurtosis; S is covariance matrix of u_i and $\bar{u}$ is mean vector of u_i.

3.4.3 Regional heterogeneity test

Homogeneous region identification is the significant step in regional frequency analysis. The statistics compare between the inter-site distributions of L-moments sample can be projected as homogeneous region. Hosking and Wallis (1993) proposed that derivation of statistical test for a homogeneous region is defined as heterogeneity measure (H). To determine the expected heterogeneity, Monte Carlo simulation of rainfall having record lengths equal to that of the observed data are performed which is familiar in hydrological analysis. The heterogeneity measure (H) can be obtained as:

$$H = \frac{V_{obs} - \mu_v}{\sigma_v} \qquad (3.22)$$

Here, μ_v and σ_v are the mean and standard deviation of simulated data, respectively. V_{obs} is calculated from the regional data, which can be employed from three V-statistics (V_1, V_2, V_3) as follows:

$$V_1 = \left[\sum_{i=1}^{N} N_i\{t^{(i)} - t^R\}^2 \Bigg/ \sum_{i=1}^{N} N_i\right]^{1/2} \qquad (3.23)$$

$$V_2 = \sum_{i=1}^{N} N_i\left\{\left(t^{(i)} - t^R\right)^2 + \left(t_3^{(i)} - t_3^R\right)^2\right\}^{1/2} \Bigg/ \sum_{i=1}^{N} N_i \qquad (3.24)$$

$$V_3 = \sum_{i=1}^{N} N_i\left\{\left(t_3^{(i)} - t_3^R\right)^2 + \left(t_4^{(i)} - t_4^R\right)^2\right\}^{1/2} \Bigg/ \sum_{i=1}^{N} N_i \qquad (3.25)$$

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For H statistics criterion, Hosking and Wallis (1993) suggested that the region is reasonably homogeneous if H < 1, possibly homogeneous region if 1≤ H < 2 and absolutely heterogeneous region if H ≥ 2.

3.4.4 Goodness-of-fit measure

The regional frequency distribution L-moment ratio diagrams and goodness-of-fit measure are chosen based on sample regional average and theoretical L-Kurtosis. For a particular distribution, the goodness-of-fit measure is calculated as follows:

$$Z^{Dist} = \frac{t_4^R - \tau_4^{Dist}}{\sigma_4} \qquad (3.26)$$

Here t_4^R is an average L-Kurtosis value from the data of a given region, τ_4^{Dist} is a theoretical L-Kurtosis value for a fitted distribution and σ_4 is the standard deviation value that obtained from simulated data. For an approximate 90% confidence level, the acceptable goodness-of-fit is found at $\left|Z^{Dist}\right| \leq 1.64$.

3.4.5 Estimation of regional rainfall frequency

The frequency distribution procedure of maximum consecutive hour rainfall data in a same homogeneous region consist of similar frequency distribution (Dalrymple 1960). In the simulations, frequency estimated for various robust probability distributions has been calculated. If the frequency estimates consists of regional growth curve $Q^m(F)$, i site non-exceedance probability F and site scaling factor $l_{1,}$ then the T-year frequency of the normalized regional distribution is computed by: $Q_i(F) = l_1 q(F)$; where q is common dimensionless function. For simulation of a homogeneous region, the regions are having the same number of stations, data record length, heterogeneity and L-moments ratio as the observed data. During simulation,

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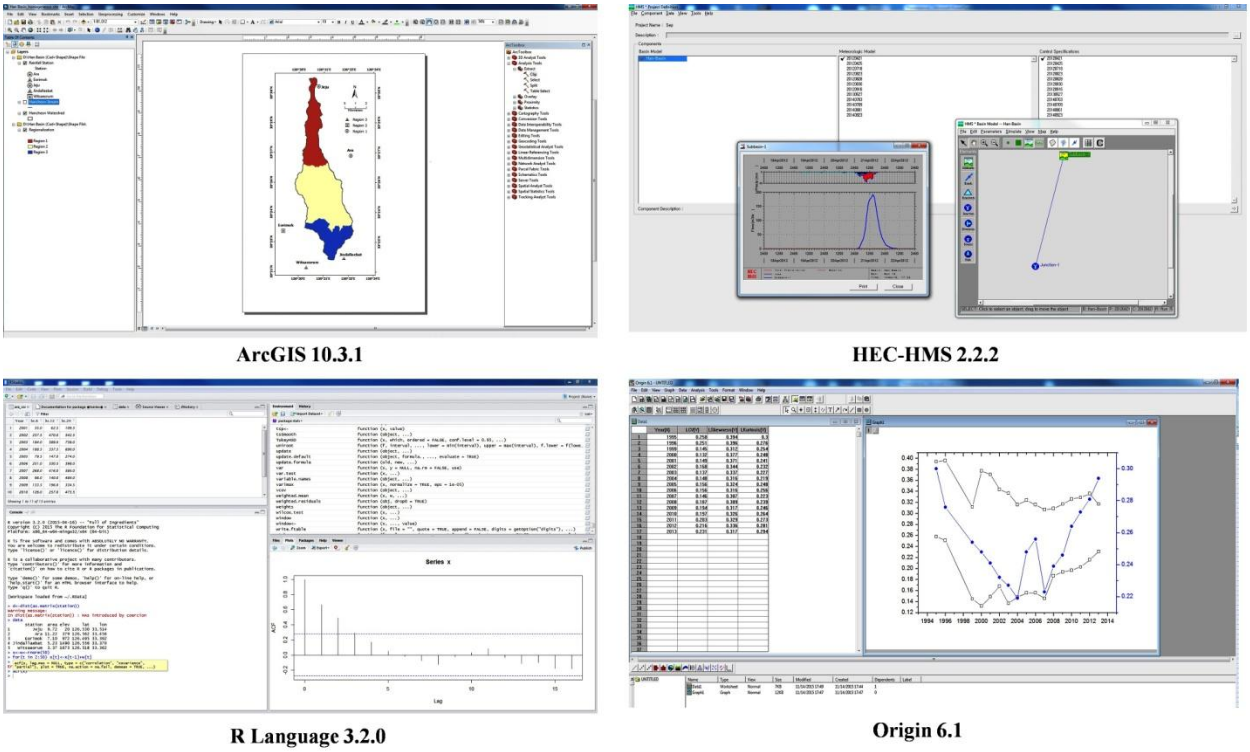
frequency error, root mean square error (RMSE), 90% error bounds are estimated for the accuracy assessment.

3.5 Using tools for the study

During NRCS CN analysis, unit hydrograph, ARF ratio and regional frequency analysis ArcGIS 10.3.1, HEC-HMS 2.2.2, R language 3.2.0 and Origin 6.1 software tools were used **(Figure 3.2)**. We also used the L-moment approach (lmomRFA 3.0-1 version) in R package, developed by Hosking (2009).


ArcGIS 10.3.1

HEC-HMS 2.2.2

R Language 3.2.0

Origin 6.1

Figure 3.2 Using analysis tools during this study.

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Chapter IV: Results and Discussion

4.1 Application of NRCS CN method for runoff volume

4.1.1 Estimation of curve number (CN)

Using the data soil class and infiltration rates, Hancheon watershed has been classified in four groups (A, B, C and D) with a mixture of soil and land cover characteristics **(Table 4.1)**. Each land cover has a unique CN value obtained in **Figure 4.1**. In this analysis assumes that watershed's drainage systems are directly connected with the impervious area. The impervious area was found 1.60 sq. km that is 4.28% of total watershed area. In methodology section narrated that infiltration and initial abstractions of soil are governed by AMC. Following the equation **3.4**, AMC-II was calculated for average condition of soil and slope. For this condition CN value was value estimated as 67.40 (Mays 2010). Meantime, the CN values for dry (AMC-I) and wet (AMC-III) conditions were found 47.50 and 82.90 respectively **(Table 4.2)**.

Table 4.1 CN values for land cover classification

Code	Area name	A	B	C	D
110	Residential	58	73	82	86
130	Commercial	-	96	97	-
140	Entertainment Facilities	95	96	97	-
150	Traffic Area	89	91	93	94
160	Public Facilities	-	88	91	93
210	Paddy Field	-	-	78	
220	Agriculture Field	64	75	82	86
230	House	-	-	98	-
240	Orchard	44	66	77	83
250	Other Cultivated Land		74	82	-
310	Broadleaf Forests	47	67	78	-

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Code	Area name	A	B	C	D
320	Coniferous	46	68	79	86
330	Mixed forest	47	68	79	-
410	Natural Grassland	30	58	71	78
420	Golf Course	-	-	80	-
430	Other Grass Land	52	70	80	85
510	Inland Wetland	-	98	98	-
520	Coastal Wetlands	-	-	98	98
620	Others Lowland	-	86	91	94
710	Inland Waterways	-	100	100	100
720	Marine	-	-	100	-

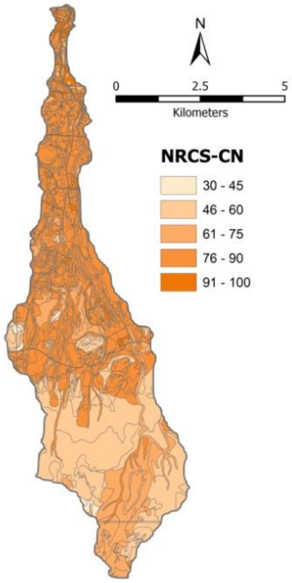

Figure 4.1 NRCS curve number (CN).

Table 4.2 Runoff curve number in different antecedent moisture condition (AMC) of soil

AMC	I	II	III
CN	47.50	67.40	82.90

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4.1.2 Five years rainfall-runoff analysis results

The runoff depth and runoff volume had been calculated based on NRCS CN method. The runoff in Hancheon watershed resulting from the given last five years rainfall, soil classification, infiltration rates and land use. After that, the runoff depth was multiplied by watershed area that conferred the total annual runoff volume. The calculations and results based on NRCS-CN method, infer the annual runoff depth for last five years in Hancheon watershed and the total volume of water **(Table 4.3)**. From the analysis result, 2009 and 2013 year showed the lower runoff volumes (where the runoff depth was 385.73 mm and 536.19 mm) that indicating arid behavior of the watershed, experiencing very little rainfall events. But 2012 year, typhoon events and continues heavy consecutive rainfall resulting the huge volume of runoff occurred in the province. The runoff percentage values varied within a range of 18% to 44%, indicating the temporal (seasonal) effects of the rainfall in cumulative runoff. In essence, the analysis result provides runoff volume extends in relation to rainfall and the maximum rainfall-runoff receiving year.

Table 4.3 Rainfall-runoff depth and volume of five years annual rainfall

Year	**Annual rainfall (mm)**	**Runoff depth (mm)**	**Runoff percentage (%)**	**Runoff volume (10^{12} Mm^3)**
2013	2317.53	536.19	23.14	20048.144
2012	4160.11	1820.63	43.76	68073.356
2011	3185.19	992.33	31.15	37103.219
2010	3186.08	1239.86	38.91	46358.365
2009	2050.07	385.73	18.82	14422.445

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4.2 Estimation of direct runoff from storm events

From the runoff volume analysis by NRCS CN method, study came out a decision that the year of 2012 was received the maximum runoff volume. Therefore, the unit hydrograph study (Clark hydrograph method) was undertaken to analyze the heavy rainfall events. Also, average CN (67.40) and percentage of impervious area (4.28%) value were used as initial input of HEC-HMS modeling.

4.2.1 Data calibration for unit hydrograph parameters estimation

The Kirpich equation had been used by many researchers' in the recent past (Kumar et al. 2002; Shaoo et al. 2006; Ahmad et al. 2009) research work, using time-area relationships and geomorphologic parameters of watershed. According to use the geomorphologic data, Kirpich's time of concentration and Clark's storage coefficient values was found 1.59 and 3.06. These initial values were used in the HEC-HMS model for peak data estimation of four different rainfall events (Peters 1993), but it showed an unstable relation between observation and simulation results. After that, trial-and-error method was applied to optimize the objective function i.e. peak weighted root mean square error (RMSE). Following the objective function and trial-and-error analysis of hydrograph parameters (Tc and R) nearest runoff simulation values were shown in **Table 4.4** and **Figure 4.2**.

During calibration of Clark unit hydrograph parameters, the peak runoff (Q_p) and time of peak (T_p) were also being estimated. Optimized values were showing good coherence between observed and simulated results. **Table 4.4** showing that, the observed peak runoff varied 162.26 to 544.38 m^3/sec, whereas maximum simulated runoffs varied by 151.89 to 545.36 m^3/sec. On the other hand, observed peak time intervals were found from 9.0 hr to 20.83 hr, whereas the

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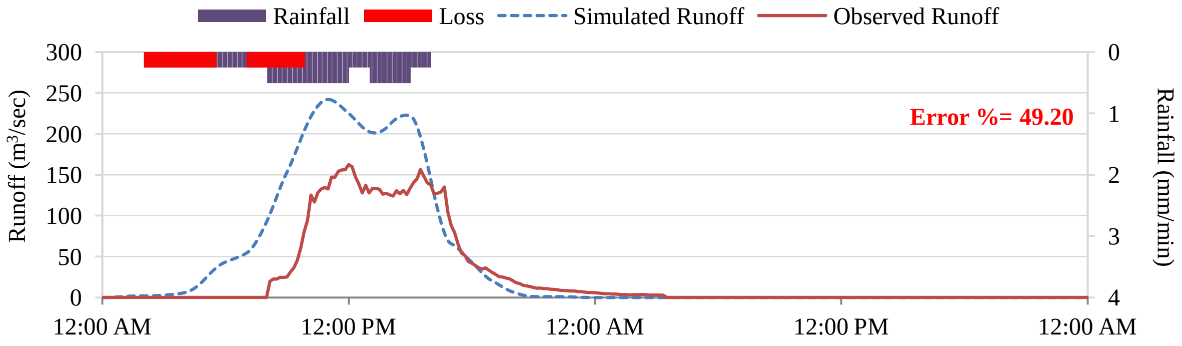
simulated peak time showed 8.33 to 26.60 hr. The maximum observed and simulated runoffs were identified for typhoon Sanba. The typhoon Sanba showed observed runoff 544.38 m^3/sec and simulated runoff 545.36 m^3/sec where 9.0 hr and 8.33 hr peak times were found.

Table 4.4 Calibration of Clark parameters and difference between peak runoff hydrographs

Storm events	**Clark's parameter**		**Observed**		**Simulated**		**Error (%)**
	Tc	**R**	**Q_p (m^3/sec)**	**T_p (hr)**	**Q_p (m^3/sec)**	**T_p (hr)**	
Heavy rainfall	1.8	0.1	162.26	12.0	242.09	11.0	49.20
Typhoon Khanun	1.05	0.4	172.65	20.83	151.89	20.67	12.02
Typhoon Dembin	1.6	0.5	157.14	18.17	219.74	26.60	39.84
Typhoon Sanba	1.3	0.32	544.38	9.0	545.36	8.33	0.18

Noticeable that storm rainfall event's rising limb to peak runoff was found within short duration (1-day). The error percentage for heavy rainfall, typhoon Khanun, typhoon Dembin and typhoon Sanba were seen at 49.2, 12.02, 39.84 and 0.18. Thus, typhoon Sanba and typhoon Khanun provides accuracy better than the other occurred events, for which, the study can be selected these two events for making decision.



Heavy rainfall (21-22 April, 2012)

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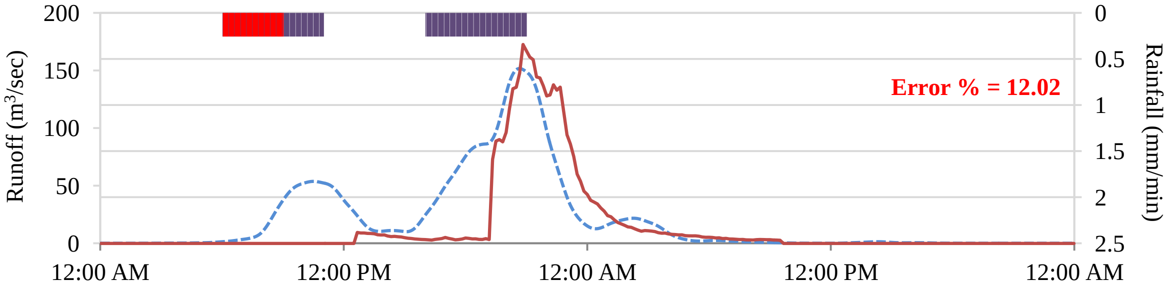
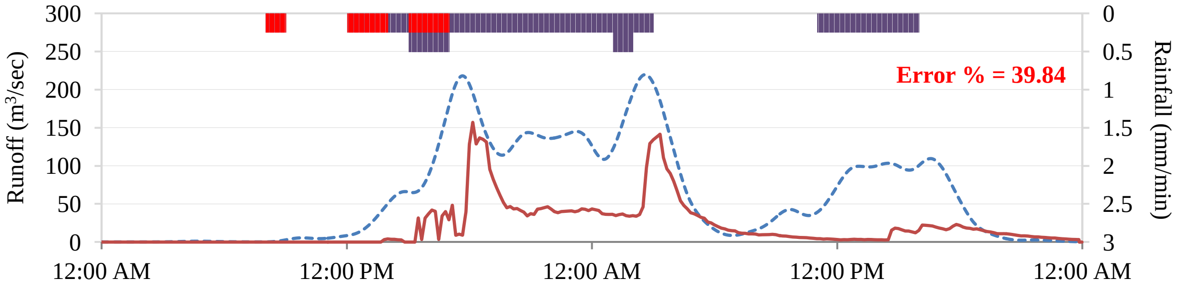
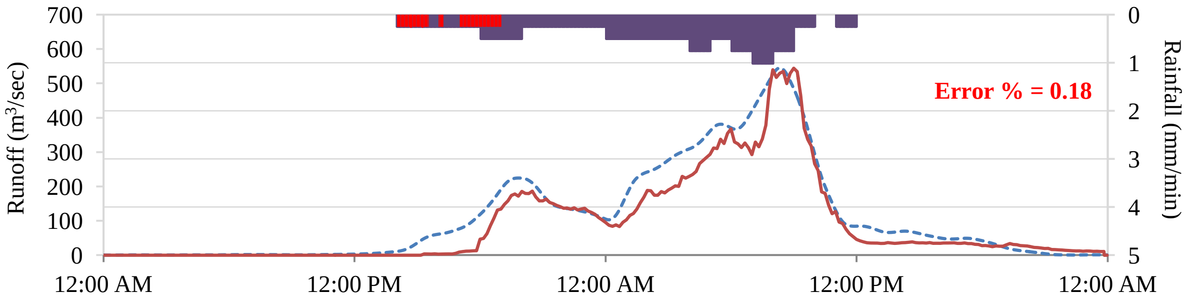


Typhoon Khanun (18-19 July, 2012)



Typhoon Dembin (22-23 August, 2012)



Typhoon Sanba (16-17 September, 2012)

Figure 4.2 Comparison between observed and simulated runoff hydrograph.

4.2.2 Statistical performance analysis for unit hydrograph parameters and runoffs

The performance of four events in terms of parameters was determined based on ANOVA analysis. This analysis obtained a probability value of 0.00009 (below 5% significance level), which is statistically considerable **(Table 4.5)**. The estimated variance of Tc and R was 1.44 and

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0.33, respectively. **Figure 4.3** shows a graphical representation with the observed and simulated runoff model comparison result where the determination factor (r-square), RMSE and NSE was 0.76, 37.52 and 0.88, respectively. The following statistical analysis also provides the assurance of accuracy.

Table 4.5 Statistical Analysis: ANOVA analysis for Clark parameters

Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value (below 5%)	F critical (5%)
Between groups	2.453113	1	2.453113	35.58029	0.000995	5.987378
Within groups	0.413675	6	0.068946			
Total	2.866788	7				

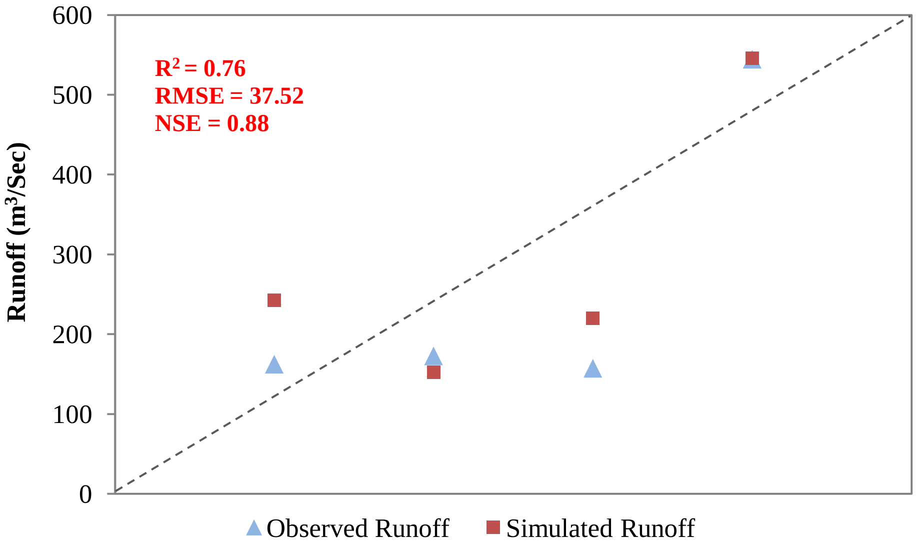

Figure 4.3 Comparison after calibration between observed and simulated runoff.

4.2.3 HEC-HMS model validation

The model has been developed for setting a reasonable pair value (Tc, R) to estimate unit hydrograph parameters. The average value of four storm events calibrated parameters (Tc, R) as (1.44, 0.33) was considered as initial value. After using trial-and-error values, the ANOVA

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statistical method was again used, until the difference in probability was found insignificant. Unit hydrograph was derived by Clark method in HEC-HMS model and accordingly, excess rain and loss were derived to get the accurate hydrograph. After the trial-and-error based validation, Tc and R values were found at 1.4 and 0.27 respectively, for typhoon Nakri 2014. Subsequently, the probability (p-value) was found below 0.00005 (below 5% significance level) which gave goodness-of-fit statistics calculation. Thereafter, a unique hydrograph was drawn that shows the rainfall access, loss, observed and simulated runoff **(Figure 4.4)**. The typhoon Nakri event hydrograph showed that observed and simulated peak runoffs was 278.86 m^3/sec and 553.09 m^3/sec meanwhile time of peaks was seen 20.35 hr and 19.58 hr, respectively. After validation, observed and simulated runoff's error percentage was found 49.6 wherever r-square value was 0.68 that is near to the calibrated r-square value. Due to the complexity of rainfall-runoff process and geophysical characteristics, a single pair (Tc, R) sometimes doesn't shows exact result, a significant deviation always be there.

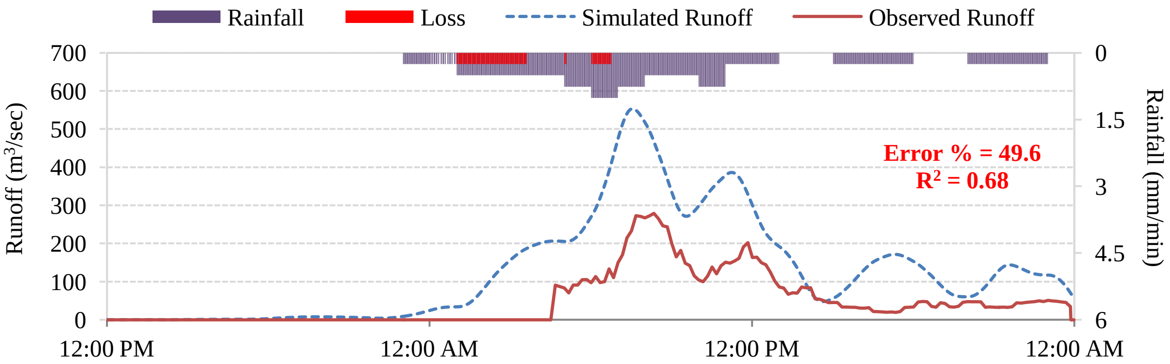

Figure 4.4 Validation of model considering typhoon Nakri (1-2 August, 2014).

In this case study, the unit hydrograph model also showing **(Figure 4.4)** the significant deviation (274.76 m^3/sec) between observed and simulated runoff for typhoon Nakri. The reasons behind this fluctuation were expected for runoff observation point which was at

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downstream (doesn’t consider any upstream discharge data), flow diversion detention pond and reservoir in Hancheon stream. According to Jung (2013) study investigation, upper portion of stream two onsite detention ponds were constructed to reduce the velocity and flood frequency of stream flow storage considering an aesthetic value (around 133 m^3/sec). Consequently, upstream reservoirs have also been developed to control the flood velocity in Hancheon stream which are considerably impacted on flood runoff. Furthermore, this Moon et al. (2014) study noted that without a reservoir operation, discharge can be obtained remarkable difference (150 m^3/sec) after simulation. Above all discussions and statistical performance, the generated model result can be reasonably accepted. The main finding from this analysis is high runoff events reveals more accurate than the lower rainfall- runoff events.

4.3 Estimation of areal reduction factor (ARF) ratio

The main objective of ARF analysis was to find ratio values for different return period which will helpful to create spatio-temporal rainfall design. Generally, the ARF ratio derived from the analysis of equation **3.12** with respect to 6-, 12-, 24-hr temporal variation. **Figure 4.5** shows, all values were within 0 to 1. The Eorimok and Jindallaebat stations’ 12-hr and 24-hr ARF ratios are between 0 and 0.60. Also, it can be seen that 6-hr ARF values were scattered. The ARF ratios for 10 years return period represented various values for the watershed; therefore random ratios are not feasible smoothly. Following the analysis, the study results would not obtain any idea as how to values are difference from one to another station. Therefore, another statistical method (L-moments approach) has been applied in next section.

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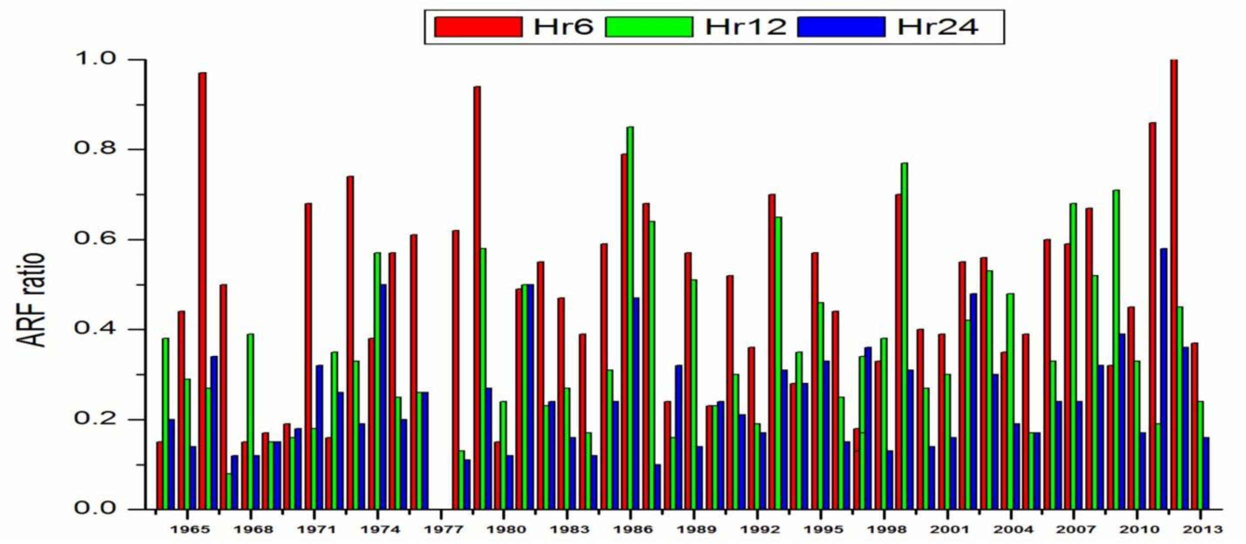
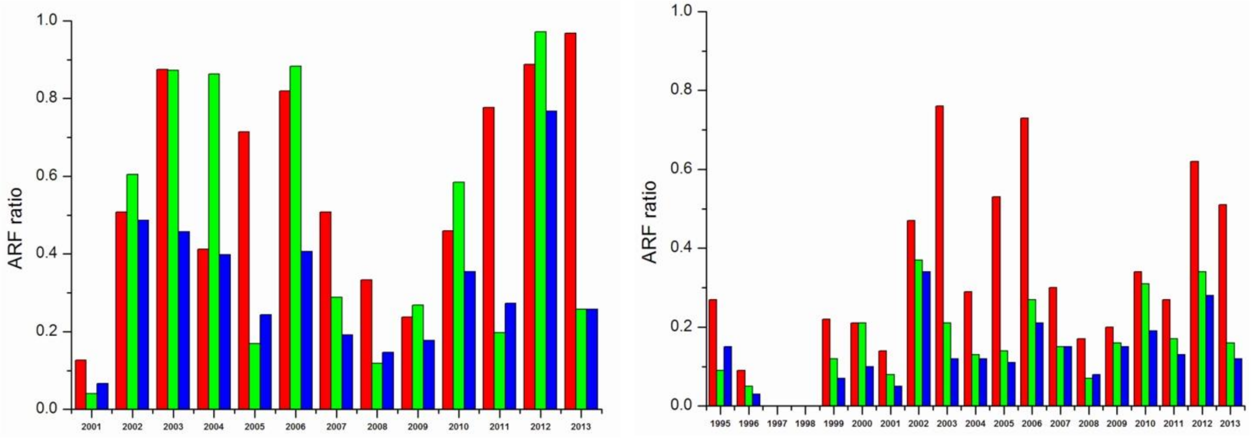
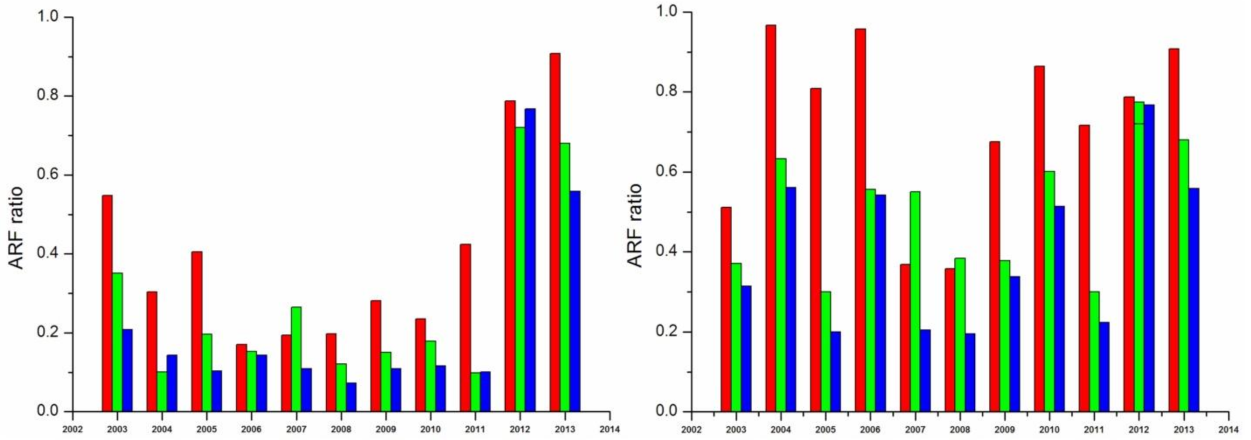


Jeju



Ara Eorimok



Jindallaebat Witsaeorum

Figure 4.5 Variation of ARF values for each station (considering 6-hr, 12-hr, 24-hr rainfall).

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4.4 Development of L-moments approach for rainfall frequency analysis

4.4.1 Stationary and independence test

The fundamental data execution was carried out using the Mann-Kendall test (Mann 1945; Kendall 1975) and auto-correlation function (ACF) analysis to verify the maximum 24 hour consecutive rainfall which is convenient for regional frequency analysis. The results of Mann-Kendall trend test presented in **Table 4.6** shows that all the stations values are constant over time. This is reasonable to infer that statistically stationary data do not have significant trends. In terms of insignificancy of maximum hour rainfall, data can be considered as of having a stationary series.

Moreover, auto-correlation function (ACF) coefficient values are shown in **Figure 4.6** for ‘lag 1’ to ‘lag 13’ plotting. The ACF values show that each stations rainfall data experiences exist within critical bounds, thus maximum consecutive hour rainfall series can be considered as time-independent. Thereafter, spatial autoregressive calculation (Dong and Harris 2015) also showed that the stations’ cross correlations (probability, *p*-value) were not significant (up to 5%), for which data can be considered as spatially independent.

Table 4.6 Summary of trend analysis of maximum hourly rainfall series using Mann-Kendall test

Serial	Station	Trend value	*p*-value
1	Jeju	1.67	0.01
2	Ara	1.28	0.02
3	Eorimok	3.40	0.02
4	Jindallaebat	-0.47	0.04
5	Witsaeorum	-0.16	0.03

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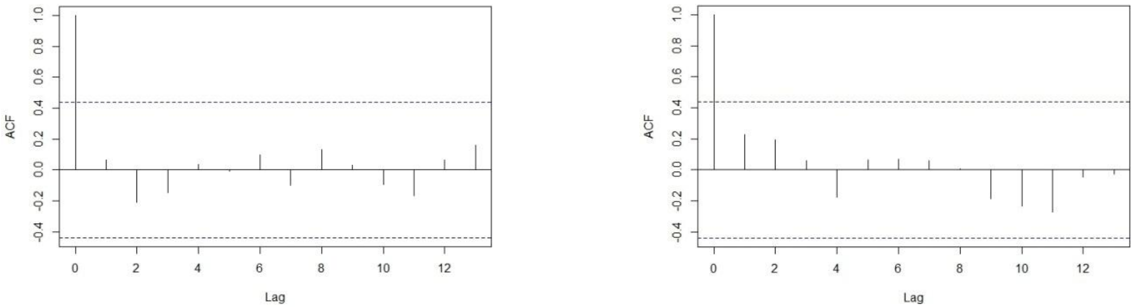
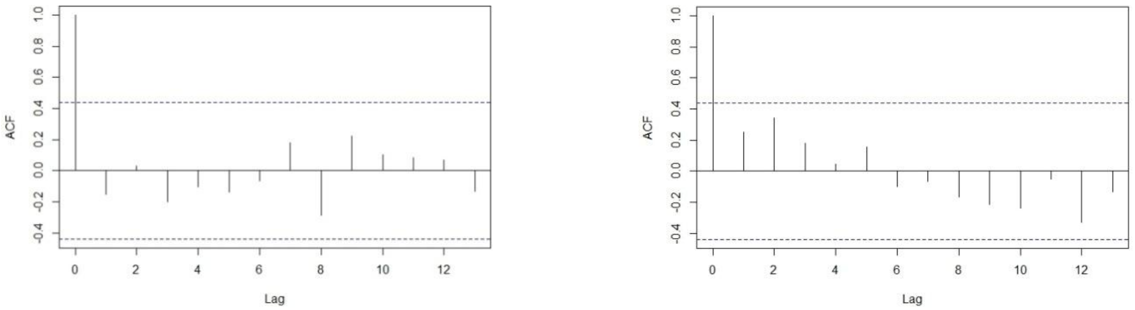
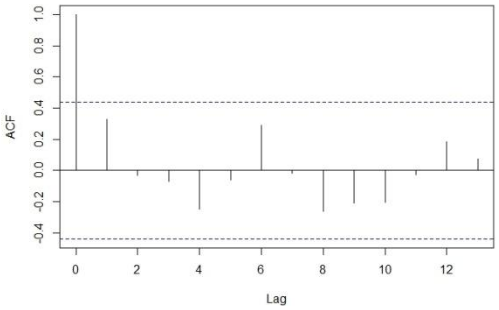


Jeju Ara



Eorimok Jindallaebat



Witsaeorum

Figure 4.6 Autocorrelation function (ACF) analysis plot of five rain gauge stations (Dashed line indicating 95% confidence interval).

4.4.2 Identification of homogeneous region by Cluster based analysis

One of the initial yet sensitive steps of regional frequency analysis was the identification of homogeneous regions, as per methodological description. A cluster based algorithmic analysis, following Ward's method (Ward 1963) was applied to identify such homogeneous regions. As such, hierarchical clustered dendrogram (tree) provided information on probable clusters and it

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was seen that study area consists of homogeneous regions. The appropriateness of this choice was also tested by heterogeneity measures (*H*). The identified three clustered region considered as different hydrometric homogeneous regions (Jeju and Ara station in region 1, Eorimok station in region 2 and region 3 is confined by Jindallaebat and Witsaeorum station) are illustrated in **Figure 4.7** and **4.8**.

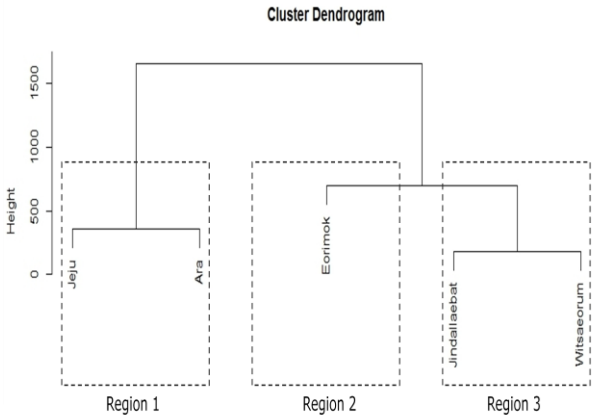

Figure 4.7 Dendrogram of clustered stations by Ward's method.

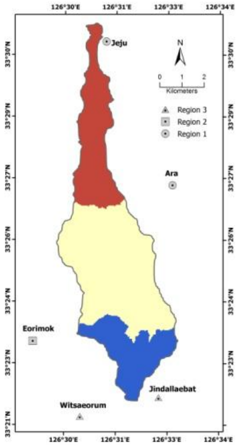

Figure 4.8 Location of three homogeneous regions in Hancheon watershed.

The first region is formed by Jeju and Ara stations, situated in the urban portion of northern part of Jeju Island with an average elevation 253 m, recording an average annual rainfall of around 1,835 mm. The second region is located in middle portion of Hancheon watershed, which is a semi urban area. This region has only one station (Eorimok) with an average elevation 950 m and 2,436 mm of average rainfall. The third region is situated near Halla Mountain, covering the Witsaeorum and Jindallaebat stations. The area has an average elevation of 1,570 m from the mean above sea level and average rainfall is nearly 2,361 mm. Rainfall characteristics of this region are fully influenced by tropical and mountainous winds.

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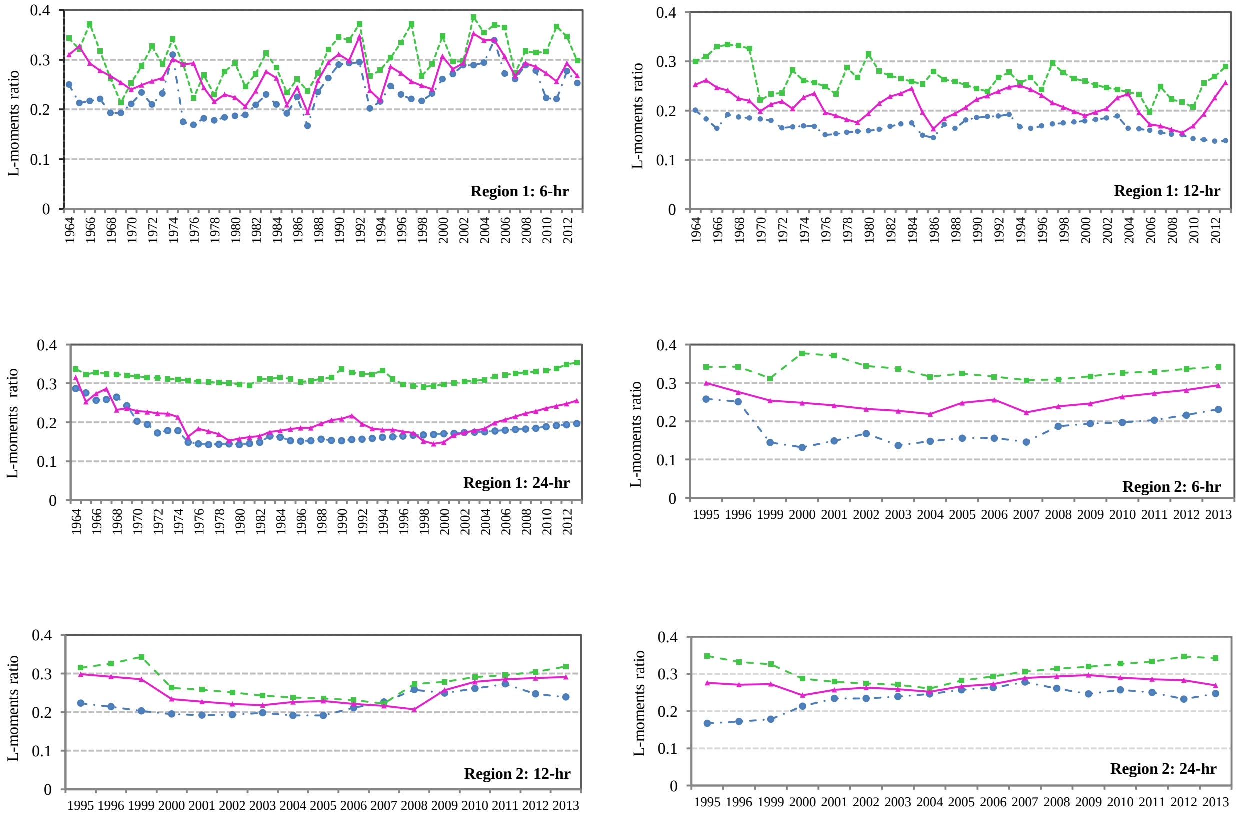
4.4.3 Estimation of L-moments, homogeneity test and best fitted distribution

The L-moments approach, discordancy (D_i) and heterogeneity measure (H) of each region were applied by the lmomRFA package in R statistical programming. Firstly, the scattered plots of yearly L-CV, L-Skewness and L-Kurtosis ratio values for each region have been shown **(Figure 4.9)**. The L-moments ratio values were bounded from 0.1 to 0.4. For region 2 and region 3, results indicated a parallel shift of values. This happened due to the abrupt daily and yearly rainfall occurrences. In particular, L-moments ratio for the three regions showed different values which show the increasing trend over the time period.



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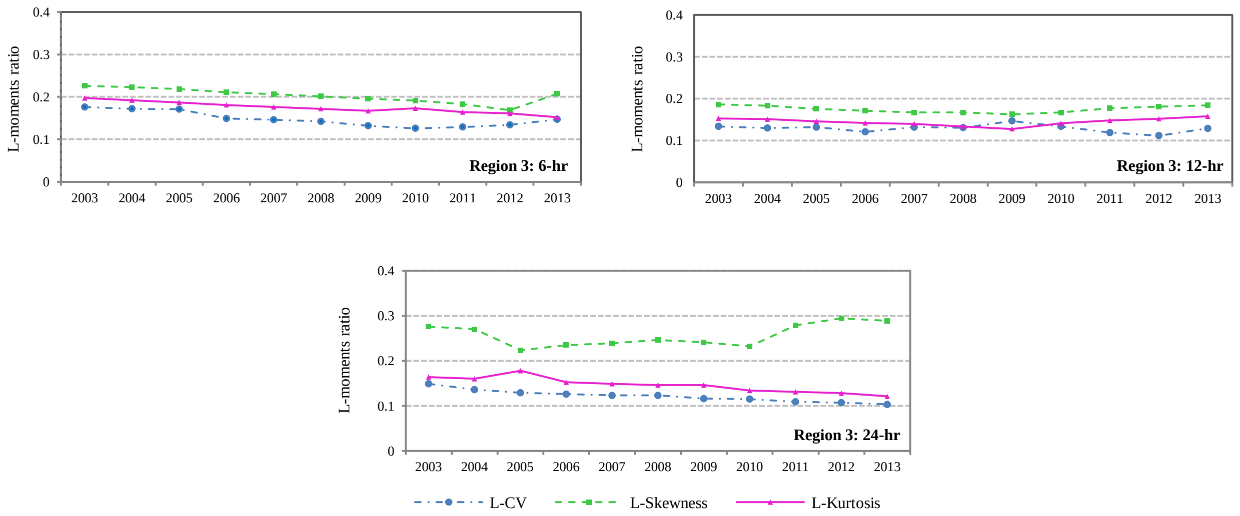

Figure 4.9 Yearly variation of average L-moments ratio for three regions.

Hereafter, the discordancy (D_i) has been computed from equation **3.21** and found as less than 3.0, suggesting that no region is discordant **(Table 4.7)**. Also, heterogeneity measures (H) were computed using equations **3.22** to **3.25** and using 500 simulated values in R programming for estimation. From the heterogeneity measure it was found that each H-statistics values are lower than one (H<1.0), indicating that those regions are reasonably homogeneous. Following the homogeneous region identification, the subsequent distribution step had been best fitted in line with the statistical candidate distribution for each region, as well as the regional data. Consequently, the proposed Z^{Dist} measure (Hosking and Wallis 1993) was calculated by equation **3.26**. The best fitted distribution inferred Z^{Dist} as 0.54, 1.25 and 1.03 (which are below 1.64), showing significant criterion to be accepted as goodness-of-fit at 90% confidence level for individual homogeneous region. The difference of results is understandable due to the hydro-geological distinctive conditions. Following the analysis, making a decision about Hancheon watershed frequency distribution for each homogeneous region using Gumbel and generalized extreme value (GEV) distribution is suggested.

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Table 4.7 Discordance, heterogeneity measure and best fitted distribution for three regions

Region	Discordance (D_i)	Heterogeneity measure			Best fitted distribution	Z^{Dist} value
		H1	H2	H3		
1	Jeju (1.61), Ara (0.95)	0.64	-0.53	-1.97	Gumbel	0.54
2	Eorimok (1.53)	-0.36	0.72	-1.78	Gumbel	1.25
3	Jinadallaebat (1.37) Witsaeorum (1.28)	-0.13	-1.40	-2.11	GEV	1.03

4.4.4 Estimation of regional rainfall frequency and growth curves

The regional frequency estimates were found reliable as those were always obtained by regional frequency analysis. Robust estimation was needed when the regional distribution was more than one. In such cases, Monte Carlo simulation was used to estimate the root mean square error (RMSE) at 90% confidence level. The estimation of $q(F)$, for different non-exceedance probabilities have been shown in **Table 4.8** and regional growth curves for three regions have also been represented in **Figure 4.10**. The error bound values varies 1.046 to 2.303 (region 1), 1.027 to 4.135 (region 2) and 0.960 to 7.829 (region 3). Furthermore, the RMSE values were found as 0.014 to 0.237 for Gumbel distribution and 0.115 to 0.301 for generalized extreme value distribution. As a result, the error value shows the accuracy of rainfall frequency.

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Table 4.8 Simulation results of estimated regional frequency, RMSE and corresponding 90% error bounds values

Region	Distribution	Return period	Confidence interval (F)	*q(F)*	RMSE	Error Bound	
						Lower	Upper
1	Gumbel	5	0.8	1.129	0.014	1.046	1.17
		10	0.9	1.347	0.032	1.263	1.481
		20	0.95	1.526	0.057	1.514	1.596
		50	0.98	1.721	0.072	1.608	1.739
		70	0.985	1.876	0.084	1.758	1.924
		80	0.987	2.039	0.094	1.982	2.145
		100	0.999	2.275	0.105	2.239	2.303
2	Gumbel	5	0.8	1.134	0.077	1.027	1.243
		10	0.9	1.632	0.148	1.522	1.801
		20	0.95	1.859	0.165	1.839	1.954
		50	0.98	2.102	0.174	2.01	2.227
		70	0.985	2.846	0.203	2.621	2.981
		80	0.987	3.64	0.218	3.105	3.764
		100	0.999	4.023	0.237	3.978	4.135
3	GEV	5	0.8	1.079	0.115	0.960	1.092
		10	0.9	1.923	0.197	1.799	2.163
		20	0.95	2.754	0.243	2.548	2.936
		50	0.98	3.628	0.266	3.332	3.847
		70	0.985	4.507	0.279	4.395	4.715
		80	0.987	5.706	0.285	5.389	5.902
		100	0.999	7.656	0.301	7.459	7.829

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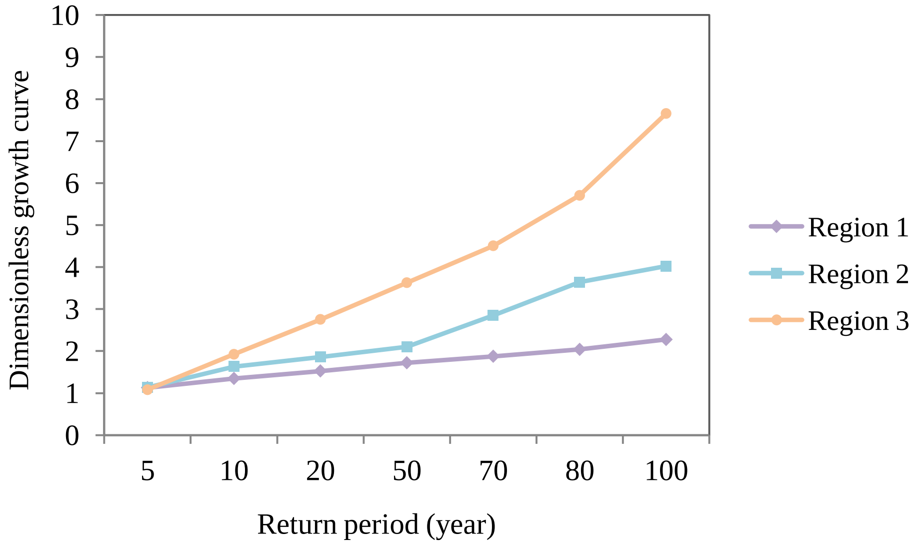

Figure 4.10 Estimated regional growth curve for three homogeneous regions (within 90% error bound).

4.4.5 Frequency analysis for five rainfall station

The present study is designed to derive rainfall patterns by L-moments based techniques for all station of Hancheon watershed. The approach has been developed for 5, 10, 20, 50, 70, 80, 100 years return period **(Table 4.9)**. Various periods of rainfall data had been used to estimate the return period. As a result, Jeju station area shows 165.12 to 333.97 mm rainfall, when the other station’s rainfall show remarkable interval of rainfall depth. Near the Halla Mountain (Jindallaebat station) the rainfall range from a minimum of 183.46 mm to a maximum of 555.18 mm. For all stations’ return period values, a statistical measure (linear regression) was done. The statistical measurement showed that the r-square values were found within 0.842 to 0.974 and the p-values were below 0.001, which indicate the results are statistically significant.

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Table 4.9 Results of the consecutive hour (6-, 12-, 24-hr) regional rainfall frequency for five station

Station	**Consecutive hour**	**Non-exceedance probability (return period, year)**						
		5	**10**	**20**	**50**	**70**	**80**	**100**
		0.800	**0.900**	**0.950**	**0.980**	**0.985**	**0.987**	**0.999**
Jeju	6	165.12	193.32	224.38	251.88	272.88	279.92	283.32
	12	208.02	233.62	259.72	285.02	298.14	308.19	312.22
	24	246.17	268.19	289.24	308.31	326.35	341.05	344.65
Ara	6	252.05	282.02	303.39	323.27	328.85	330.85	333.97
	12	400.77	442.71	471.45	497.04	503.96	506.42	510.20
	24	548.88	621.50	672.30	708.57	731.33	735.89	742.94
Eorimok	6	163.23	181.40	199.52	211.81	224.15	230.93	235.11
	12	185.15	208.19	226.42	241.89	256.45	265.21	270.64
	24	227.03	253.18	272.91	288.67	301.06	307.18	311.03
Witsaeorum	6	243.76	267.47	287.90	306.16	321.45	332.16	337.09
	12	307.39	337.54	363.72	383.59	400.87	410.60	414.27
	24	418.49	452.76	478.54	498.62	518.11	531.48	539.54
Jindallaebat	6	183.46	209.58	229.37	244.70	257.49	268.84	276.60
	12	318.26	352.45	374.80	391.29	407.08	420.66	427.51
	24	452.03	484.46	509.57	530.73	544.10	551.75	555.18

The station analysis showed that Eorimok stations probable rainfall (163.23 mm to 311.03 mm) is lower than the other stations. Eorimok station situated in forest and near to hilly region which can be change due to the elevation and slope change. Above all, L-moments technique shows all kind of statistical analysis accurately, therefore, the study is suggested for decision making on hydrological design.

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Chapter V: Conclusions and Future Work

5.1 Conclusions

In this thesis work, rainfall-runoff characteristics have been intensively studied for rainfall frequency analysis. The first method (NRCS CN) application reveals the 2009 and 2013 year showed lower runoff volumes and experiencing fewer rainfall events. Second method named unit hydrograph was conducted to estimate peak runoff and time. The values of selected model parameters (Tc, R) showed a range of Tc: 1.0 to 1.5 and R: 0.1 to 0.5 during calibration and validation. From the unit hydrograph analysis, peak time variation was seen 8 to 27 hour that discloses the 6 to 24 hour consecutive hour rainfall can select for rainfall frequency analysis. Therefore, L-moments based analysis need to quantify the hourly design rainfall (frequency). Accordingly, the L-moments approach was found best distribution for developing regional rainfall. This study amply indicates careful data screening from the historical rainfall events which carried out by cluster based tree analysis. From ward's classification, three reasonably homogeneous regions were suggested for Hancheon watershed (Jeju and Ara in region 1, Eorimok in region 2 and Jindallaebat and Witsaeorum in region 3). Afterwards, the Gumbel distribution for region 1, region 2 and generalized extreme value (GEV) distribution for region 3 was identified as best fitted models. These distributions provided lower bound (within 90% error) values during return period analysis. The return period analysis procedure can be used not only for the Jeju Island but also for other areas where the rainfall data records are limited and the land slope is high.

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5.2 Recommendation for the future work

- In this study, Thiessen polygon area ratio method applied for rainfall-runoff estimation. As, Jeju Island considered as high steep slope variation area therefore Isohyetal method could be applicable. Subsequently, estimation of last ten years or more available rainfall depth can be helpful to explain elaborately about rainfall-runoff characteristics of Hancheon watershed.

- The HEC-HMS model requirements are very significant concern for unit hydrograph analysis. Therefore, other unit hydrograph methods (Kraven I, Kraven II and Sabol) could be applied to minimize the time and runoff accuracy.

- The study considered only five rainfall stations during L-moments approach application and the watershed area was small (37.39 sq. km). Therefore, complete Jeju Island area and all rainfall (24 nos.) stations consideration could improve the understanding on rainfall frequency.

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List of Publications

Journal manuscript

- **Kar KK,** Yang SK, Lee JH (2015) Regional frequency analysis for maximum consecutive hour rainfall using L-moments approach in Hancheon catchment of Jeju Island, Korea. (under review)
- **Kar KK,** Yang SK, Lee JH (2015) Assessing Unit Hydrograph Parameters and Peak Runoff Responses from Storm Rainfall Events: A Case Study in Hancheon Basin of Jeju Island. ***Journal of Environmental Science International***, KENSS, 24(4):437-447. doi:10.5322/JESI.2015.24.4.437

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- Yang SK, **Kar KK**, Lee JH (2015) Surface Rainfall-Runoff Analysis Using NRCS Curve Number and Semi-Distributed Model in Urban Watershed of Jeju Island, Korea, *AGU Fall Meeting*, 14-19 December, San-Francisco, California, USA
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- **Kar KK,** Yang SK, Lee JH (2015) Spatial Interpolation of Rainfall by Areal Reduction Factor (ARF) Analysis for Hancheon Watershed. *Proceedings of the Korea Water Resources Association (KWRA) Conference*, 28-29 May 2015, Gangwon-do, South Korea
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- Kim MC, Yang SK, Oh ST, **Kar KK** (2014) Flow of Ground Water according to the Structure of Sedimentary Layer in Sung-san Basin, *Proceedings of the Korea Water Resources Association (KWRA) Conference*, 15-16 May, Busan, South Korea

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