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ORIGINAL ARTICLE

A Comparative Analysis of the Accuracy of Areal Precipitation According to the Rainfall Analysis Method of Mountainous Streams

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Abstract

The purpose of this study was to evaluate the method of estimating the areal precipitation reflecting the altitude of the mountainous terrain on Jeju Island by comparing and analyzing the areal precipitation using the Thiessen polygon method and the isohyetal method in mountainous streams. In terms of constructing the Thiessen polygon network, rainfall errors occurred in 94.5% and 45.8% of the Thiessen area ratio of the Jeju and Ara stations, respectively. This resulted in large areal precipitation and errors using the isohyetal method at altitudes below 600 m in the target watershed. In contrast, there were small errors in the highlands. Rainfall errors occurred in 18.91% of the Thiessen area ratio of Eorimok, 2.41% of Witseoreum, and 2.84% of Azalea Field because of the altitudinal influence of stations located in the highlands at altitudes above 600 m. Based on the areal precipitation estimation using the Thiessen polygon method, it was considered to be partially applicable to streams on Jeju Island depending on the altitude. However, the method is not suitable for mountainous streams such as the streams on Jeju Island because errors occur with altitude. Therefore, the isohyetal method is considered to be more suitable as it considers the locations of the rainfall stations and the orographic effect and because there are no errors with altitude.

Key words : Areal rainfall, Thiessen polygon method, Isohyetal method

1. Introduction

Abnormal global climate conditions cause many disasters. In particular, typhoons and localized heavy rains have caused a significant amount of damage. As Jeju Island is surrounded by the sea, it is exposed to disasters throughout the year. Due to geographical characteristics, the island is also located in the path of many typhoons, so the damage caused by storms and floods is increasing every year.

The damage caused by storms and floods increases with the scale of typhoons and torrential rains as well as the frequency of outbreaks. In 2012, the Korean peninsula was struck by four typhoons for the first time in 50 years, including Typhoon Khanun in July and Typhoon Sanba in September. In July, Typhoons Khanun, Bolaven, and Tembin hit Korea in close succession, causing heavy property damage and human casualties (CCIC, 2012). In recent years, unlike in the past, typhoons have also occurred in September and October. In October 2018, Typhoon Kong-rey struck Jeju Island causing such damages as loss of farmland and severe flooding.

To reduce damage caused by storms and floods,

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Korea has established a comprehensive flood control plan and a basic river plan according to city and province. The probable precipitation and the design flood discharge are evaluated by referring to the guidelines for estimating the flood discharge (2012), as presented by the Ministry of Land, Infrastructure, and Transport. The purpose thereof is to develop plans to prevent disasters, which is a very important standard for establishing hydraulic structures and flood control plans to prevent flood damage (Kang, 2014).

Most of the streams on Jeju Island are normally dry, and sudden runoffs occur as a result of typhoons and heavy rains. Moreover, the areas have a very high initial loss of rainfall because of high permeability. In addition the hydrologic and geological characteristics of Jeju Island differ considerably from those of the inland area. Thus, many errors may occur when applying the probable precipitation and design flood discharge calculation methods based on the inland area.

Recently, the frequency of heavy rainfalls exceeding 500 mm has been increasing near the summit of Mt. Halla, and the daily rainfall of Jeju-si and Seogwipo-si frequently exceeds 200 mm. In particular, Typhoon Nakri, which struck Korea in August 2014, recorded a daily rainfall of 1500 mm, which is the largest ever observed by the Korea Meteorological Administration. Preventive measures need to be developed as the risk of damage from storms and floods is increasing as a result of frequent torrential rains and record-breaking daily rainfalls caused by abnormal weather conditions. Establishing basic river plans and comprehensive flood control plans by accurately calculating flood discharge is critical to reducing flood damage due to rapid climate change.

In terms of calculating the areal rainfall, Yoon and Yoon(1981) found that the isohyetal method was more reasonable than the Thiessen polygon method when analyzing precipitation points and regional frequencies. Yoo and Jung(2001) proposed an isohyetal method that considers the variability in rainfall this variability causes many errors when applying the arithmetic average method or Thiessen polygon method to mountainous areas.

In Korea, the guidelines for estimating the design flood discharge (2012) were established to estimate rainfall and flood discharge, and the Thiessen polygon method is recommended to estimate the areal precipitation. The areal precipitation should accurately analyze the spatial distribution of rainfall. However, as conventional methods do not consider the altitude of rainfall, they do not reflect the orographic effect on Jeju Island, where Mt. Halla is located in the center. Therefore, the purpose of this study is to evaluate the method of estimating the areal precipitation reflecting the altitude of the mountainous terrain on Jeju Island by comparing and analyzing the areal precipitation using the Thiessen polygon method and the isohyetal method in mountainous streams.

2. Materials and Method

2.1. Study area

As the streams on Jeju Island have very good permeability, most are normally dry and are located on the steep southern and northern slopes (Kang, 2014).

In this study, we selected a stream in the downtown area (Han Stream, Byeongmun Stream, Doksa Stream, Sanji Stream) of Jeju Island as the research area; we chose this from among the streams that pass through the downtown area damaged by flooding due to Typhoon Nari (Fig. 1, Table 1).

2.2. Rainfall events selection

In terms of the rainfall data for estimating the areal precipitation, we selected events that showed heavy rainfall from the storm events that occurred since 2010. Typhoons Bolaven and Tembin caused heavy rainfalls that lasted nine days in August 2012. Typhoon Chaba, which struck Korea in October 2016, recorded the

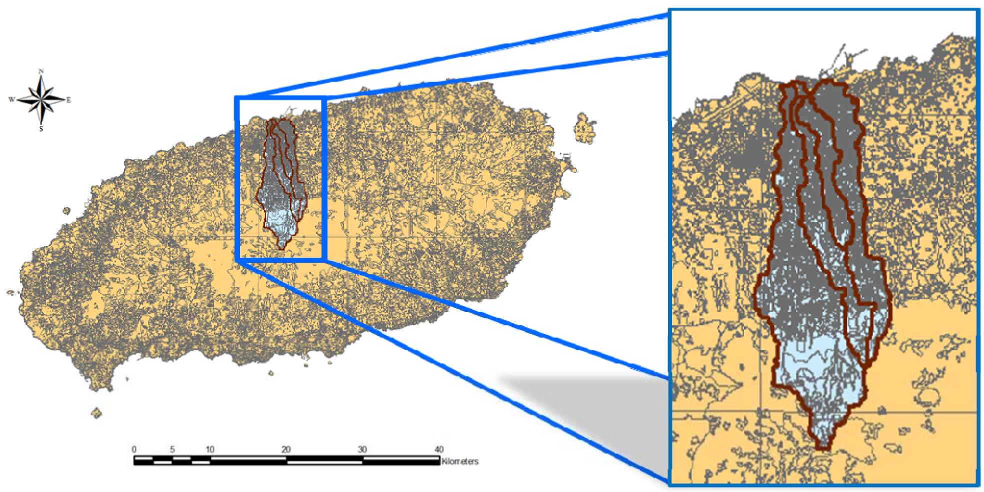

Fig. 1. Location of study watershed in Jeju Island.

Table 1. Geographical characteristics and shape of study watershed

Stream	Area (km^2)	Length (km)	Mean width of Basin (km)	Shape factor
Han Stream	36.69	20.18	1.82	0.09
Byeongmun Stream	22.69	19.43	1.17	0.06
Doksa Stream	5.90	7.25	0.81	0.11
Sanji Stream	14.65	13.47	1.09	0.08

highest rainfall intensity, even though the rainfall lasted only two days (Table 2).

2.3. Estimation of areal rainfall

2.3.1. Thiessen polygon method

The Thiessen polygon method is commonly used in domestic practice, and this method calculates the areal average precipitation by weighting the area ratio of the Thiessen polygons enclosing the watershed stations that observe the rainfall.

$$P_m = \frac{A_1P_1 + A_2P_2 + \cdots + A_nP_n}{A_1 + A_2 + \cdots + A_n} = \frac{\sum_{i=1}^{n} A_iP_i}{\sum_{i=1}^{n} A_i}$$

where P_m is the average precipitation in the watershed, $P_1, \cdots, P_n$ the rainfall observed at

Table 2. Rainfall events using the Thiessen method

No	Rainfall event	Time of occurrence	Rainfall duration
1	Typhoon ‘Khanun’	2012. 07. 17 ~ 19	3 days
2	Typhoon ‘Bolaven’, ‘Tembin’	2012. 08. 22 ~ 30	9 days
3	Typhoon ‘Sanba’	2012. 09. 15 ~ 17	3 days
4	Typhoon ‘Nakri’	2014. 07. 31 ~ 08. 04	5 days
5	Typhoon ‘Chaba’	2016. 10. 04 ~ 05	2 days

n-stations in the watershed, and $A_{1}, \ldots, A_{n}$ the areas of each observation point.

The Thiessen polygon method obtains the average precipitation by weighting the area of each station. This method takes into account the relative locations of the rainfall stations in the watershed, and the relative density of the observation network. As a result, the method performs better than the arithmetic average method; however, it does not consider changes in the precipitation due to altitude.

2.3.2. Isohyetal method

The isohyetal method can consider the orographic effect by estimating the average precipitation in the watershed by calculating the area between the isohyets after drawing estimated lines of equal rainfall. This can be attained by using the rainfall data observed at each storm station and the information needed to interpolate the precipitation between stations. Contour data are important because the rainfall is closely related to the altitude when drawing isohyets. This method estimates the average rainfall of the entire watershed by weighting the area between isohyets to the average rainfall between isohyets.

This method is similar to the Thiessen polygon method in terms of using the area as a weighting factor. However, the isohyetal method applies the area weight to the average rainfall between isohyets rather than directly weighting the observed rainfall.

$$P_{m}=\frac{A_{1}P_{1m}+A_{2}P_{2m}+\cdots+A_{n}P_{nm}}{A_{1}+A_{2}+\cdots+A_{n}}=\frac{\sum_{i=1}^{n}A_{i}P_{im}}{\sum_{i=1}^{n}A_{i}}$$

where P_{m} is the average precipitation in the watershed, P_{im} the average precipitation in the area between two adjacent isohyets, n is the number of area sections divided by the isohyets, and $A_{1}, \ldots, A_{n}$ are the areas divided by the isohyets.

3. Results and Discussions

3.1. Spatial distribution of rainfall stations

Five rainfall stations affect the target watershed in the Thiessen polygon network namely Jeju (20.5 m) and Ara (374.7 m) stations, which are located at an altitude of 600 m or less; and Eorimok (965 m), Azalea Field (1,489 m), and Witseoreum (1,672 m) stations, which are located at an altitude of more than 600 m (Fig. 2).

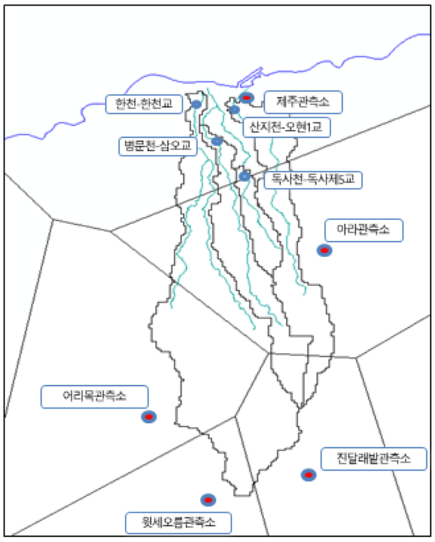

Fig. 2. Location of rainfall observatories in urban stream watershed and thiessen network.

In the case of typhoons and heavy rains, Jeju Island has more rainfall in the central region (highlands) where Mt. Halla is located than in the coastal areas (lowlands). Therefore, we can calculate the areal precipitation more accurately if more rainfall stations are located at higher altitudes in the construction of the Thiessen polygonal network.

As Jeju station (20.5 m) is located in the lowest point of the coastal area, it does not accurately reflect rainfall up to 160 m, the highest of the area ratios of Jeju station. Analysis results of the Thiessen area ratio of the urban stream watershed based on the location of

Table 3. Altitude distribution and area ratio of Thiessen method

Rainfall Observatory	Altitude (m)	Altitude distribution of Thiessen method		Area ratio of Thiessen method	
		Min (m)	Max (m)	Downstream (%)	Upstream (%)
Jeju	20.5	10	160	5.55	94.45
Ara	374.7	110	650	54.23	45.77
Eorimok	965	320	1280	81.09	18.91
Witseoreum	1672	1120	1850	97.59	2.41
Jindallaebat	1489	620	1680	97.16	2.84

Jeju station show that the area ratio up to 20 m where Jeju station is located was 5.55% and the area ratio between 20 and 160 m was 94.45%. Therefore, large errors occur if using the Thiessen polygon method to estimate the areal precipitation below 160 m. Because Ara station is located near the center of the area ratio, it cannot take into account the rainfall at altitudes above the observation point (up to 650 m). The area ratio up to 375 m where Ara station is located was 54.23% and the area ratio between 375 and 650 m was 45.77%. Therefore, large errors occur when estimating the areal precipitation below 650 m, which accounts for the Thiessen area ratio of Ara station (Table 3).

In contrast, Eorimok (965 m), Witseoreum (1,672 m), and Azalea Field (1,489 m) stations are located in mountainous areas at the top of the target watershed and the Thiessen polygonal network. In terms of the Thiessen area ratios of Eorimok, the area ratio between 320 and 965 m, which is lower than the altitude of Eorimok, was 81.09% and the area ratio between 965 and 1280 m was 18.91%. Regarding the Thiessen area ratios of Witseoreum, the area ratio between 1,120 and 1,672 m, which is lower than the altitude of Witseoreum, was 97.59% and the area ratio between 1,672 and 1850 m was 2.41%. In terms of Azalea Field, the area ratio of low altitudes between 620 and 1,489 m was 97.16% and the area ratio of high altitudes between 1489 and 1680 m was 2.84%, similar to that of Witseoreum (Table 3).

Therefore, with the Thiessen polygon method, we were able to accurately estimate the area precipitation reflecting the effect of altitude in high watersheds. In contrast, large errors occurred when estimating the area precipitation in the lowlands because the effect of altitude was not reflected properly.

3.2. Density of rainfall stations

Analysis results of the density of the rainfall observation network for streams in Jeju Island show that the density of the rainfall observation points relative to the watershed area was high compared with that of the inland area.

The rivers in the inland area of Korea are divided into five major river watersheds and the rainfall station density is 136 km^2/EA. Analysis results of the density of rainfall stations by watershed show that the Han River watershed was 140.5 km^2/EA, Nakdong River watershed was 135.4 km^2/EA, Geum River watershed was 120.9 km^2/EA, Yeongsan River watershed was 182.6 km^2/EA, and Seomjin River watershed was 126.0 km^2/EA. Although the Han River watershed had the most rainfall stations, the density was low because of the large area of the watershed. The Geum River watershed had the highest density of rainfall stations. Meanwhile, the Yeongsan River watershed had 19 rainfall stations, resulting in the lowest density of rainfall stations relative to the area among the five major river watersheds.

However, 38 rainfall observation points are located

Table 4. Density of rainfall observatories in urban streams basin of Jeju Island

	Area (km^2)	Rainfall observatory (EA)	Density	
			A/R.O (km^2/EA)	R.O/A (EA/km^2)
Han Stream	36.69	5	7.34	0.136
Byeongmun Stream	11.87	3	3.96	0.253
Doksa Stream	6.35	2	3.18	0.315
Sanji Stream	14.67	3	4.89	0.204

across Jeju Island, and Hancheon is under the influence of five rainfall observation points (Jeju, Ara, Eorimok, Azalea Field, Witseoreum) in the construction of the Thiessen polygon network. Analysis results of the density of rainfall stations by each stream show that the Hancheon watershed was 7.34 km^2/EA, Byeong -muncheon watershed was 3.96 km^2/EA, Doksacheon watershed was 3.18 km^2/EA, and Sanjicheon watershed was 4.89 km^2/EA. Unlike the streams in the inland area, the streams in Jeju Island do not have a large watershed area and the rainfall stations on the island are densely distributed. Consequently, the density is about 25 times higher than that of the inland area and the rainfall observation network has a very high density of less than 10 km^2 per observation station (Table 4).

3.3. Comparison and analysis of areal precipitation accuracy

The Thiessen polygon method estimates the average precipitation by weighting the relative areas of each station and considers the relative location of rainfall stations in the watershed and the relative density of the observation network. However, this method does not consider the changes in precipitation according to the altitude (orographic effect). In addition, since there is no ARF suitable for estimating the area probability rainfall of mountainous streams on Jeju Island, we compared it with the areal precipitation using the isohyetal method.

This study estimated the areal precipitation by altitude at 200 m intervals to consider the effect of altitude, which is the biggest difference between the Thiessen polygon method and the isohyetal method. In terms of comparing the areal precipitation, we analyzed the correlation coefficient between the two methods by applying the same rainfall data for each hour.

The comparison results of the areal precipitation by altitude show that the correlation coefficient of the areal precipitation between the two methods was 0.48-0.53 at altitudes below 600 m where most urban areas are located, resulting in many errors. In contrast, the correlation coefficient of the areal precipitation between the Thiessen polygon method and the isohyetal method was high at 0.7-0.96 at altitudes above 600 m, and the correlation coefficient was very high at 0.8-0.96 at high altitudes above 1200 m. Although Jeju station has an altitudinal influence up to 160 m in the construction of the Thiessen polygonal network, the network is installed at an altitude of 20 m. As this range accounts for only 5.5% of Jeju station's Thiessen area ratio, the rainfall errors that occur in the watershed correspond to 94.5%. In addition, as rainfall errors occur in 45.8 % of the Thiessen area ratio of Ara station, there are large errors in the correlation coefficient in the watershed below 600 m. However, at altitudes above 600 m, the correlation coefficient was also high. This was due to rainfall errors in 18.91% of the Thiessen area ratio of Eorimok, 2.41% of Witseoreum, and 2.84% of Azalea Field because of the altitudinal influence of stations located at high

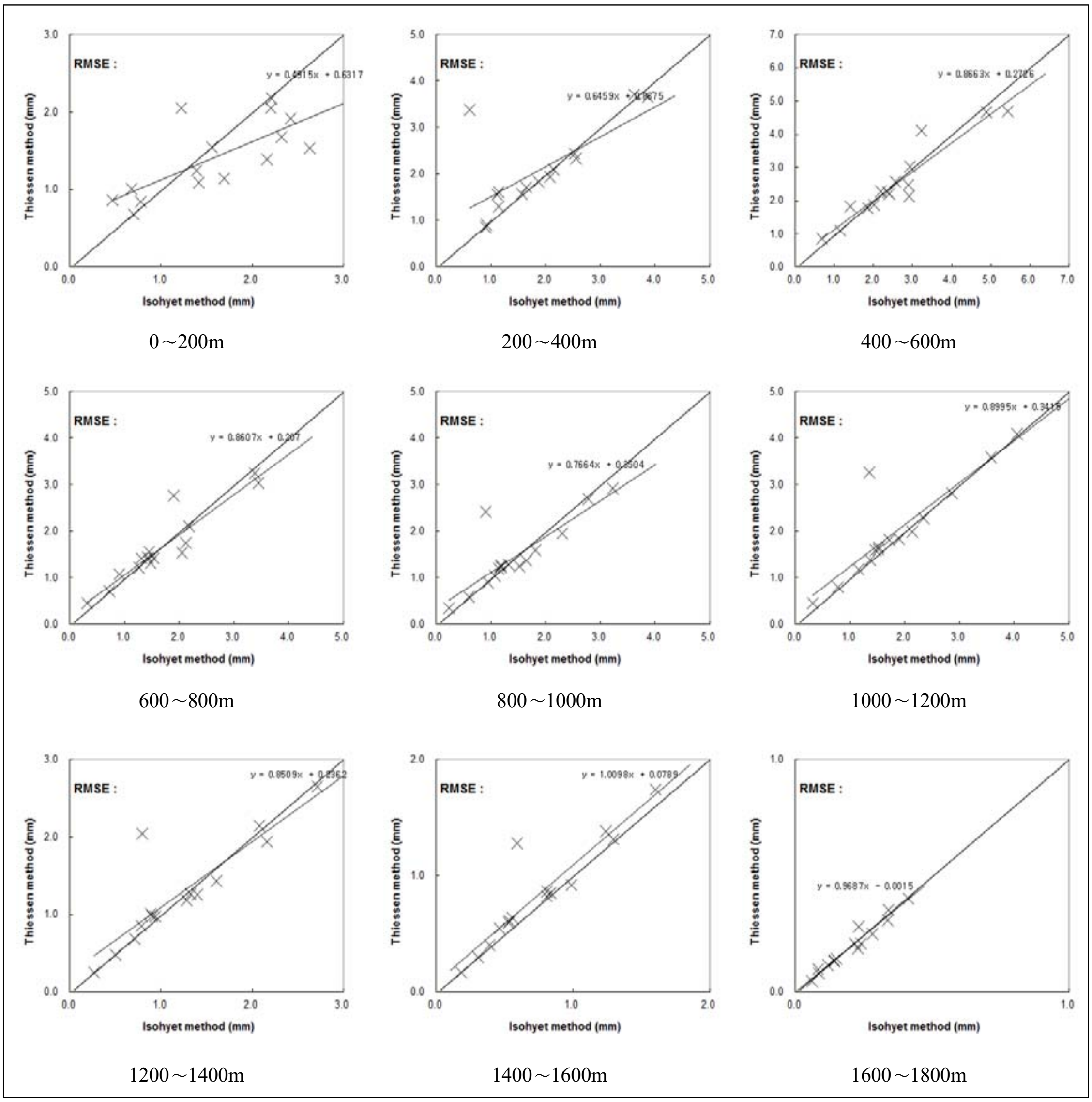

Fig. 3. Comparison of area rainfall of altitudinal distribution with thiessen method and isohyetal method.

altitudes. In particular, the area error of areas at altitudes higher than 1200 m was less than 3% owing to the altitudinal influence of the Witseoreum and Azalea Field stations. Furthermore, the areal precipitation and correlation coefficient using the isohyetal method was very high (Fig. 3).

The Thiessen polygon method may be partially applicable to estimate the areal precipitation of streams on Jeju Island, depending on the altitude. However, the method is not suitable for mountainous streams such as the streams on Jeju Island because errors occur with altitude. Therefore, the isohyetal method is more suitable because it considers the locations of the rainfall stations and the orographic effect and because there are no errors with altitude.

4. Conclusions

Although areal precipitation should accurately analyze the spatial distribution of rainfall, conventional methods do not consider the altitude of rainfall. Therefore, this study compared and analyzed areal precipitation using the Thiessen polygon method and the isohyetal method, based on mountainous streams. The evaluation results of suitable methods to estimate the areal precipitation on Jeju Island reflecting the altitude are as follows.

As a result of analyzing the density of rainfall stations by watershed, the streams on Jeju Island do not have a large watershed area like those in the inland area. In addition, because the rainfall stations are densely distributed, the density is about 25 times higher than that of the inland area and the rainfall observation network has a very high density of less than 10 km^2 per observation station. Therefore, we can accurately analyze the rainfall and estimate the areal precipitation.

In terms of constructing the Thiessen polygon network, rainfall errors occur in 94.5% and 45.8% of the Thiessen area ratio of the Jeju and Ara stations, respectively, resulting in large areal precipitation and errors with the isohyetal method at altitudes below 600 m in the target watershed. In contrast, there were small errors in the highlands. Rainfall errors occurred in 18.91% of the Thiessen area ratio of Eorimok, 2.41% of Witseoreum, and 2.84% of Azalea Field because of the altitudinal influence of stations located in the highlands at altitudes above 600 m.

The correlation coefficient of the areal precipitation between the two methods was 0.48-0.53 at altitudes below 600 m, where most urban areas are located, resulting in many errors. However, the correlation coefficient of the areal precipitation between the Thiessen polygon method and the isohyetal method was high (0.7-0.96) at altitudes above 600 m. In particular, the area error of areas at altitudes higher than 1200 m was less than 3% owing to the altitudinal influence of the Witseoreum and Azalea Field stations. Moreover, the areal precipitation and correlation coefficient by the isohyetal method was very high (0.8-0.96).

Based on the areal precipitation estimation using the Thiessen polygon method, it was considered to be partially applicable to streams on Jeju Island, depending on the altitude. However, the method is not suitable for mountainous streams such as those on Jeju Island because errors occur with altitude. Therefore, the isohyetal method is considered to be more suitable as it considers the locations of the rainfall stations and the orographic effect and because there are no errors with altitude.

In conclusion, we confirmed that calculating the accurate precipitation is critical in the process of estimating the flood discharge in mountainous areas such as Jeju Island. We expect that estimating the flood discharge using the isohyetal method will be applicable in practice such as in developing various flood control plans in the future.

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References

CCIC (Climate Change Information Center), 2012, The abnormal climate report.

CCIC (Climate Change Information Center), 2014, http://www.climate.go.kr.

English, E. J., 1973, An Objective method of calculating areal rainfall, Meteo, Magazine, 102, 292-298.

Eulogio, P. I., 1998, Comparison of geostatistical method for estimating the areal average climatological rainfall mean using data on precipitation and topography, International J. Climatology, 18(9), 1031-1047.

Goovaerts, P., 2000, Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. J. Hydrology, 228(1/2), 113-129.

Jung, W. Y., Yang, S. K., 2009, Simulation of runoff of rivers in Jeju island using SWAT model, J. Environ. Sci., 18(9), 1045-1055.

Kang, B. S., Yang, S. K., Jung, W. Y., Kim, Y. S., 2014, Calculation of the flood runoff of the river with imaging equipments, J. Environ. Sci., 23(4), 585-594.

Lee, J. H., Choe, H. I., Jeon, H. D., 2015, The Effect of raingauge network on areal average rainfall estimation, J. Korea Water Res. Asso., 48(9), 36-49.

Ministry of Land, Transport and Maritime Affairs, 2012, Guideline of design flood estimation, Ministry of Land, Transport and Maritime Affairs, Korea.

Pardo-Iguzquiza, B., 1998, Optimal selection of number and location of rainfall gauges for areal rainfall estimation using geostatistics and simulated annealing, J. Hydrology, 210(1), 206-220.

Yang, S. K., Kim, D. S., Jung, W. Y., Yu, K., 2011, Analysis and comparison of stream discharge measurements in Jeju island using various recent monitoring techniques, J. Environ. Sci., 20(6), 738-788.

Yoo, C. S., Jung, K. S., 2001, Estimation of area average rainfall amount and its error, J. Korea Water Res. Asso., 34(4), 317-326.

Yoo, C. S., Lee, J. H., Yang, D. M., Jung, J. H., 2011, Spatial analysis of rain gauge networks: Application of uniform and Poisson distributions, J. Korea Soc. Hazard Mitig., 11(4), 179-187.

Yoon, T. H., Yoon, S. B., 1981, Plotting of Isohyetal Maps and Estimation of Mean Areal Rainfall by Finite Element Method, J. Korean Soc. Civ. Eng., 29(3), 153-161.

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