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Investigation of Depth-Area-Duration (DAD) Curves for Kuantan River Basin (KRB)

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Abstract. Depth-area-duration (DAD) analysis of rainfall is performed to evaluate the maximum amount of rainfall over areas of various sizes within different durations. It is frequently used to characterize precipitation extremes for the specification of so-called rainfall, with DAD curves resembling the correlation between rainfall depth and area. Kuantan River Basin (KRB) is one of the major rivers in Pahang that typically experiences heavy precipitation during the northeast monsoon season from November through March. In this study, DAD curves for KRB were developed for the duration of 1-day to 7-day. Daily rainfall data between 2008 to 2019 from eight stations in KRB were used to develop the DAD curves. DAD curve development initially requires an isohyet map's illustration that can be constructed through the interpolation of Inverse Distance Weighting (IDW) method. The isohyet maps were developed in the ArcGIS software to purposely obtain the average maximum rainfall depths for each rainfall duration. The maximum rainfall amount of 1-day up to 7-day durations increased from 394.45 mm to 857.61 mm. The results indicated that the maximum amount of rainfall will increase along with the duration from 1-day to 7-day. The gap between the final DAD curve of 6-day and 7-day was less compared to other duration curves; however, the gap for both curves increased from the 800 km^2 to 1000 km^2 areas where the gap differences between the curves accelerated from 12 mm to 34 mm. Final DAD curves of KRB were produced from the combination of initial DAD curves with durations ranging from 1 to 7 days. The DAD curves produced in this study can provide further information on the maximum rainfall depth under different storm durations for hydrological planning purposes, particularly in KRB.

1. Introduction

Malaysia has two monsoon seasons, which are the southwest and northeast monsoons. The northwest region is believed to be the wettest region during the southwest monsoon while also stands as the driest region during the northeast monsoon. Therefore, engineers must be familiar with the area's annual rainfall when developing hydraulic structures to manage river flow.

The maximum amount of rainfall over different time periods across a variety of geographical areas is commonly determined using depth-area-duration (DAD) analysis. The maximum rainfall for various durations across various areas are initially determined using the DAD curve analysis technique. The depth of rainfall in a certain location is referred to as point rainfall values, which are usually used to represent design rainfall values. A relationship analysis between the depth, area, and duration of the rainfall is one of the fundamental tools used in the study of the spatial variation of rainfall for flood analysis and assessment [1]. Methods for converting point rainfall amounts over a given area into average rainfall amounts are required by engineers and hydrologists to determine the average values for that area. It requires extensive computation to prepare the DAD curves, which also needs meteorological and local topography data [2].

Generally, the amount of rainfall in any given location is measured daily by rain gauges. However, rain gauge stations sometimes fail to record the daily rainfall events as well as the highest average rainfall. In hydrological analysis, the characteristics of the spatial distribution of rainfall over time are known as a depth-area relationship, in which the depth, area, and duration of the rainfall are all interrelated. The objective of DAD analysis is to ascertain the maximum amount of rainfall for different time spans throughout various locations [3]. Additionally, DAD analysis is an important part of hydrometeorological research since it helps to develop the association between maximum DAD for a given area. The construction of the maximum depth-area plot for different durations is based on the assumption that rainfall will occur in different regions, which are referred to as DAD curves. The development of DAD curves demands a significant amount of computer effort and meteorological along with regional topographical data. The DAD curves are developed to ascertain the maximum amount of rainfall for the chosen study locations, considering different rainfall durations, which will be monitored using rainfall stations. However, the stations regularly overlook the need to record the average amount of maximum rainfall. Therefore, detailed information on the most severe storms in the past is required [2]. Furthermore, radar-based technology has made it possible to detect and track rainfall. As stated by Durrans et al. [4], for the same duration and return period, the average point rainfall depth derived from isopluvial maps can be linked to the average areal rainfall depth determined from the same maps by a geographically fixed depth-area curve.

Using a geostatistical approach, Solaimani et al. [1] developed the DAD curves of rainfall in a semi-arid and arid region at the Sirjan Kafeh Namak Watershed. The Kriging method was used to design the isohyets maps with a timeframe of one to three days, leading to the creation of DAD curves. It was discovered that the ratio of rainfall in the center to the rainfall in a 20,000 km^2 area is 1.98, 1.74, and 1.48 for 1-, 2-, and 3-day durations, respectively. In the Kurdistan Province in 2009, Mohammadi and Mahdavi [3] obtained the daily DAD curves for the time periods from 1 to 4 days. Isohyet maps were also created using the Moving Average computations. It was discovered that rain that lasts for two days or longer implies a stable environment. The amount of rainfall is always higher in such steady climatic regimes.

Parzybok et al. [5] created precipitation depth-area relationships using information from precipitation radar algorithms. It gives a general overview of the importance of DAD for keeping track of storms that already happened, are happening, or are expected to happen across a specific region, watershed, or catchment. Flood warnings and emergency action plans (EAPS) could both be activated using the data in near real-time DAD curves. The DAD analysis also offers a framework for assessing drought events when storm depth is replaced by an appropriate indicator of drought severity, as evidenced by Kim et al. [6] who reported drought severity-effective using area-drought duration (SAD) curves. It was reported that the severity reduction rate in SAD curves decreased as the duration or effective area of a dry event increased.

Meanwhile, in Malaysia, Patrick et al. [7] created the DAD of maximum rainfall analysis for the Sungai Sarawak Basin as a case study. The study found that the maximum area-average rainfall will decrease if a particular area increases over a set period of time. Furthermore, the study found no significant connection between rainfall and elevation.

This work aims to analyze the historical rainfall depth data from 2008 to 2019 obtained from operational hydrological stations in the Kuantan River Basin (KRB). The analysis involves generating daily DAD curves for periods ranging from 1 to 7 days in the study area. The findings may provide further data on the maximum rainfall depth for different rainfall durations, which can be utilized in hydrological engineering applications in the KRB. The average maximum rainfall depth for each timeframe was investigated and both the isohyet mapping preparation and IDW technique were conducted by utilizing the GIS software. The DAD curves would emerge after the isohyet map was processed in GIS. Both rainfall data and DAD curve analysis would be useful to support the theories discovered in this study.

2. Methodology

2.1 Study Area

This study focused on the entire KRB located in Pahang Darul Makmur between latitude N 3°35' and N 4°10' and between longitude E 102°50' and E 103°25'. After the Pahang River Basin and the Rompin River Basin, KRB is the third-largest basin, which is in eastern Pahang, with an area of 1,703.15 km^2. From Ulu Sg. Kuantan and Chereh sub-basins at the upstream areas of the basin, the Kuantan River flows downstream about 100 kilometers into the South China Sea at Tanjung Lumpur in Kuantan City. Figure 1 shows the KRB map with the location of rainfall stations. The average rainfall is from 2,500 to 3,000 mm annually, while the extreme temperature ranges from 20 to 36°C. The monsoon season significantly influences the rainfall in the KRB. In Malaysia, there is more rainfall during the northeast monsoon, referred to as the wet season, in comparison to the southwest monsoon, referred to as the dry season. The northeast monsoon mostly affects rainfall in this region, especially along the coast.

Because of its tropical climate, KRB has a long history of experiencing floods. The frequent flooding of surface runoff from rivers and low-lying areas brought on by heavy rains imposes significant social and economic difficulties, especially for the local people. After 30 years of terrible floods in 1971, the northeast monsoon that affected the majority of Peninsular Malaysia in 2001/2002 caused disaster flooding with a magnitude of 3.9. Again in 2013, the unexpectedly large flood caused by continuous heavy rain and changes in land-use posed serious risks to society. Rapid urbanization and land use degradation are the main factors causing flash floods in KRB. If this continues, there will be more chances for increased flood intensity, which will be more disastrous and wreak havoc on physical, environmental, and economic costs [8].

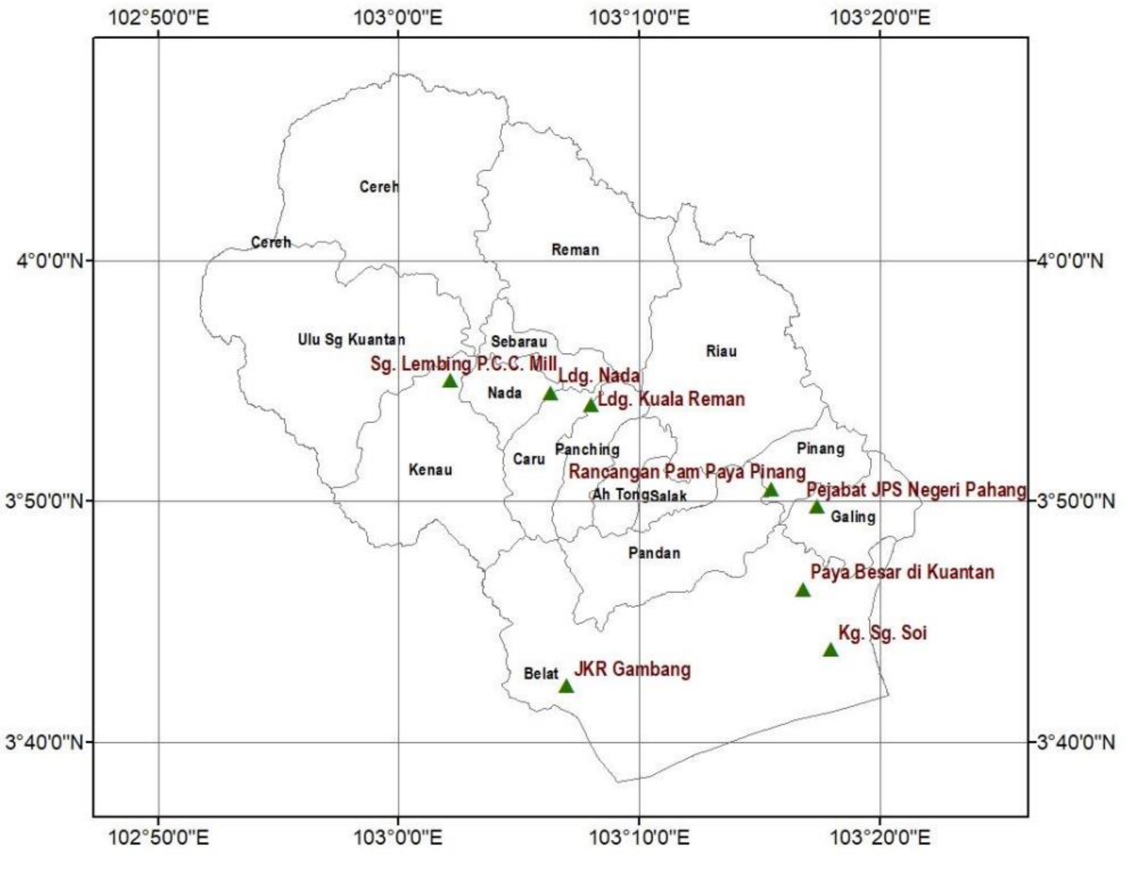

Figure 1. Location of rainfall stations in KRB.

2.2 Data Collection

For this study, the Department of Irrigation and Drainage (DID) Malaysia provided rainfall data from eight active rainfall stations in the KRB, covering the years 2008–2019. Then, the daily maximum rainfall during a period of one to seven days was retrieved from the collected records for the next analysis purpose in ArcGIS software. Table 1 below shows the coordinates of rainfall stations used in the study for DAD analysis purposes.

Table 1. List of rainfall stations in KRB.

Station ID	Station Name	Latitude	Longitude
3731018	JKR Gambang	03 42 20	103 07 00
3732020	Paya Besar di Kuantan	03 46 20	103 16 50
3732021	Kg. Sg. Soi	03 43 50	103 18 00
3832015	Rancangan Pam Paya Pinang	03 50 30	103 15 30
3833002	Pejabat JPS Negeri Pahang	03 48 30	103 19 45
3930012	Sg. Lembing P.C.C.L Mill	03 55 00	103 02 10
3931013	Ldg. Nada	03 54 30	103 06 20
3931014	Ldg. Kuala Reman	03 54 00	103 08 00

2.3 Selection of Rainfall Data

The daily rainfall data over an 11-years period (2008–2019), with a selected interval of 1–7 days, was acquired for this study before the next process to develop isohyet maps using ArcGIS software. Six of the highest daily rainfall events had been selected for each duration once the maximum daily rainfall for that period was assessed, making a total of 42 rainfall events for all rainfall durations.

2.4 Drawing of Isohyetal Lines

Isohyetal method is a technique for calculating the average rainfall over a specific area and it is the most rational way to evaluate the rainfall of a catchment. Based on selected daily maximum rainfall data for 1–7 days from 8 selected rain gauge stations in KRB, including the location of each station, the isohyetal lines for this study were created using ArcGIS software.

The isohyetal lines were constructed via the interpolation method of Inverse Distance Weighting (IDW), which is the simplest interpolation technique that can evaluate unknown values by defining the search distance, nearest points, power setting, and barriers. This method estimates the value of any unmeasured location by considering the measured values in close proximity to the prediction location due to their stronger influence on the predicted value [9]. Moreover, the method assumes that the impact of each measurement point decreases as the distance increases. Using interpolation to create the spatial distribution of the rainfall, the IDW method can be a useful tool for engineers to comprehend and analyze extreme rainfall events [10].

This study utilized the ArcGIS software to conduct the IDW interpolation. Figures 2 and 3 show the developed isohyet map using the IDW method for the selected durations of 1-day and 7-day for events occurring on 1 January 2018 and 20 January 2017, respectively. The maps clearly illustrate that the heaviest rainfall was concentrated in the coastal area and less rainfall was detected in the upper parts of the study area.

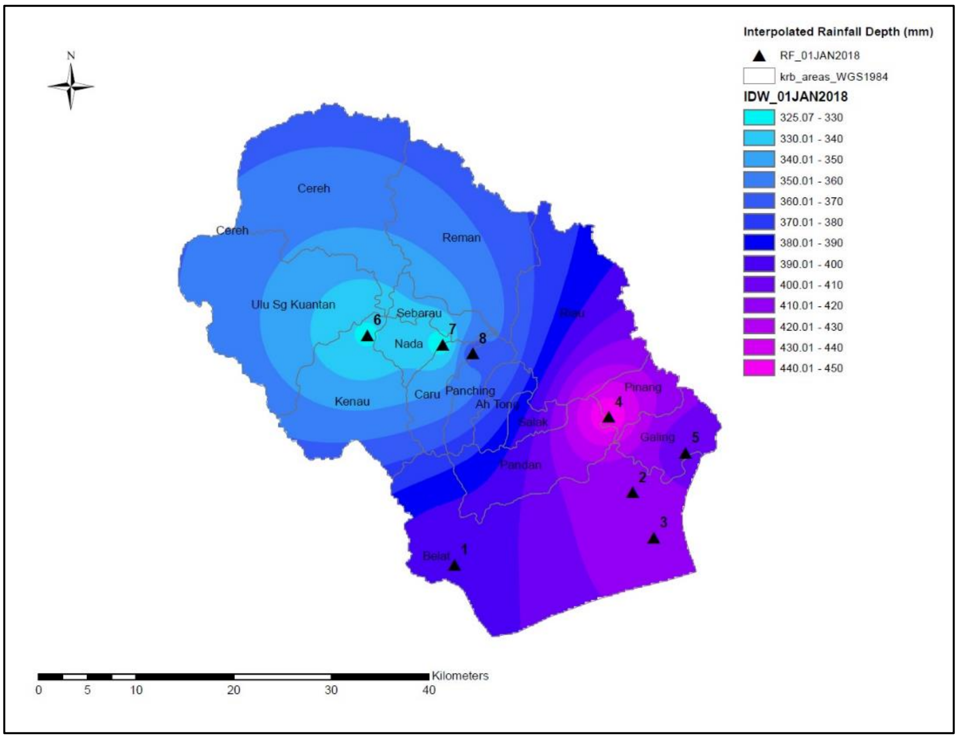

Figure 2. Isohyet map of 1-day (1 January 2018).

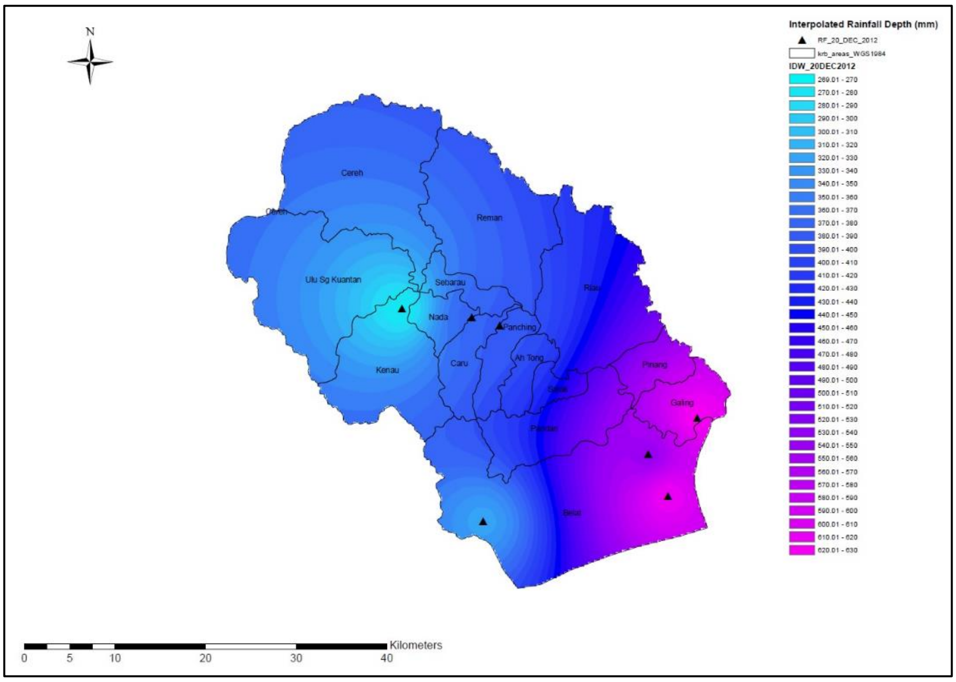

Figure 3. Isohyet map of 7-day (20 January 2017).

2.5 Initial DAD curves

The acquired isohyet maps were used to plot the initial DAD curves, consisting of the calculations of the cumulative area and average maximum rainfall for each rainfall event and duration. The curves were plotted using the cumulative area and the mean of the highest rainfall on the X- and Y-axis, respectively (Figures 4 and 5).

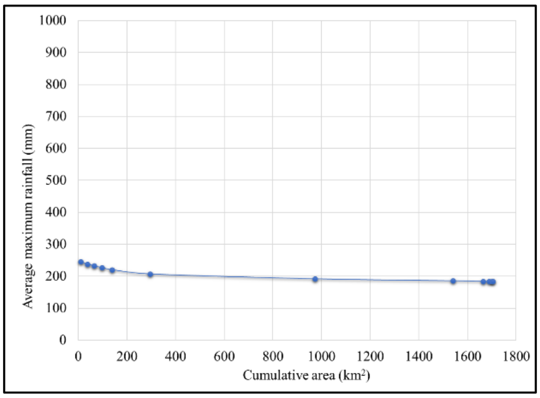

Figure 4. Initial DAD of 1-day (1 Jan 2018).

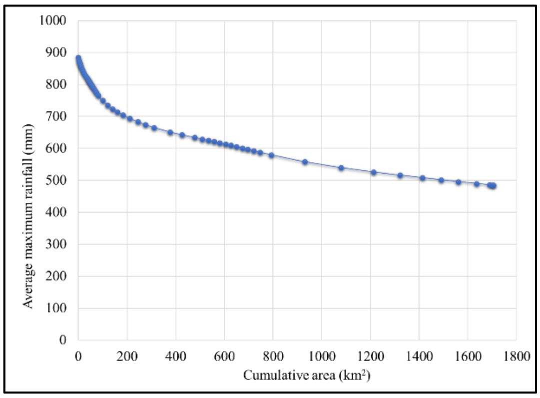

Figure 5. Initial DAD of 7-day (20 Jan 2017).

2.6 Final DAD curves

The set of selected initial values of maximum DAD curves for every specific rainfall duration is known as the final DAD curves. Tables 2 and 3 show examples of maximum rainfall amounts for 1-day and 7-day durations, respectively, after determining the corresponding maximum rainfall for each area covered by rainfall.

Table 2. The value of maximum rainfall of 1-day.

Area (km^2)	Date/Month/Year						Maximum rainfall (mm)
	2.1.2009	3.1.2009	12.1.2012	24.12.2012	24.1.2017	1.1.2018	
10	193.75	206.92	234.21	312.43	394.45	245.03	394.45
20	189.63	204.98	230.39	305.82	388.64	242.33	388.64
50	180.74	199.15	221.85	290.44	378.50	235.15	378.50
100	169.24	192.25	217.64	266.55	368.22	225.90	368.22
200	156.95	188.64	207.26	244.61	351.64	214.47	351.64
400	147.29	181.76	187.12	223.47	325.54	204.30	325.54
600	141.97	176.53	196.65	206.35	306.05	199.53	306.05
800	138.73	172.94	193.00	193.61	289.90	194.75	289.90
1000	135.49	169.60	189.36	184.38	278.79	190.94	278.79
1350	130.64	164.26	186.17	171.61	262.56	187.08	262.56
1700	126.24	158.98	182.72	160.59	251.21	182.80	251.21

Table 3. The value of maximum rainfall of 7-day.

Area (km^2)	Date/Month/Year						Maximum rainfall (mm)
	28.12.2008	20.12.2012	19.1.2017	20.1.2017	28.12.2017	29.12.2017	
10	625.62	624.02	839.89	857.61	668.55	639.10	857.61
20	616.09	620.31	823.42	840.38	661.82	632.21	840.38
50	596.21	612.07	787.85	803.86	647.44	617.58	803.86
100	567.38	601.68	736.26	751.47	632.34	601.93	751.47
200	540.02	580.94	685.15	698.29	616.76	584.94	698.29
400	516.77	540.89	634.69	647.20	600.66	568.83	647.20
600	506.19	503.77	601.34	614.39	589.50	560.15	614.39
800	500.19	476.70	565.76	578.59	580.33	552.46	580.33
1000	494.19	457.00	537.64	549.71	572.64	544.96	572.64
1350	486.50	432.06	502.73	513.75	561.50	533.88	561.50
1700	479.10	410.63	474.81	485.01	551.28	524.28	551.28

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Then, it was followed by creating the final DAD curves as seen in Figures 6 and 7. The covered area by rainfall in KRB is shown on the X-axis and the maximum rainfall values can be observed on the Y-axis.

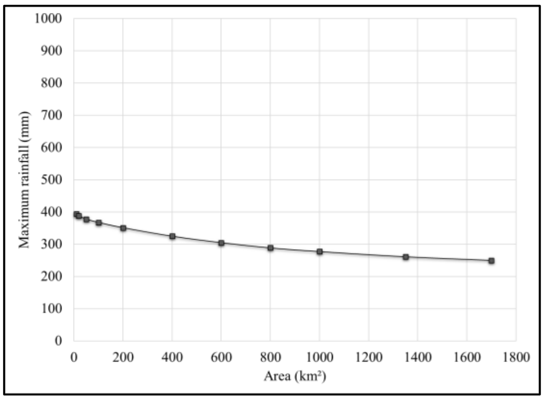

Figure 6. Final DAD of 1-day.

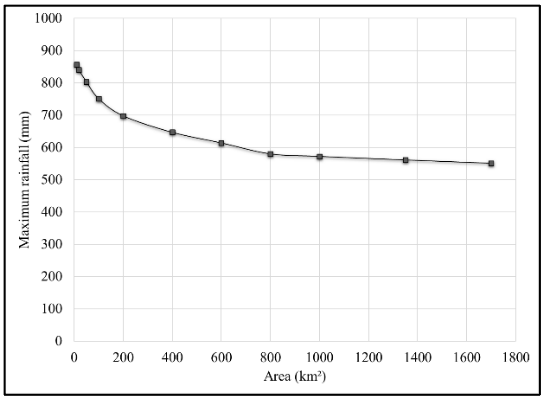

Figure 7. Final DAD of 7-day.

3. Result and Discussion

After the isohyetal lines were created in ArcGIS using the IDW method for 42 maximum rainfall events for all rainfall durations, it was followed by analyzing the average maximum rainfall and cumulative area. Because the maximum value of rainfall was required in this circumstance, the initial DAD curves were utilized to calculate the corresponding quantity of rainfall for each location with the same duration. The maximum rainfall over different time spans and areas is tabulated in table 4.

The maximum rainfall depth for all periods was calculated using the initial DAD curve, and subsequently, the extracted maximum rainfall depth for the corresponding area was utilized to generate the final DAD curves. Figure 8 illustrates the combination of the final DAD curves for each duration.

Table 4. Maximum rainfall depth of each duration.

Area (km^2)	Maximum Rainfall (mm)						
	1-Day	2-Day	3-Day	4-Day	5-Day	6-Day	7-Day
10	394.45	474.42	580.75	605.57	778.25	840.18	857.61
20	388.64	467.00	574.73	602.63	764.16	824.14	840.38
50	378.50	458.43	561.77	595.13	733.15	788.60	803.86
100	368.22	449.52	548.25	585.96	687.41	734.98	751.47
200	351.64	437.52	532.41	572.11	644.15	683.90	698.29
400	325.54	407.83	498.96	537.10	601.56	635.87	647.20
600	306.05	374.64	461.68	497.56	572.56	603.68	614.39
800	289.90	350.21	432.84	466.43	539.27	568.35	580.33
1000	278.79	336.83	411.41	455.43	511.28	538.72	572.64
1350	262.56	318.12	393.45	446.16	476.88	528.78	561.50
1700	251.21	303.87	386.25	438.92	449.09	519.89	551.28

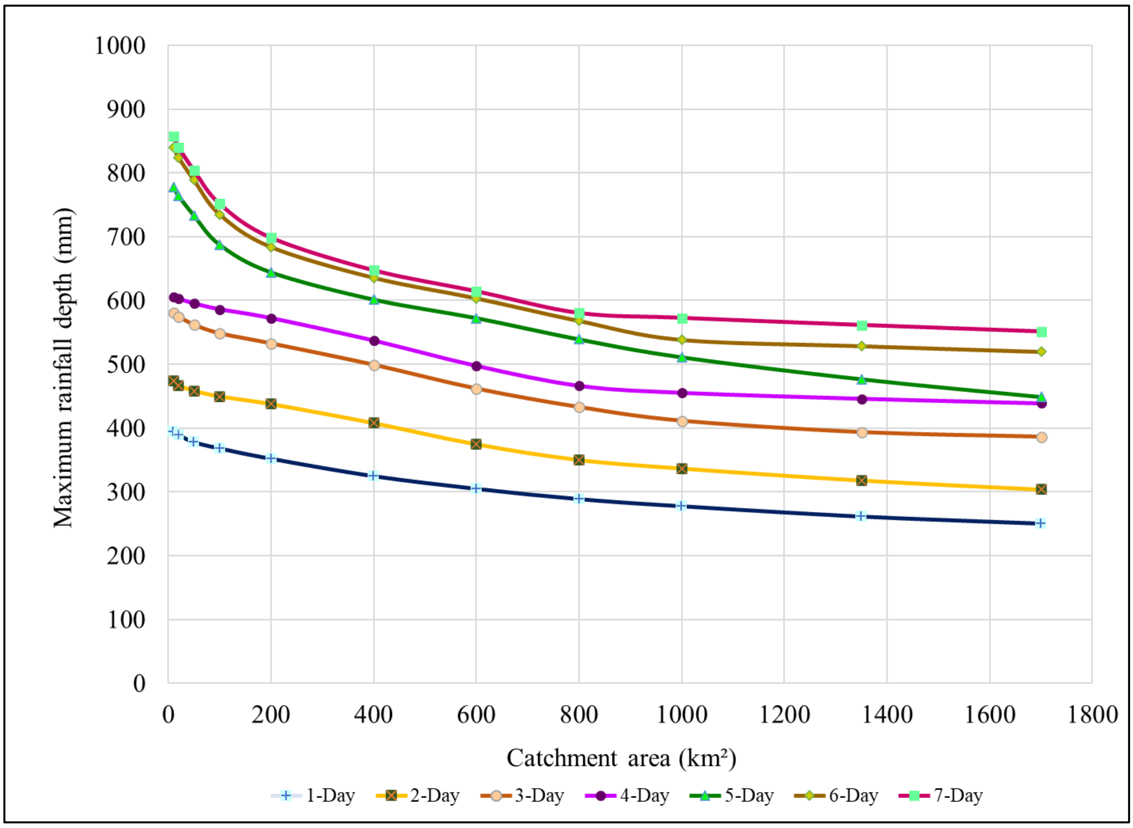

Figure 8. Final DAD curves of KRB.

According to the established DAD curves, the maximum rainfall depth decreases with increasing KRB area. The maximum rainfall depths are 394.45 mm, 474.42 mm, 580.75 mm, 605.57 mm, 778.25 mm, 840.18 mm, and 857.61 mm for the 1-day, 2-day, 3-day, 4-day, 5-day, 6-day, and 7-day durations, respectively. Across these durations, the 10 km^2 area received the most rainfall. The findings also conclusively show that the increase in duration leads to an increment in the maximum amount of rainfall. In comparison to the 1,700 km^2 area, the final DAD curve of the KRB exhibited a 54% larger gap between the 1-day and 7-day duration rainfalls for point rainfall. This indicates that the distribution of rainfall over longer time periods, which frequently results in localized rainfall events for shorter durations, is becoming more stable and producing more rainfall. Furthermore, the gap between 1-day and 3-day is fairly constant while the gap between 4-day and 7-day is not constant. Similar results were demonstrated by the DAD curves for the 6-day and 7-day durations where the curve points were closer together until the 800 km^2 area.

The curves also showed that the 4-day and 5-day durations had a significant difference during the first 10 km^2 to 100 km^2, where the difference reduced from 173 mm to 102 mm. Clearly, the amount of rainfall for 4-day and 5-day periods converged as the area increased. The difference in rainfall also decreased from 172.68 mm for a 10 km^2 area to barely 10.17 mm for a 1,700 km^2 area. Meanwhile, a different trend was detected for 6-day and 7-day durations, in which the amount of rainfall was close to one another for a range area of up to 800 km^2, with an average rainfall difference of 14.23 mm. Nevertheless, for the larger area, the average rainfall difference became slightly higher at a value of 32.67 mm.

In the 1,700 km^2 area, the ratios of point rainfall to average rainfall are 1.57, 1.56, 1.50, 1.38, 1.73, 1.62, and 1.56 for time periods ranging from 1-day to 7-day, respectively. The ratio was shown to decrease as the duration increased from 1-day to 4-day, but it reached its peak at the duration of 5-day and decreased again until the duration of 7-day.

4. Conclusion

In summary, this study has successfully attained the intended objective. The final DAD curves indicate the overall relationship between the depth, area, and duration of rainfall in the study area, which ranged from 1-day to 7-day. IDW interpolation was effectively used to create the isohyet maps for rainfall that occurred over a period of 1 to 7 days, which allowed the researchers to observe the amount of rainfall over an extended period of time in KRB. Assessment of the isohyet maps revealed that KRB received a significantly increasing amount of rainfall from the upper part to the coastal area, which is one of the main reasons for the flood events occurring in the lower part of the study area.

This study also found that if rainfall in a certain location increases over a particular period, it will decrease the maximum area average rainfall. This is evidenced by the initial DAD curves for KRB from 1-day to 7-day whereas the period increases, so does the maximum rainfall depth. Results from the computation of several specific rainfall occurrences also revealed that, at some sites, the average maximum rainfall falls as the area grows. The greatest rainfall on days 4 and 5 was quite distant for the first 50 km^2, while the curve's end was closer than on other curves for the remaining 1,700 km^2. The same thing happened to the DAD curves of 6-day and 7-day durations where the curve points were closer to one another until 800 km^2. Finally, the curves of the DAD analysis can offer important information to determine another hydrological analysis, such as the probable maximum precipitation (PMP) for water resource planning or hydraulic design purposes, especially in KRB.

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