Engineering Infrastructure for Water Resources Development - Impact of Design Rainfall Pattern on Safety Considerations

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Abstract: Safety of the Water Resources Development infrastructure is fully assured only if they are tested for the design flood event of appropriate design return period.

The literature review highlighted the design rainfall pattern as a critical factor for the estimation of design flow. Alternate Block Method (ABM) is considered as a simple and consistent method for estimating design rainfall pattern. The runoff hydrographs, peakflows and time to peak values from a storm event based rainfall distribution and uniform rainfall distribution were compared with ABM estimates for the sub catchments of Attanagalu Oya at four locations. The study revealed that ABM results in the highest peak values compared to Storm Event based and Uniform rainfall distributions. Larger catchment areas display hydrographs of similar shape for all three rainfall patterns. The disparity between the peakflows from the three rainfall patterns becomes lower in larger catchments, indicating 42%, 58%, 62% and 73% peakflow estimates of the ABM estimate, from smallest to largest catchment, with storm event based distribution. The time to peak values from storm event based and uniform intensity distributions indicate an irregular behaviour with the catchment area. In the absence of a proper rainfall pattern that can be used confidently, ABM provides a better and reliable methodology ensuring the safety of the structure. If the rainfall pattern is not selected carefully there will be a threat to the safety of the structure.

Keywords: Water Resources Development, Rainfall Distributions, Peakflow Estimation, Design Rainfall.

1. Introduction

Water resources development is the task of enhancing the availability of water, for human use. Among the many uses of water, the needs such as storage reservoir development for irrigation, hydropower and water supply receive high priority. The long history of water resources development starts with the time when the humans changed from being hunters and food gatherers to developing agriculture and settlements; a change which resulted in harnessing water for irrigation [1]. Development of water storage systems require the design of such systems with appropriate capacity while fulfilling safety requirements of the associated structure, the stored water and the concerned environment.

In Sri Lanka, apart from the large multipurpose reservoirs that primarily cater to hydropower while providing water for major irrigation systems and the large and medium irrigations schemes managed by the Irrigation Department, there are over 35,000 minor reservoirs serving the poor farming communities in the dry zone (Fernando, 1982, [2], Wijsekera, 2010 [3]). Large systems

obviously, due to their large capacities, carry a heavy weightage and the safety therefore, becomes crucial. Though the minor reservoirs in the water scarce dry zone are with smaller capacities, they carry similar importance with respect to safety because of the vulnerable status of the dependent farming community and the sustainability concerns of the surrounding environment. As such, in case of water resources development, safe design of water storage reservoirs is of great importance.

Reservoir safety considerations require to ensure a strong bund section that will be partially tested during impoundment by exercising a gradual exposure to the expected loading. Similarly, the designated safety structure which is the spillway should have a sufficient spill length with the fluxes suitably

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designed in order to prevent overtopping of the bund. The stilling basin should be capable of taming the spill water, while the spill tail requires a careful design to drain the water in a safe manner. Both the spill structure and the embankment would be tested fully only when exposed to the design storm event. Therefore, it is of great importance that the design event is quantified to satisfy the safety objective stipulated for the infrastructure.

The design levels usually, are determined by considering the importance of an infrastructure. Suitable values are usually determined with the help of guidelines. But in case of structures that are of great importance, specific computations are performed using methods such as hydro-economic analysis [4]. Once a design level is established then the design storm magnitude should be determined to arrive at the design hyetograph. The common method is to use the rainfall Intensity Duration Frequency (IDF) relationships. The widely used source for Sri Lankan conditions is the set of curves developed by the Irrigation Department (ID, [5] and Dharmasena and Premasiri, [6]).

The Irrigation Department design guidelines for catchments up to 52 km² [5] recommends the use of a uniform intensity storm for the computation of inflow for spillway designs. Lin, Chen and Kao [7] in a study to find out a method to establish regional design hyetographs indicate that the choice of the

design hyetograph has a significant influence on the shape and peak of the hydrograph. There are many methods to establish a design hyetograph [4]. The Colombo Stormwater Master Plan [8] and the Hydrologic Design of Structures for the Colombo Katunayaka Expressway [9], have used a storm event based pattern. A study of Colombo Harbour watersheds [10] has used the Alternate Block Method (ABM). In the absence of a suitable guideline to adopt the correct rainfall pattern, the practicing engineers, using various rainfall patterns, would arrive at different peakflow estimates for the same catchment and the same return period thus finalising an infrastructure which is either an over design or an under design. An under design would pose a serious problem because the infrastructure would experience the design flood at a time unexpected by the stakeholders. This would lead to a serious concern with respect to safety. Therefore, considering the importance to human life and environment, the present work carried out a study of peakflow estimation for a 100 year design return period rainfall and for three design rainfall patterns. The study attempted to determine the most reliable rainfall distribution to estimate peakflow, in terms of safety of the water resources infrastructure. The comparisons used four catchments in the Attanagalu Oya river basin (Figure 1) located in the western province of Sri Lanka.

Figure 1 - The Four Catchments in the Attanagalu Oya Catchment Cascade

2. Literature Survey

Identifying the time sequence of precipitation pertaining to a design storm requires the analysis of observed storms. Discussing about the temporal patterns of storm events, Institution of Engineers, Australia [11] mentions the use of zoned patterns developed using an approach aimed at conforming with design requirements. Levy et al [12] in their work indicate a recommendation to use a centre loaded distribution based on data from the United Kingdom. Peyron Nguyen, and Rivard [13] developing an optimal design rainfall pattern for Southern Qubec, Canada with a marked single peak and two portions representing water before and after the peak, with 199 critical storm events recorded in the region, mention that there is no accepted guideline regarding the selection of appropriate design storm for a particular site. Evaluating the accuracy of several design hyetographs for the evaluation of peak discharges, Alfierilaio and Claps [14] concludes that all selected methods produce flood peak estimates that are consistently biased; rectangular hyetographs tend to provide significant under estimations; and a centrally loaded hyetograph with a biased estimate was very stable with respect to basin and climatic parameters.

The Stormwater Drainage Plan for the Colombo Metropolitan Region in Sri Lanka (SDPC) [8] covering the Attanagalu Oya, Kalu Oya, Greater Colombo and Bolgoda basins, used a 24 hour design rainfall pattern based on the rainfall event recorded at Colombo on 20th April 1999. In the Hydraulic study for cross drainage structures of Colombo Katunayaka Expressway of Sri Lanka, SMEC [9], has used nine events from Colombo and 8 events from Katunayaka to define "representative" temporal patterns of design storms for 6 durations ranging from 12 hours to 96 hours.

FHWA [15] discussing options for small catchments, indicate the option to use a design storm pattern derived from IDF relationships and equivalent to a relatively short single burst pattern in a longer rainfall with a duration of rainfall equal to the time of concentration for an entire storm drain system.

ABM and Instantaneous Intensity Method [4] are two very similar methods to determine a design hyetograph from IDF curves. ABM is a simple centre loaded method which rearranges the rainfall intensities of a desired time interval into a time sequence with the maximum

occurring at the centre of the required duration and the remaining blocks arranged in descending order to the right and left of the central block. Jain, Singh and Seth [16] in a design flood estimation study, carried out a comparison of the ABM with a modified version incorporating several bell shapes developed on the same principal as the ABM and concludes that the peak characteristics of the design flood are more sensitive to the various storm patterns as well as method of critical sequencing of design storm patterns. AQUA TERRA (2010) [17], in a recent work for the Ventura County of United States has used the ABM which was selected by the Ventura County Watershed Protection District staff in conjunction with the Los Angeles County Department of Public Works, and U.S. Army Corp of Engineers (USACE) Los Angeles District.

Literature review clearly leads to the fact that the design rainfall pattern is a critical factor when estimating the design flow characteristics. Work in most regions, where sufficient studies, using significantly large historical records have been performed, in order to determine critical storm patterns, had opted pattern based methods. Comparative evaluations performed in the research arena shows that comparisons have always considered the selection of a centrally loaded single peak storm which shows a wide spread use of such systems. In the literature, the ABM is suggested as a simple consistent method for estimating the design rainfall pattern. It is interesting to note that, though the literature indicates that the uniform distribution of design rainfall leads to underestimations, it is worthy of evaluation further, because of the recommendations made by the Irrigation Department of Sri Lanka [4]. Though it is stated that ABM leads to conservative designs in literature, the present work focuses on its behaviour with respect to the safety of the structures.

2. Methodology and Results

The main objective of the present work is to study the effect of rainfall patterns on the design flood estimates. In order to compare the evaluations, a 100 year return period was taken as the design level. The four Attanagalu Oya sub catchments selected for the study are shown in Figure 1. Computation of direct runoff hydrographs for comparison of design streamflows was done using the SCS Unit Hydrograph (UH) concept [18]. Parameters of

the catchments used for the development of the Unit Hydrographs are shown in the Table 1. The longest stream of the Elenegoda catchment, which is the largest, was divided into three segments, to represent coastal, mountainous and intermediate areas and the slope of each segment was calculated separately. The catchment slope was then calculated averaging them. An average slope was also computed taking the longest stream as one segment. The slope values from the two methods are 0.32% and 0.31% respectively, with percentage difference of 5%. The average slope from the single segment method was therefore, used for the computations in other catchments. As the catchment sizes increased, the average slope values decreased, while the longest stream lengths increased. The time of concentration was computed using Kirpich Equation [4] and the values showed a steady increase with increasing catchment area and the stream length. The design rainfall pattern of 24 hour duration that has been identified for catchments including Attanagalu Oya by SDPC [8], was selected. This temporal distribution was the only available design rainfall pattern in the documents that could be accessed during the literature survey. In addition, the Uniform Distribution recommended by ID [5] and ABM, which is considered as a simple consistent method were selected for the comparative computations. Considering the rainfall event time of 24 hours, a 60 minute temporal resolution was selected to generate the design streamflow hydrographs. Accordingly, one hour unit hydrographs were developed for all four catchments (Figure 2). System mass balance was checked twice during the computations. The area under the developed Unit Hydrographs was checked for unity [19] and the adjustments were carried out proportionate to the ordinates. The area under the direct runoff hydrographs was also checked with the total depth of design rainfall of the event.

Figure 2 - One hour Unit Hydrographs for the Four Catchments

Attanagalu Oya catchment is in the Hydrological Zone III [5]. IDF relationship developed by the Irrigation Department [5] was used to compute the rainfall intensity and then to compute the design rainfall events based on the said patterns. The rainfall patterns pertaining to ABM, SDPC [8] and Uniform Intensity (UI) are shown in Figure 3. The curvilinear hydrographs for the design storm corresponding to each catchment are shown in the Figure 4. Peakflow values for each catchment are indicated in Table 2, Figure 5 and 6. The relative ratios of the peakflows of UI and SDPC relative to ABM, calculated using Equation (1), are also indicated..

$$\% \text{ Ratio} = \frac{\text{Peakflow from SDPC or UI}}{\text{Peakflow from ABM}} \times 100 \dots\dots (1)$$

Time to Peak (T_p) values were computed and the results are in Table 3, where the respective values from each method for each catchment are given (Figure 7). Relative Changes with respect to the ABM, calculated using Equation (2), are also in Table 3 and Figure 8.

$$\text{Relative Change} = \frac{[T_p(\text{UI or SDPC}) - T_p(\text{ABM})]}{T_p(\text{ABM})} \times 100 \dots\dots (2)$$

Table 1 - Summary of Catchment Parameters

	Catchment of Attanagalu Oya at			
	Karasagala	Attanagalla	Gampaha	Elenegoda
Area (km ²)	53.36	172.05	378.92	715.27
Longest stream Length (km)	9.741	23.684	37.775	56.871
Elevation Difference (m)	140	150	170	175
Slope (%)	1.44	0.63	0.45	0.31
Time of Concentration (hours)	1.96	5.32	8.69	13.79

4. Discussion

4.1 Behaviour of the Peakflow

Estimation of peakflow is a key concern when designing engineering infrastructure for water resources development. The present study focused on meeting the safety consideration of such structures. This work identified the selection of the design storm pattern as a critical activity in the design sequence. Peakflow estimates from a 100 year return period and 24

hour duration design rainfall were compared with UI, ABM and SDPC distributions and found to have a significant difference.

From Figure 5, it is clear that ABM gives the highest peak values compared with the peaks from the other two rainfall distributions. The lowest peakflow value is given by the UI while an intermediate peak value is given by SDPC.

The concentration of higher percentage of the design rainfall depth at the centre of the rainfall distribution in the ABM leads to a higher peak. In the other two distributions the rainfall depth is either distributed uniformly or scattered with several peaks. This factor therefore, leads to lower estimates of peakflows from UI and SDPC distributions.

4.2 Shape of the Hydrographs and the Catchment Area

In order to assess the variations of the outputs with catchment area, sub catchments of Attanagalu Oya at four locations were taken for the study. The selected areas increase by 3.2, 7.1 and 13.4 times with respect to Karasagala sub catchment. Though, there are several factors that affects the shape of the hydrograph and the time to peak, such as catchment area, slope and the length of the longest watercourse, according to literature, it expected that these factors are proportional to the catchment area. As expected, peakflow values from all three methods increase with the increase of catchment area. UI displays a flat peak runoff hydrograph shape for smaller catchments.

Variation of the rainfall distribution is also prominently reflected in the runoff hydrograph when the SDPC distribution is used. When the shapes of the runoff hydrographs are considered, ABM has a consistent shape. In case of the catchment at Elenegoda, which is the largest of the selected catchments, a single peak hydrograph is observed, though there are several peaks in the SDPC rainfall distribution.

The reflection of the rainfall pattern variation in the streamflow peaks diminishes with increase of the catchment size.

The longer response time of the lumped UH approach, the assumptions of the uniform rainfall over the entire catchment can be stated as the major attributes for this response.

4.3 Behaviour of the Peakflow Magnitude
SDPC and UI distributions indicated an approximately linear variation with catchment area (Figure 5). ABM indicated a reduction of

the rate of change of the peak discharge when compared with the peaks from the other two distributions as indicated in Figure 6. It is apparent from Figure 5 that the difference of the peak discharges from the UI and SDPC distributions is increased with the increase of catchment area. However, when the peakflows from the SDPC and UH distributions relative to the ABM, is considered, the disparity becomes lower for larger catchments as depicted by Figure 6. The peakflow percentage of the ABM estimates are 42%, 58%, 62% and 73% from the smallest to the largest catchment, with SDPC distribution.

4.4 Behaviour of Time to Peak

In contrast to the peakflow magnitude, the behaviour of time to peak (T_p) reflected a contrasting behaviour with respect to each pattern. Computations showed an increase with the increase of catchment area but the rate of increase varied with the pattern. The ABM showed a steady increase where as the other two indicated varying reactions.

The time to peak variation among the catchments showed that the UI pattern except for Karasagala, resulted a longer time than the ABM. In case of SDPC, the time to peak was earlier than the ABM, except for Elenegoda catchment, where both occurred at the same time.

4.5 Selection of the Rainfall Distribution

The selection of rainfall distribution is critical for the design of engineering structures associated with Water Resources Development. However, a proper guideline for Sri Lanka can not be found to select the design rainfall pattern.

The recommendation for the usage of a uniform rainfall distribution, for Sri Lankan catchments, is for small catchments of size less than 52km²[5]. In the present work, the smallest catchment considered is also greater than 52km². The two hydrological studies carried out by SMEC [9] and Nippon Koei [8] use storm event based patterns. In the study by SMEC [9] there are several indications to be understood that the data sets need to be enhanced or improved. It is important to note that, as at present, there is a lack of observations or work to verify the correct rainfall distribution for designs. Therefore, a comparative evaluation would facilitate an infrastructure designer.

If ABM is the best estimate to represent a target design level, then by using either SDPC or UI for designs would lead to a structure capable of catering to a lesser design level. In case of catchment at Elenegoda, the SDPC would cater only to a 73% (Table 3) of the peakflow that would result from ABM. This leads to a situation of serious concern with respect to safety. This situation would therefore, lead to either overtopping or upstream inundations or both.

If the SDPC or UI distributions are suitable and a structure is designed using ABM, then the design would satisfy safety and drainage although the structure is over designed.

As far as the safety of the engineering structures for water resources development is concerned, there is a risk of using storm event based pattern and uniform distributions for peakflow estimation due to their unreliability. The safety of the structure is always assured when ABM is used, since ABM always results the highest peak discharge as shown in Table 2.

Table 2 - Peakflow Magnitude Ratios with Selected Rainfall Patterns

	Peak Discharges (m ³ /s)			% Ratio Relative to ABM Estimate	
	ABM	SDPC	UI	SDPC	UI
Karasnagala	933	388	152	42%	16%
Attanagalla	1654	959	492	58%	30%
Gampaha	2572	1588	1081	62%	42%
Elenegoda	3425	2514	1967	73%	57%

Table 3 - Time to Peak Values in hours with Selected Rainfall Pattern

	Time to Peak (hours)			% Change Relative to ABM Estimate	
	ABM	SDPC	UI	SDPC	UI
Karasnagala	13	10	9	-23%	-31%
Attanagalla	15	11	19	-27%	27%
Gampaha	17	13	24	-24%	41%
Elenegoda	21	21	25	0%	19%

Figure 3 - 24 hour Rainfall Patterns for 100 Year Return Period

Figure 4 - Curvilinear Hydrographs Corresponding to Each Design Storm Catchment

Figure 5 - Peakflow Change with Rainfall Pattern

Figure 6 - Peakflow Change with Rainfall Pattern Relative to ABM

Figure 7 - Change of Time to Peak with Catchment Area

Figure 8 - Relative Changes of Time to Peak with Respect to ABM Estimates

5. Conclusions

1. Uniform Intensity and Storm Event Based Rainfall distributions result in lower peakflow values when compared with the estimates from the Alternate Block Method (ABM).
2. The shape of the rainfall distribution pattern is not prominent in the runoff hydrographs for larger catchment areas and they display hydrographs of similar shape for all three rainfall distribution methods.
3. If the rainfall pattern is not selected carefully there will be a threat to the safety of the engineering structure in Water Resources Development. Therefore, if a pattern based method is use, then a sufficient sample should be studied to determine the design pattern.
4. The disparity between the peakflows from the three rainfall distributions becomes lower in larger catchments, indicating 42%, 58%, 62% and 73% peakflow estimates of the ABM Estimate, from smallest to largest catchment, with the storm event based distribution.
5. The time to peak from the pattern based and uniform intensity examples show an irregular behaviour with respect to the catchment area. In comparison, the ABM reflects a better variation.
6. When the safety of the water resources development infrastructure is concerned

the ABM provides a better and reliable methodology in the absence of a design rainfall pattern that could be used with confidence.

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