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# Mathematical Modelling of Watershed Runoff Coefficient for Reliable Estimations to meet the Future Challenges of Water Resources Development in Sri Lanka

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**Abstract:** Major purpose of water resource development is to enhance water availability. These activities which faces a huge competition requires careful assessment of water reaching a particular point of interest. In this regard runoff coefficient is a quick and popular tool among water engineers and planners. Although the event runoff coefficient provides a simple and clear indication, only limited work could be found on event based or watershed characteristic based runoff coefficient estimates. Present study used event and base flow separations to capture runoff coefficients for selected events and then to develop a regression model for estimation of watershed runoff coefficients. Incorporating the influence of event rainfall, antecedent wetness and average rainfall intensity as independent variables, the model was calibrated and verified the model using 54 events of Attanagalu Oya watershed at Karasnagala (52.6km$^2$). Model performance was very good with Mean Ratio of Absolute Errors showing values of 0.3942 and 0.3567 during calibration and verification respectively. Model coefficients indicated that the influence of antecedent conditions was approximately one order of magnitude lower than that of the other two. This model provides water resources developer with opportunity to make better estimates, identify changes to a watershed by observing changes to runoff coefficients, and also to arrive at future research needs. Present runoff coefficient modelling incorporating a systematic calibration and verification process demonstrates the applicability of the method to any gauged watershed irrespective of its location.

**Keywords:** Event Runoff Coefficient, Baseflow, antecedent, rainfall, intensity, mathematical modelling

## 1. Introduction

The objective of water resources development is to enhance the water availability for use as a resource. The major purposes include human requirements such as Irrigation, hydropower, drinking, fishery, environmental sustenance and recreation. Water resources development has a long history in capturing, controlling and transporting water for irrigation and hydropower engineering. The first successful efforts to control the flow of water had been in Egypt and Mesopotamia [1]. In the efforts to capture and store water for various purposes it is necessary to evaluate water availability at a particular location. In the early days when water and land were in abundance, the water resources development was seen as a resource to be developed and was done basically unilaterally. Most developers local and international now realise that these efforts need to be looked at from the point of view of integrated resource development. Rapid population increases requiring more water for consumption and together with the increased awareness of water rights, the water resources developers face an immense challenge to satisfactorily evaluate the water availability for development and especially with the water that are involving transboundary issues [2]. Braga, Salati, & Mattos, [3] carrying out a water resources development study have taken a critical look at the options in terms of its ecological system, legal and institutional framework highlighting the importance of very good water quantity assessments in the light of cooperation treaties. Though Sri Lanka does not have international transboundary issues with respect to freshwater, in future with the most likely scenario of full devolution of power, there is a strong likelihood for the need of transboundary water treaties. The first and foremost assumption in all agreements and treaties is that the water resource quantifications are done to an acceptable accuracy so that rational distribution among a spectrum of stakeholders can be performed with suitable methods. Therefore, determination of surface runoff from a watershed due to a particular storm, and hence the runoff coefficient, becomes a major component in hydrologic analysis and design of water resources development. Most commonly

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used method is to use a runoff coefficient to compute the surface flow or the direct runoff generated from the rain received at the catchment. The determination of runoff coefficient is not a precise task. It is generally known that runoff coefficient is dependent on the rainfall, watershed slope, soil and land cover/use. The methods available to compute the value of runoff coefficient for a watershed are based on guidelines and in this context, there are only very limited research reported with respect to Sri Lanka. The present work is to identify the direct runoff from observed hydrographs and then to estimate the runoff coefficient for the Attanagalu Oya watershed at Karasnagala gauging station.

## 2. Literature Survey

Though the common definition of a runoff coefficient is that it is the ratio of the peak rate of direct runoff to the average intensity of rainfall in a storm, it can also be defined as the ratio of runoff to rainfall over a given time period[4]. Savenije [5] working with the annual cycle, state that since the runoff coefficient is widely mapped, it is a very simple and very useful parameter to evaluate the degree of recycling of moisture, the change over time of the recycling of moisture in a catchment, and also to monitor the change over time to capture land degradation. Longobardi, Villani, Grayson, & Western [6] considering runoff coefficient as the ratio between quick flow and rainfall volume on an event basis, have found that the antecedent conditions, pre-event soil moisture and pre-event base flow are well correlated to runoff ratio from humid catchments. Viglione, Merz, & Biö schl[7] in a study of runoff coefficients and return periods, identified the importance of both antecedent conditions and the storm characteristics on the runoff coefficient within a dry and wet framework. Merz, Bloschl, & Parajka[8] form a study of event runoff coefficients of 459 Austrian catchments with the area ranging from 5-10,000 km$^2$, and for the period 1981-2000 (~64,000 events) concluded that while climate and antecedent soil moisture are very important in controlling the runoff coefficients, land use, soil types and geology do not seem to exert a major control for the climates and catchment scales examined. Perera & Wijesekera [9] developed a Geographic Information System (GIS) based streamflow model for three Sri Lankan watersheds by considering the runoff coefficient of the Rational Formula [10] as a function of land cover, soil and slope. In this work the authors also report a survey of guidelines to estimate the runoff coefficient of land parcels and have computed composite runoff coefficients for Kelani, Kalu and Attanagalu Oya watersheds. Wijesekera [11] reviewing over 100 research papers on surface water resources in Sri Lanka to capture research gaps and priorities has identified that research directly linked to the functionality of water data and information systems is at an early stage of development and the review did not find any studies on rainfall-runoff ratios relating to watershed land cover. Therefore focused research is necessary in order to strengthen the identification of rainfall contribution to surface runoff along with its spatial variation at a scale meaningful for Sri Lankan applications.

## 3. Methodology

Literature review makes a clear direction that the event runoff coefficients of a watershed depend on the storm characteristics such as its amount and intensity, along with the antecedent conditions of the catchment. However the relationships observed in the reported work does not provide clear functions between such factors so that an engineer could make use of the values for designs at least for the studied basins. Therefore it is important to note that the stated responses provide a direction for watershed based case studies to arrive at specific coefficients and relationships. Once a sufficient number of watersheds are analysed then it may be possible to find relationships that could be used for ungauged watersheds. Though the work of Perera & Wijesekera [9] for Sri Lankan watersheds, provide opportunity to compute runoff coefficients for the Rational Method based on spatially distributed watershed characteristics, the estimation of event based runoff coefficients requires an analysis based on observed rainfall events and streamflow hydrographs. In the absence of a clear guide on the runoff coefficient determination for Sri Lankan watersheds and considering the importance of the requirement to enable rational water resources management, the present study used daily rainfall and streamflow data of Attanagalu Oya at Karasnagala from 1971-1981 for the analysis. In this work, the event runoff coefficient was taken as the ratio of the direct runoff to rainfall pertaining to a particular rainfall event.

Attanagalu Oya is draining from the hilly regions of Kegalle District in Sri Lanka, towards the west coast of the island (Figure 1). The

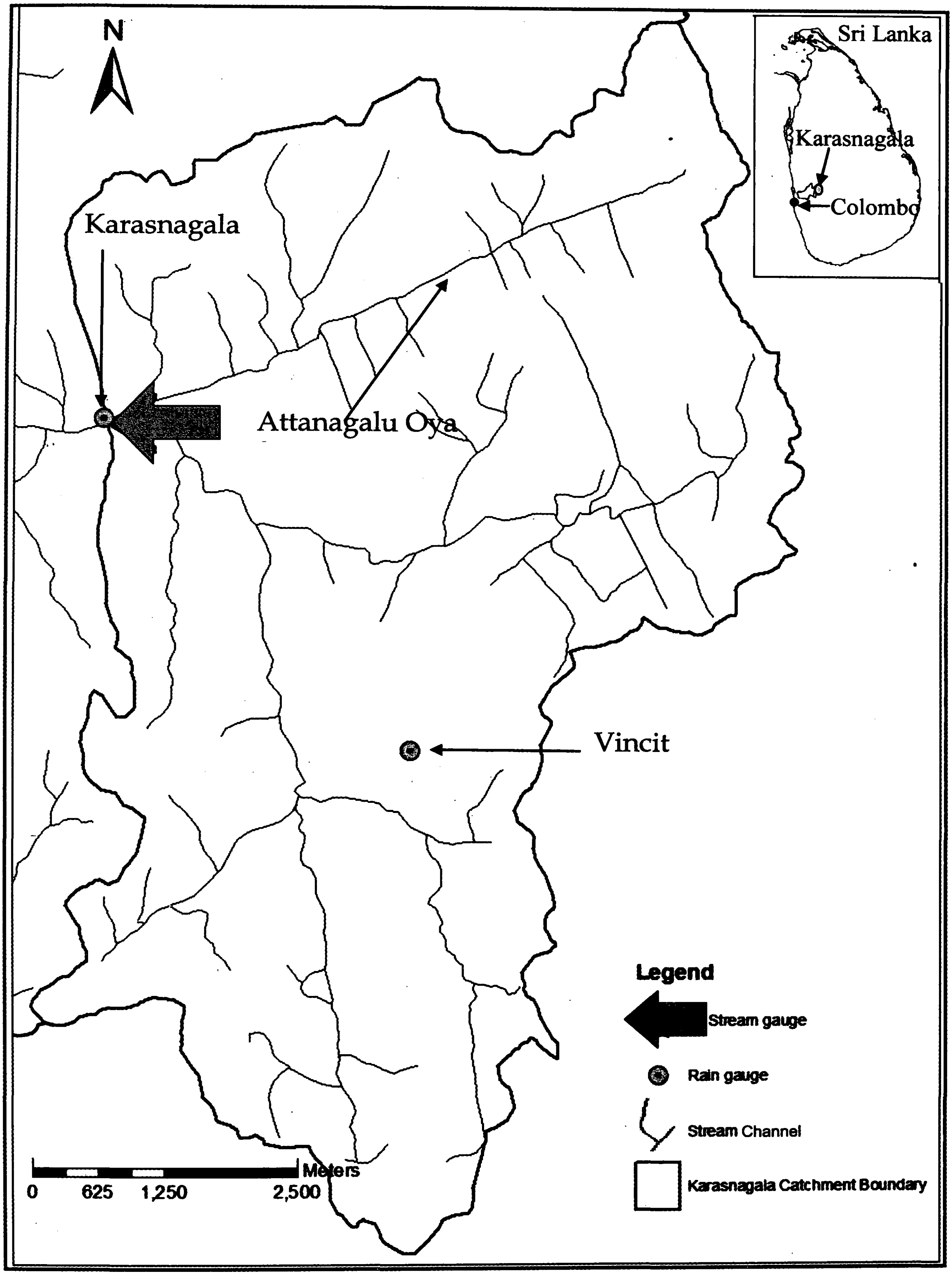



**Figure 1- Attanagalu Oya River Basin and the Watershed at the Karasnagala Gauging Station**

watershed at Karasnagala covers a spatial extent of 52.6km$^2$. There are two rain gauges at Karasnagala and Vincit which are in the vicinity of the catchment. Thiessen averaging which is the most commonly opted method [12] for the computation of areal average rainfall was used to determine the rainfall input for the analysis.

Since the event runoff coefficient relates to direct runoff, base flow was separated using the concave method [13]. A graphical method was used for the event baseflow separation because of its simplicity [14]. The concave method was chosen considering its representativeness to the conceptual behaviour of surface and groundwater runoff [15].

Event separation was carried out by first separating the rainfall events. Though the literature recommends a Minimum Inter-event Time (MIT) between 3min to 24 hours [16] for hourly resolution data, there is a lack of indication for data of daily time resolution. In the present work, the event separation recognised that the response time of streamflow from a one day rainfall event should be taken as the basis for capturing the MIT. Guidance for the response time of a one day rainfall can be obtained from the time base of a one day Unit Hydrograph (UH). Using the UH method [17] it was identified that the time base for a one day UH for Karasnagala catchment is 4 days. Therefore for the present work, MIT for rainfall was taken as 4 days. Rainfall events were carefully screened by considering the inter event time periods and the possibility of graphical base flow separation without much subjectiveness. Time point at which the streamflow hydrograph indicated a response to the first rainfall input was identified as the starting point of the event. The end point of the direct runoff of streamflow hydrograph was taken by identifying the inflection point on the baseflow recession curve. End point of an event was captured with the same consideration of MIT. In the present work, the representative antecedent condition taken was the rainfall received in the 30 days prior to the starting point of the event. It was assumed that soil moisture content is directly proportional the rainfall received during 30 days prior to the starting point of the event.

Separated event data were first plotted to capture any visible behaviour pattern. Scatter plots were done for the parameters of significance as suggested in the literature. A simple regression model as shown by the equation (1) was developed to calculate the Event Runoff Coefficient (ERC) using (i) event rainfall (TRF), (ii)antecedent rainfall of the 30 days prior to the starting point of the event (ARF) and the (iii)event rainfall intensity (RFI). In this, TRF and ARF are in mm and TRF is in mm per day. Accordingly, linear coefficients $m_1$, $m_2$ and $m_3$ respectively are with units of mm$^{-1}$, mm$^{-1}$ and day mm$^{-1}$.

$$ERC = m_1 \times TRF + m_2 \times ARF + m_3 \times RFI \text{----------} \quad (1)$$

The separated events were then divided into two sets as calibration and verification. Parameter optimisation was done with Mean Ratio of Absolute Error (MRAE) [18][19] as the objective function.

## 4. Results and Discussion

### 4.1. Parameter Behaviour

57 events were separated from the rainfall and streamflow time series for Karasnagala. Two typical cases representing the base flow separation of a single peak event and a multiple peak event are shown in the Figure 2. During data checking three events with non representative rainfall streamflow behaviour was identified and was removed from the analysis. It was felt that this observed response could be related to a deficiency in capturing the spatial variability of rainfall. Rainfall durations varied from 5 to 62 days with an average of 25 days. Concave method of separation captured the base flow ordinates and accordingly the direct runoff components. Runoff coefficients for each event was computed and were plotted against the total event rainfall (Figure 3), cumulative rainfall of 30 days prior to the starting point of the event (Figure 4) and the average rainfall intensity during the event (Figure 5). Runoff coefficient demonstrated an increase with the increase of both the event rainfall and the average intensity. The results indicated an encouraging linear behaviour of runoff coefficient with lower values of event rainfall and its average intensity. However at higher values of both these factors, a wider scatter of results could be observed. Contrary, to the widely reported observation of an increasing event runoff coefficient with increasing antecedent watershed moisture level, the Figure 4 did not show a direct relationship.

### 4.2. Calibration and Verification

Model parameter optimisation used 30 rainfall events for calibration and 24 events for verification. Optimized values of $m_1$, $m_2$ and $m_3$ are 0.0004, 0.00007 and 0.00417 respectively. MRAE for calibration was 0.3942, while the same for verification was 0.3567. The comparison of runoff coefficients computed from the observed hydrographs and the model during calibration and verification is shown in the Figure 6. The data set used for the Calibration has shown the possibility of a few outliers while the verification dataset has shown a better behaviour as shown by the MRAE values. Though the observed runoff coefficients in the calibration data set have even reached 0.7, the modelled value has not exceeded 0.5.

### 4.3. Parameter Behaviour

Values of TRF, ARF and RFI of an event, in the units used for the model had their respective mean values at 887, 727, and 30. This indicates that the coefficients of TRF and the RFI represented a relationship having the same order of magnitude while the ARF represented a relationship approximately one order less than the coefficients of TRF and RFI. The optimised parameters for the linear model to predict event runoff coefficients indicated a significant influence from the antecedent rainfall though it was not evident in the simple mapping that was done at the beginning of the study to capture relationships. The spatial distribution of rainfall was considered using Thiessen averaging technique and the event separation was done with the use of MIT values guided by the Unit Hydrograph development methods and concepts. Though such techniques had been in practice for over many decades, it is important to compare the model results with variations that are can be observed at the field level when such computations are practiced. The method of derivation of runoff coefficients in this work enables a water resources developer to observe the changes to runoff coefficients over time. Since the catchment characteristics and runoff coefficients relationships are reasonably conceptualized, any change in behaviour can be investigated to identify catchment changes. This provides very important information to incorporate suitable watershed management activities.

### 4.4. Quantity Estimation

In this work which needs field observations to develop the runoff coefficient model facilitates a water resources developer to plan, develop and manage water resources of the Karasnagala watershed. In practice, the Rational formula with the use of an estimated runoff coefficient is widely used for the peak flow computations. Peak flows are very important for drainage design. However for a water resources developer attempting to estimate the quantity of flow has to either use the same estimated runoff coefficient or otherwise convert the peak flows to hydrographs. The ambiguities in runoff estimation with respect to data in guidelines and the need to convert rational formula computations cause difficulties in arriving at reliable water quantity estimations. The present work through the calibrated and verified model provides a better and direct estimation of streamflow quantities from a given rainfall event. The methodology presented in this work can be easily applied to gauged watersheds and hence would be of immense value to rational watershed management activities. Many such applications would enable the researchers to develop guidelines for similar watersheds.

### 4.5. Research Directions

It can be noted that runoff coefficient tables such as in Chow, Maidment, & Mays, 1988 [4] for peak flow estimation using rational formula, embed the influence of rainfall intensity through the incorporation of return periods. Therefore watershed runoff coefficients not only vary with land cover, slope and soil but also on event return period. In contrast to this, the present modeling work enables an engineer to design a particular return period storm and then capture the associated runoff coefficient through the model by making reasonable assumptions for antecedent rainfall values. By comparing the values of model and the values computed from literature cited tables using catchment parameters, it is possible to arrive at better insights to the behaviour of catchment parameters and associated processes, thus opening future research directions.

## 5. Conclusions

1. Baseflow separation of observed hydrographs enables the computation of direct runoff generated within a watershed. In the present work, a linear conceptual model assuming that the most influencing

parameters to predict runoff coefficients are rainfall quantity, rainfall intensity and the antecedent rainfall enabled a very good reproduction of runoff coefficients from the observed direct runoff hydrographs of the Karasnagala watershed.

2. Runoff coefficient modelling results for the Karasnagala watershed showed that the antecedent rainfall has an impact of one order of magnitude lower than the characteristics of the rainfall event.

3. Though a good matching of the model outputs during calibration and verification was displayed by the respective MRAE values of 0.3942 and 0.3567, more work on the methods of evaluating the spatial variability of rainfall, and the event separation would lead to better performance of the model.

4. The determination of a linear model and its parameters enable a developer to not only evaluates the expected water resources in the Karasnagala watershed but also to evaluate watershed behaviour if changes to the prevailing patterns are observed.

5. Observed event based runoff coefficient model is a very useful approach which provides a better opportunity to compute runoff quantities when compared with the use of literature reported guideline values. This systematic methodology enables practitioners to carryout application to other gauged watersheds.

6. Computation of runoff coefficient of this model with known estimates provides the opportunity to study the behaviour of watershed parameters and processes facilitating future research.

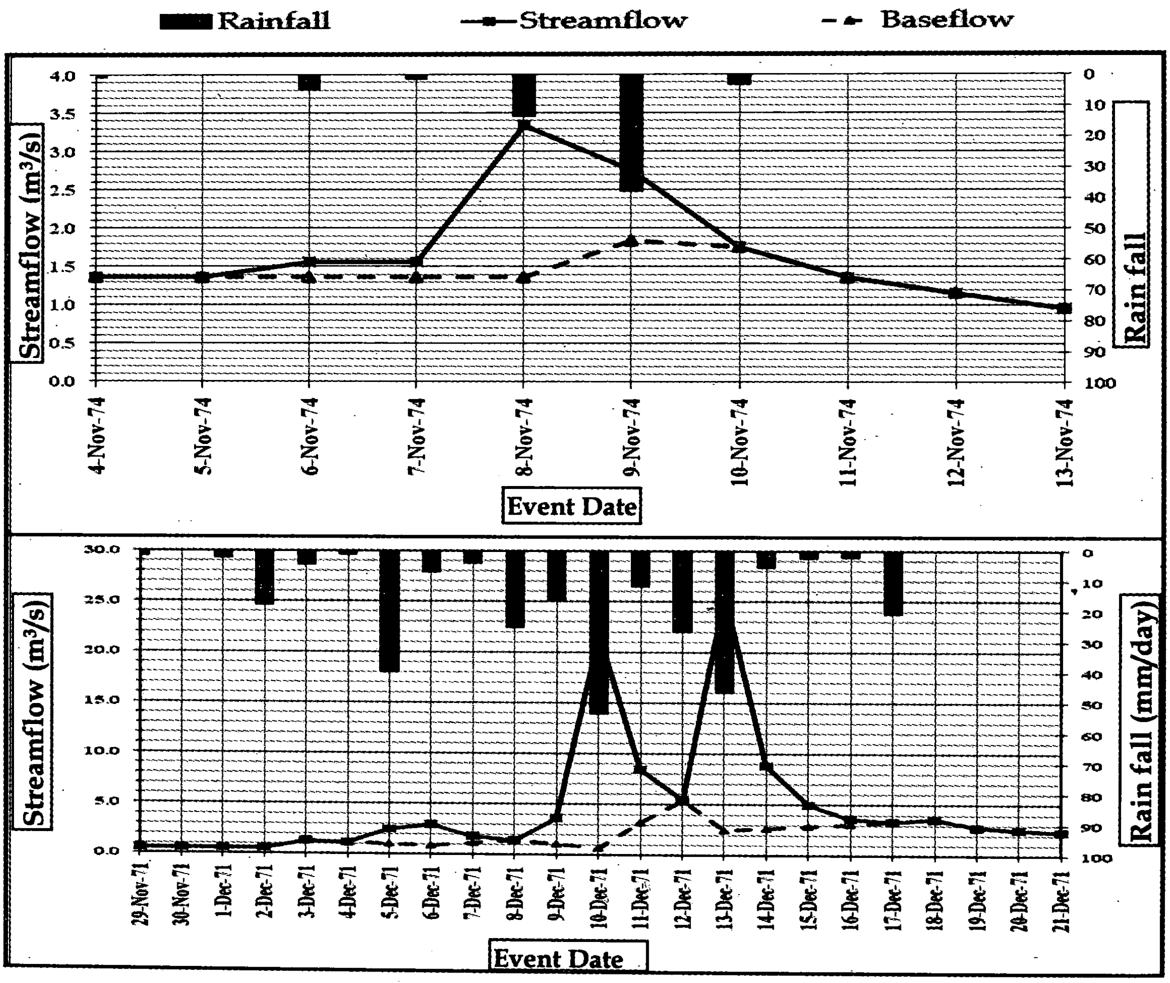



**Figure 2- Two Events Displaying the Rainfall, Streamflow and Separated Baseflow**

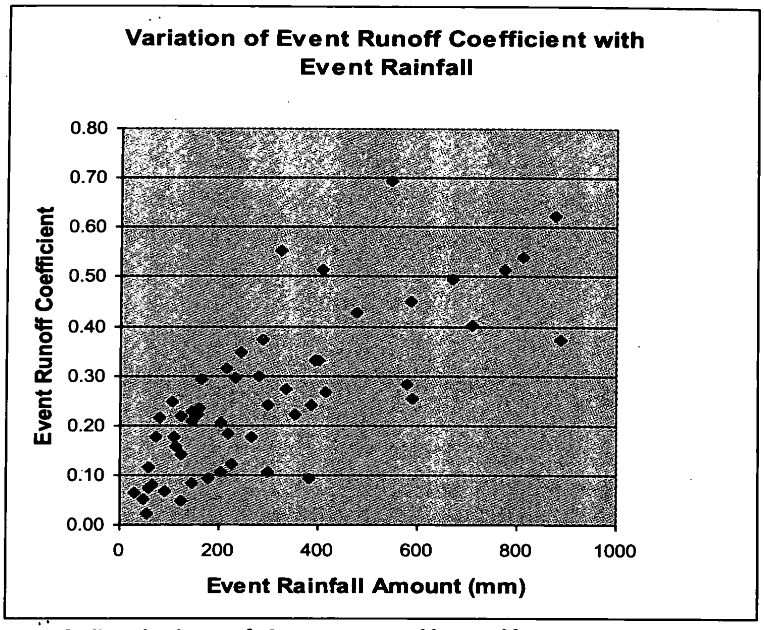



Figure 3- Variation of Event Runoff Coefficient with the Event Rainfall

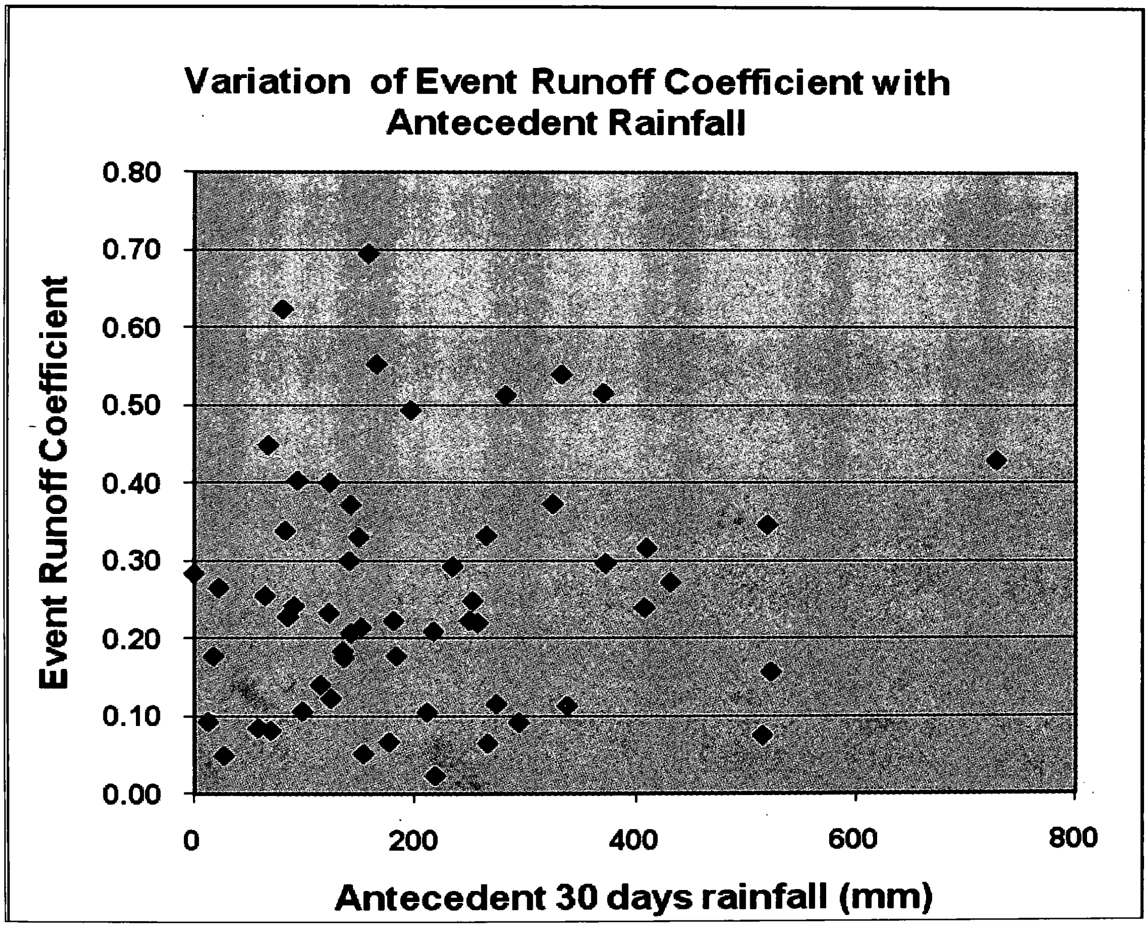



Figure 4- Variation of Event Runoff Coefficient with the Rainfall received 30 days prior to the Event

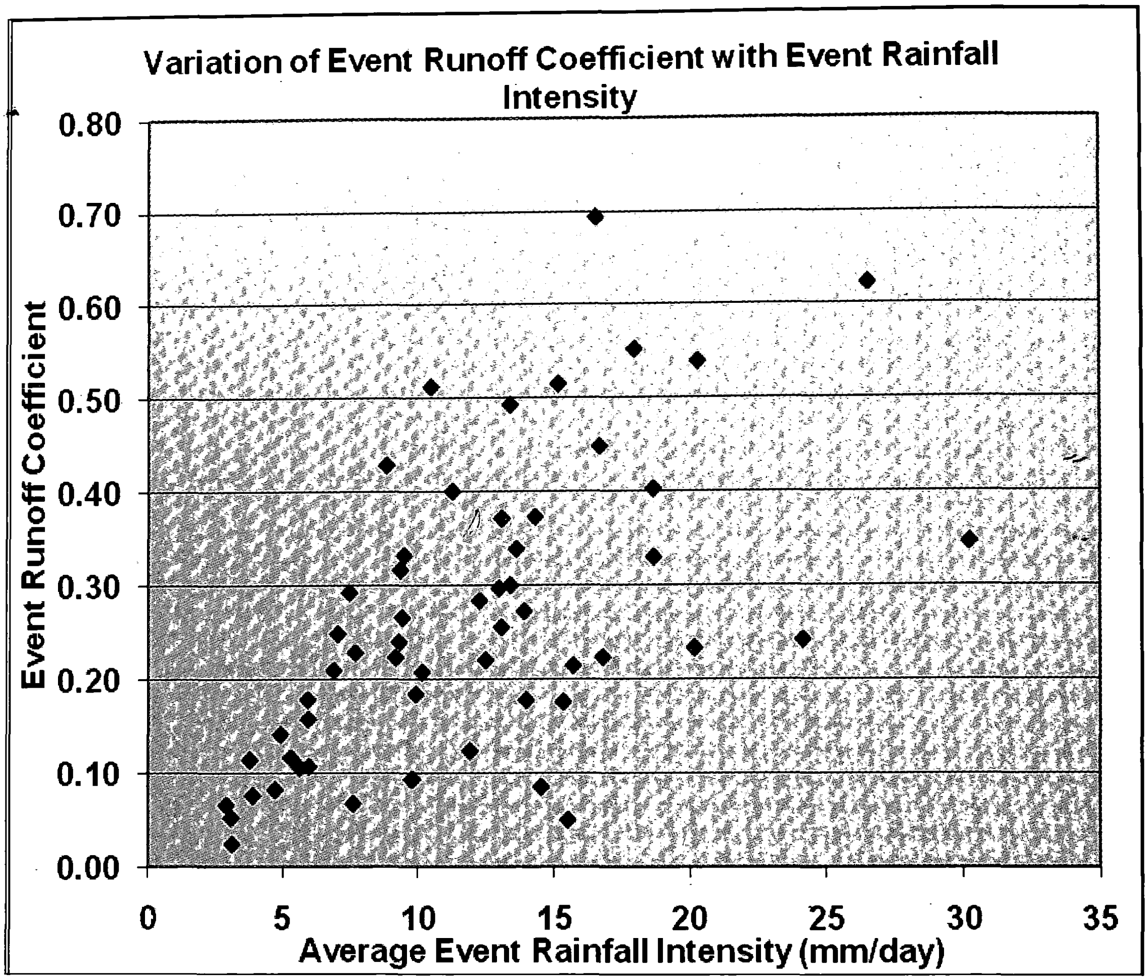
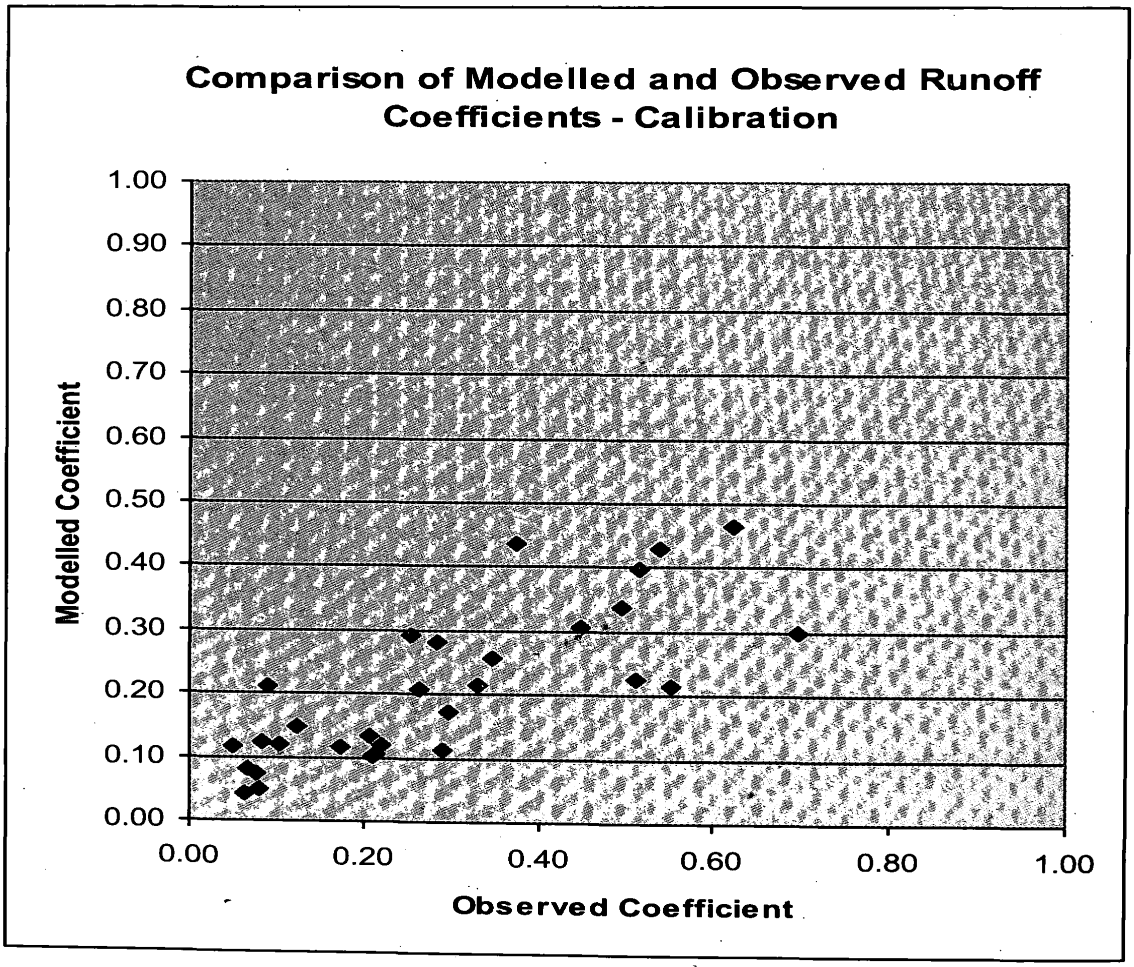



Figure 5- Variation of Event Runoff Coefficient with the Average Rainfall Intensity of the Event



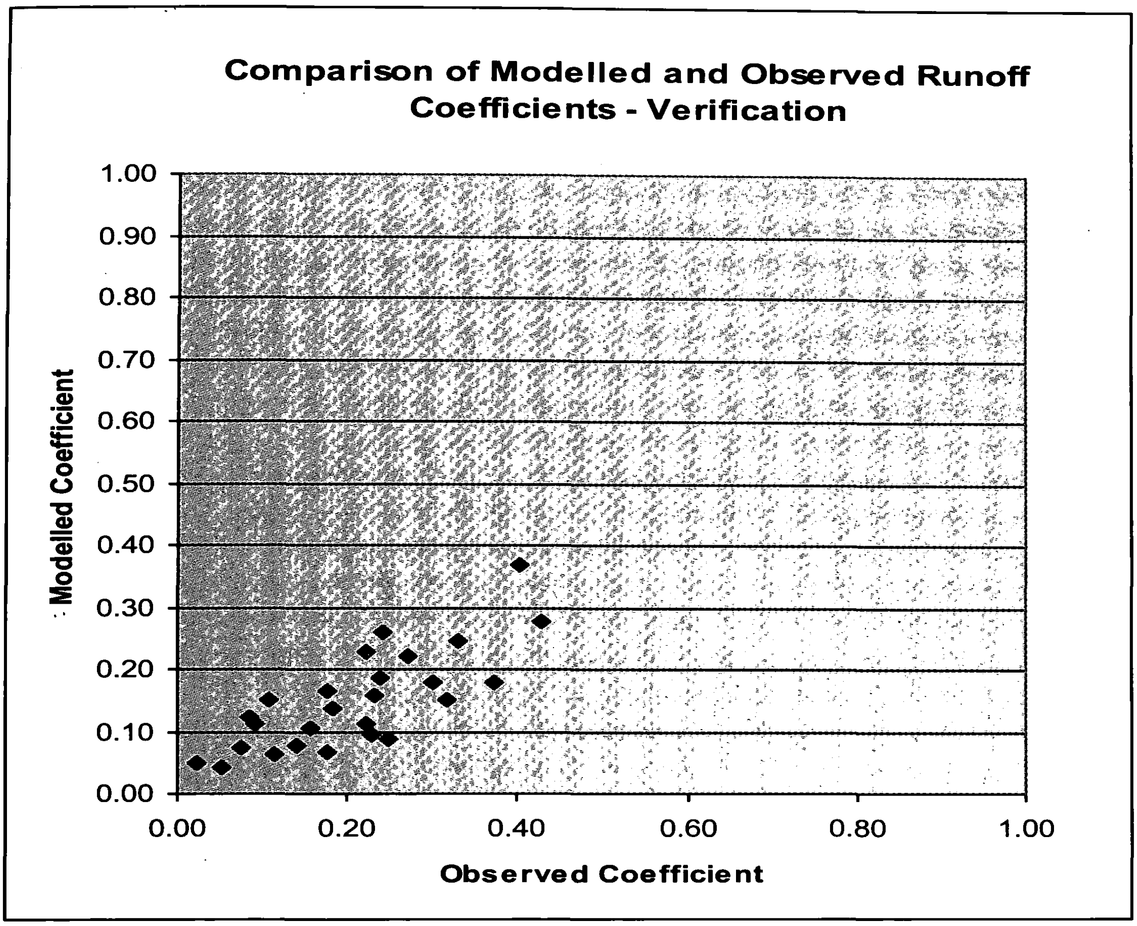



**Figure 6- Comparison of Observed and Modelled Runoff Coefficients during Calibration and Verification**

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