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MODELING BALLASTED TRACKS FOR RUNOFF COEFFICIENT C

Albert Molinas
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16. Abstract

In this study, the Regional Transportation District (RTD)'s light rail tracks were modeled to determine the Rational Method runoff coefficient, *C*, values corresponding to ballasted tracks. To accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted at Colorado State University's Hydraulics Laboratory. The input to this model was provided by using RTD's design criteria, data from existing installations, and a field study to sample surface materials along ballasted tracks. By subjecting the 1:1 scale model railroad segment to 1-hour rainfall events with various recurrence intervals and measuring the corresponding runoff volumes, runoff coefficients were computed for Denver hydrology. For the more frequent 2-year, 5-year, 10-year events, the average *C* value is approximately 0.55. For the 25-year, 50-year, and 100-year return frequency rainfall events, the *C* value is in excess of 0.55 and is expressed in terms of multiplication factors of this average value. The runoff coefficient for ballasted tracks is significantly larger than the previously tabulated values for railroad yards. The higher runoff coefficient reflects the design of ballasted tracks to drain rainfall as quickly as possible. As a part of the research, detention times in the ballasted tracks were also determined. The detention time is a function of antecedent soil moisture content and rainfall intensity. In general terms, for dry antecedent conditions the initial 0.3 inch-0.4 inch of rainfall is detained in the ballasted tracks. The initial 0.5 inch of rainfall produces only a small amount of runoff. For 25-year, 50-year, and 100-year events, the runoff starts 9 minutes, 7 minutes, and 6 minutes after the start of the event.

Implementation

It is recommended that the CDOT use the newly determined C values in the CDOT Drainage Design Manual.

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FINAL REPORT

MODELING BALLASTED TRACKS FOR RUNOFF COEFFICIENT C

FOR

COLORADO DEPARTMENT OF TRANSPORTATION

DENVER, COLORADO

BY
ALBERT MOLINAS
AND
AMANULLAH MOMMANDI

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EXECUTIVE SUMMARY

In this study, the Regional Transportation District's (RTD's) light rail tracks were modeled to determine Rational Method runoff coefficient, *C*, values corresponding to ballasted tracks. To accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted. The input to this laboratory model was provided by using RTD's design criteria, data from existing installations, and a field study to sample surface materials along ballasted tracks.

The study was directed to answer the question: *"What is the state of runoff in regards to inflows: What is the quantity of runoff for a given rainfall event (i.e., determine the Runoff Coefficient, C used in hydrologic computations)?"*

A rainfall-runoff physical model of the light rail system was constructed at the Colorado State University (CSU) Daryl B Simons Hydraulics Laboratory to study the runoff characteristics of the as-built ballasted tracks. This model was subjected to Denver hydrology and environmental conditions using the available local rainfall information.

a. A 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. The railroad segment was placed in a rainfall simulator that could vary rainfall duration and intensity. The experimental facility was designed to accurately measure the rainfall volume introduced in to the model and to capture all of the runoff for volumetric measurement.

b. Peak runoff discharge computations using the Rational Method require the use of a runoff coefficient (ratio between runoff and rainfall volumes) reflecting characteristics of ballasted tracks. In order to determine runoff coefficients from a typical ballasted track section, laboratory experiments were conducted to measure runoff corresponding to various rainfall events experienced in Denver, Colorado. By subjecting the model railroad segment to 1-hour rainfall events with 25-year, 50-year, and 100-year recurrence intervals and by measuring the corresponding runoff volumes, runoff coefficients corresponding to various recurrence intervals were computed.

Conclusions from the study:

1. Runoff resulting from various return frequency rainfall events was determined. A relationship between return frequency and the runoff coefficient, *C*, was developed for Denver hydrology. For the more frequent 2-year, 5-year, 10-year events, the average *C* value is approximately 0.55. For 25-year, 50-year, and 100-year return frequency rainfall events, the *C* value is in excess of0.55 and is expressed in terms of multiplication factors of this average value.

2. In general, the runoff coefficient for ballasted tracks is significantly larger than the previously tabulated values for railroad yards that vary between 0.2 and 0.4. The higher runoff coefficient reflects the design of ballasted tracks to drain rainfall as quickly as possible.

3. The detention time in the ballasted tracks was determined. According to the laboratory study, the detention time is a function of antecedent soil moisture content and rainfall intensity. In general terms, for dry antecedent conditions the initial 0.3 inch-0.4 inch of rainfall is detained in the ballasted tracks. The initial 0.5 inch of rainfall produces only a small amount of runoff. For 25-year, 50-year, and 100-year events, the runoff starts 9 minutes, 7 minutes, and 6 minutes after the start of the event.

EXPECTED BENEFITS

In this study, a rainfall-runoff physical model of the light rail system was developed to determine the runoff characteristics of the as-built ballasted tracks. This model was developed based on Denver hydrology and environmental conditions using the available local rainfall intensity, duration, and frequency information.

The study answers the question of how much runoff is generated from the railroad right of way for a given event. This information is necessary in designing drainage facilities along the light rail installations.

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1. INTRODUCTION

The RTD is in the process of constructing light rail through Denver and surrounding counties, as well as CDOT right-of-way. Since the areas along the ballasted tracks are located within smaller urban watersheds, the Rational Method is recommended to estimate the peak runoff discharges generated from the light rail tracks.

Prior to this research study, as shown in Table 1, both the CDOT Drainage Design Manual and the Urban Drainage and Flood Control District (UDFCD) Criteria Manual have tabulated Rational Method runoff coefficient, C, values for railroad yard areas for different recurrence intervals but neither agencies have provided values for ballasted tracks.

This research was initiated by RTD and CDOT to determine the runoff coefficients for various recurrence interval events through a full-scale laboratory model study at Colorado State University. In the study, RTD's light rail tracks were modeled to determine Rational Method runoff coefficient, C, values corresponding to ballasted tracks. In order to accomplish this, a laboratory study utilizing a rainfall-runoff facility was conducted. The input to this laboratory model was provided by using RTD's design criteria, data from existing installations, and a field study to sample surface materials along ballasted tracks.

2. STUDY OBJECTIVES

Some of the statistics related to RTD's light rail operations can be listed as:

- Locale: Denver-Aurora Metropolitan Area
- Transit type: Light Rail
- Number of lines: 5
- Number of stations: 36
- Daily ridership: 54,779
- Operation Began: October 7, 1994
- Operator(s): Regional Trans. District (RTD)
- System length: 39.4 miles
- Electrification: Overhead lines

In this research study, a 1 to 1 scale model of a typical railroad segment is subjected to Denver rainfall conditions in order to estimate Rational Method C values for ballasted tracks used in light rail installations.

The study was directed to answer the question: "*What is the state of runoff in regards to inflows? What is the quantity of runoff for a given rainfall event (i.e., determine the Runoff Coefficient, C used in hydrologic computations)?*"

As a philosophy, the study uses a conservative worst-case approach to support its findings. The infiltration losses into the subgrade are minimized in the experiments by introducing an epoxy-coated plywood surface for simulating the subgrade.

Table1. Recommended runoff coefficients for use in Rational Equation as a function of percent impervious area and land use types (from CDOT Drainage Design Manual, Table 7.4, 2004).

Land Use or Surface	**Percent**			**Frequency**	
Characteristics	**Impervious**	**2**	**5**	**10**	**100**
Business:					
Commercial Areas	95	0.87	0.87	0.88	0.89
Neighborhood Areas	70	0.60	0.65	0.70	0.80
Residential:					
Single-Family		0.40	0.45	0.50	0.60
Multi-Unit (detached)	50	0.45	0.50	0.60	0.70
Multi-Unit (attached)	70	0.60	0.65	0.70	0.80
1/2Acre Lot or Larger		0.30	0.35	0.40	0.60
Apartments	70	0.65	0.70	0.70	0.80
Industrial:					
Light Areas	80	0.71	0.72	0.76	0.82
Heavy Areas	90	0.80	0.80	0.85	0.90
Parks, Cemeteries:	7	0.10	0.10	0.35	0.60

Playgrounds:	13	0.15	0.25	0.35	0.65
Schools:	50	0.45	0.50	0.60	0.70
Railroad Yard Areas:	40	0.40	0.45	0.50	0.60
Railroad Ballasted Tracks	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Undeveloped Areas:					
Historic Flow Analysis,					
Greenbelt, Agricultural:	2		See Lawns		
Offsite Flow Analysis:	45	0.43	0.47	0.55	0.65
(When land use not defined)					
Streets:					
Paved	100	0.87	0.88	0.90	0.93
Gravel	13	0.15	0.25	0.35	0.65
Drive and Walks,	96	0.87	0.87	0.88	0.89
Roofs:	90	0.80	0.85	0.90	0.90
Lawns, Sandy Soil:	0	0.00	0.01	0.05	0.20
Lawns, Clayey Soil:	0	0.05	0.10	0.20	0.40

Note: These Rational Formula coefficients may not be valid for large basins.

Source: Urban Storm Drainage Criteria Manual (UDFCD, 2001).

3. RESEARCH APPROACH

CDOT's Drainage Design Manual (2004) identifies the Rational Method as one of the methods for peak runoff computation for smaller watersheds. The Rational Method was first introduced in 1889. It is appropriate for small urban and rural drainage areas up to 160 acres where there is no significant storage in the drainage basin. It is best suited to urban drainage basins. The widely-used Rational Method is a simple method given by:

$$Q = C\,i\,A$$

Where Q = rate of runoff in cubic feet per second corresponding to the rainfall frequency; C = runoff coefficient of the area, an empirical coefficient representing a relationship between rainfall and runoff; i = average rainfall intensity in inches per hour for a duration equal to the time of concentration; and A = Area of contributing watershed in acres.

In the use of Rational Method, rainfall intensity is a necessary input. The Rational Method assumes constant rainfall intensity across the entire basin and that the rainfall duration exceeds the time of concentration. The coefficient C is generally obtained from tabulated values corresponding to different land use areas. In the absence of such information, it is determined by approximation or by experience.

The research approach used in the study is to determine C values experimentally for inclusion in CDOT Drainage Design Manual in order to improve drainage design computations. To accomplish this, a rainfall-runoff physical model of the light rail system was constructed at the Colorado State University (CSU) Daryl B Simons Hydraulics Laboratory. This model was subjected to Denver hydrology and environmental conditions by using the available rainfall intensity, duration and frequency information.

1. A 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. The railroad segment was placed in a rainfall simulator that could vary rainfall duration and intensity. The experimental facility was designed to accurately measure the rainfall volume introduced in to the model and to capture all of the runoff for volumetric measurement.

2. Peak runoff computations using the Rational Method require the use of a runoff coefficient (ratio between runoff and rainfall volumes) reflecting characteristics of ballasted tracks. In order to determine runoff coefficients from a typical ballasted track section, laboratory experiments were conducted to measure runoff corresponding to various rainfall events experienced in Denver, Colorado. By subjecting the model railroad segment to 1-hour rainfall events with 25-year, 50-year, and 100-year recurrence intervals and by measuring the corresponding runoff volumes, runoff coefficients corresponding to various recurrence intervals were computed.

3. Drainage characteristics of the ballast and sub-ballast are affected by the grinding of gravel through time. Even though the light rail design criteria tries to minimize the adverse effects of introducing finer sediments by proper selection of material, an existing light rail installation that has been in operation for 15 years was sampled for fine materials and pollutants from light rail operations. The objective of the field sampling was to quantify the finer materials (if found in larger quantities) and pollutants and introduce them into the ballasted track experiments to simulate their fate.

4. DETERMINATION OF RUNOFF COEFFICIENTS

4.1 Laboratory Model of Ballasted Tracks

For the laboratory experiments, a 1-to-1 model of an 8-foot railroad segment was constructed using RTD's design criteria and materials. The concrete railroad ties, steel tracks and other hardware used in the model were supplied by RTD and are currently being used in RTD's existing installations.

Figure 1 below shows half of a double-track ballasted section constructed for the experiments. By using a half-model, the runoff collection system is greatly simplified eliminating a major source of error. The runoff from the track is collected by a gutter at the toe and discharged into a runoff catchment box. According to RTD's design criteria for the ballasted tracks, the slope of the subgrade is 2.5%. In the model, the compacted clay subgrade was simulated by a painted plywood surface. This arrangement provided a more conservative runoff characteristic since it allowed no infiltration losses in the system.

A rainfall simulator with 4 spray nozzles was placed 14ft above the 8-foot railroad segment to provide uniform distribution of rainfall. The selection of 4 nozzles was to attain a more uniform cover and was made after trials with 1-nozzle and 2-nozzle systems and after sensitivity testing. Figures 2 through 5 provide views of the laboratory model and rainfall simulator. In Figure 2, the overall model is shown during a rainfall simulation event. Figure 3 shows the runoff catchment box with two compartments; Figures 4 and 5 show various elements of the rainfall simulation model. In order to have similar antecedent conditions, a drying period of 7 to 10 days between runoff experiments were implemented.

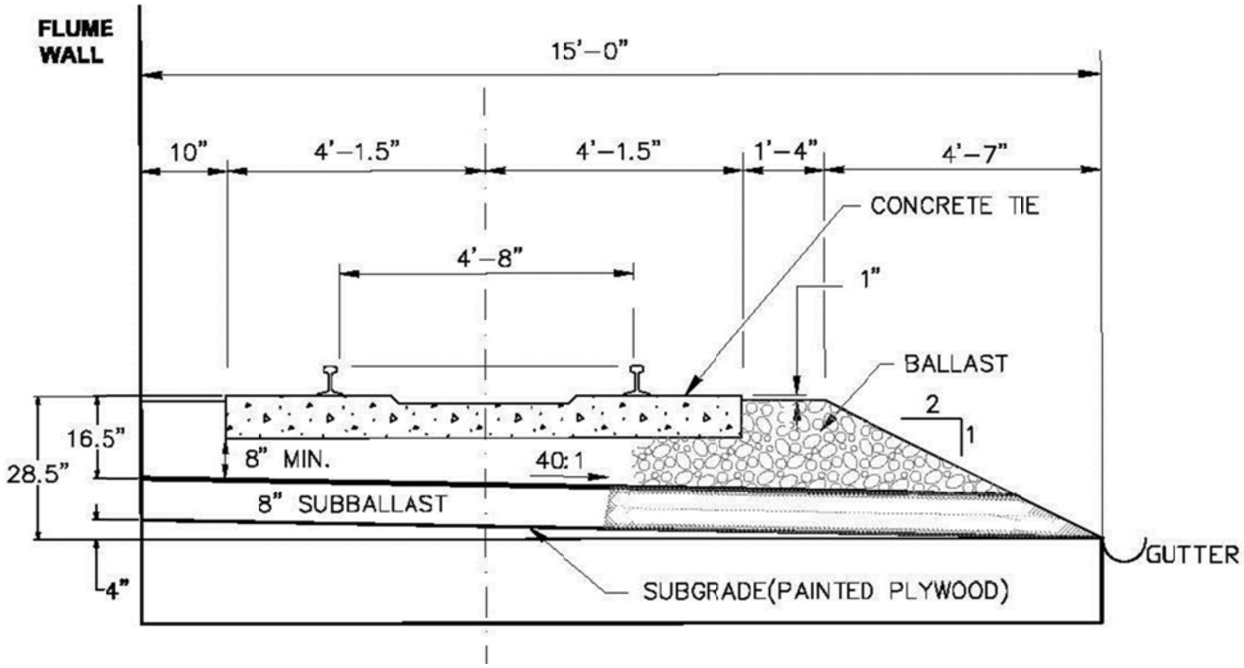

Figure 1. Half of a double-track ballasted section used in the laboratory modeling study.

Figure 2. The overall model during a rainfall simulation event.

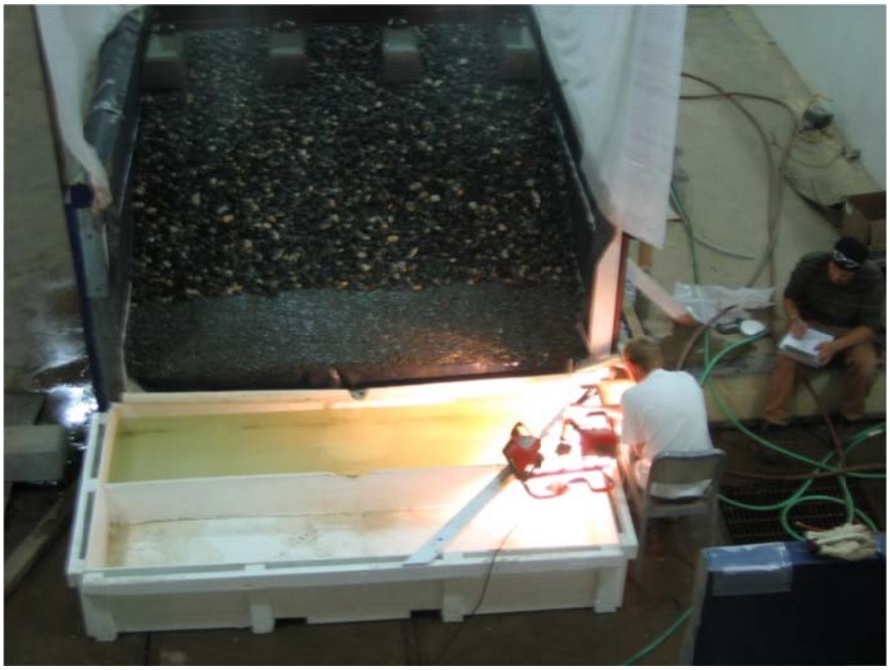

Figure 3. Runoff collection system and the catchment box with two compartments.

Figure 4. The rainfall simulator with 4 spray nozzles.

Figure 5. Pressure regulator and flow meter to measure inflow into the rainfall simulator.

4.2 Sediment Characteristics

The ballast and sub-ballast materials used in the experiments were acquired from a main RTD supplier. The size gradation characteristics of these sediments are given in below and are shown in Figure 6. As shown in Figure 6, the ballast material has a median diameter of approximately 2/3" (16mm) with almost no fine material. The median diameter of sub-ballast material is approximately 0.1" (2.36mm) with 14 percent sediments falling in the silt-clay size groups.

Sediment Size Distribution for the Ballast and Subballast Material

SIZE (MM)	BALLAST Percent Finer	SUBBALLAST Percent Finer
75.00	100	100
63.00	100	100
50.00	100	100
37.50	100	100
25.00	100	96
19.00	72	91
12.50	28	78
9.50	11	72
4.75	2	61
2.36	2	51
0.002	1	14

4.3 Experimental Procedure

The experimental procedure for the runoff coefficient experiments was:

1. Calibrate and verify each of the elements used in the rainfall-runoff modeling. These elements included the rainfall water supply line including the pressure regulator and flow meter, spray nozzle system including the mounting hardware, and runoff catchment boxes. Volumetric tests were conducted to verify supply line accuracy. For the spray nozzle system, various nozzle configurations utilizing 1-, 2-, and 4 nozzles were tested; final configuration utilized 4 nozzles.
2. Set the intensity of rainfall to a desired level by adjusting line pressure and valve opening.
3. Collect inflow measurement data into the rainfall simulator every 1 minute using a flow meter.
4. Collect runoff from the ballasted tracks into a catchment box. Measure the water levels in the catchment box every 30 seconds. Track the runoff volume through the duration of the 1-hour rainfall event and through the recession limb of the runoff hydrograph.

5. Convert water levels in runoff catchment boxes into cumulative runoff volumes using calibration curves. Figures 7, 8, and 9 show the calibration curves used for catchment boxes to convert runoff depths to cumulative volumes.
6. Using curve fitting through different periods of cumulative runoff-duration data, derive runoff discharge for different periods of runoff event (Qi = Change in runoff volume/time increment).
7. Develop runoff hydrographs.
8. Determine the rainfall into the model and the corresponding runoff at the end of an event
9. Determine the average runoff coefficient for the event.
10. Repeat the procedure for different rainfall intensities to establish variation of runoff coefficient with intensity (return period).

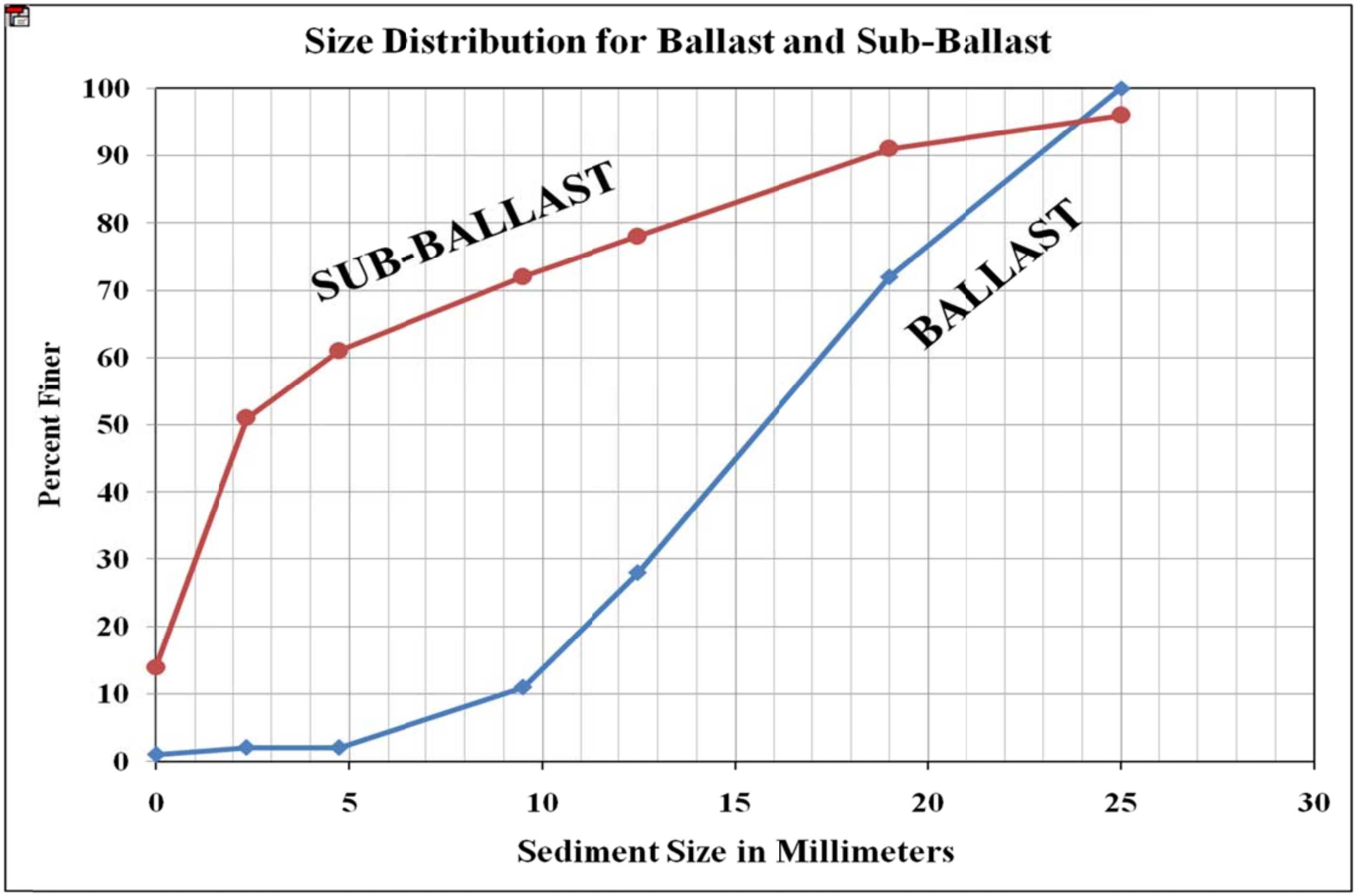

Figure 6. Sediment size distribution for the ballast and sub-ballast materials used in experiments.

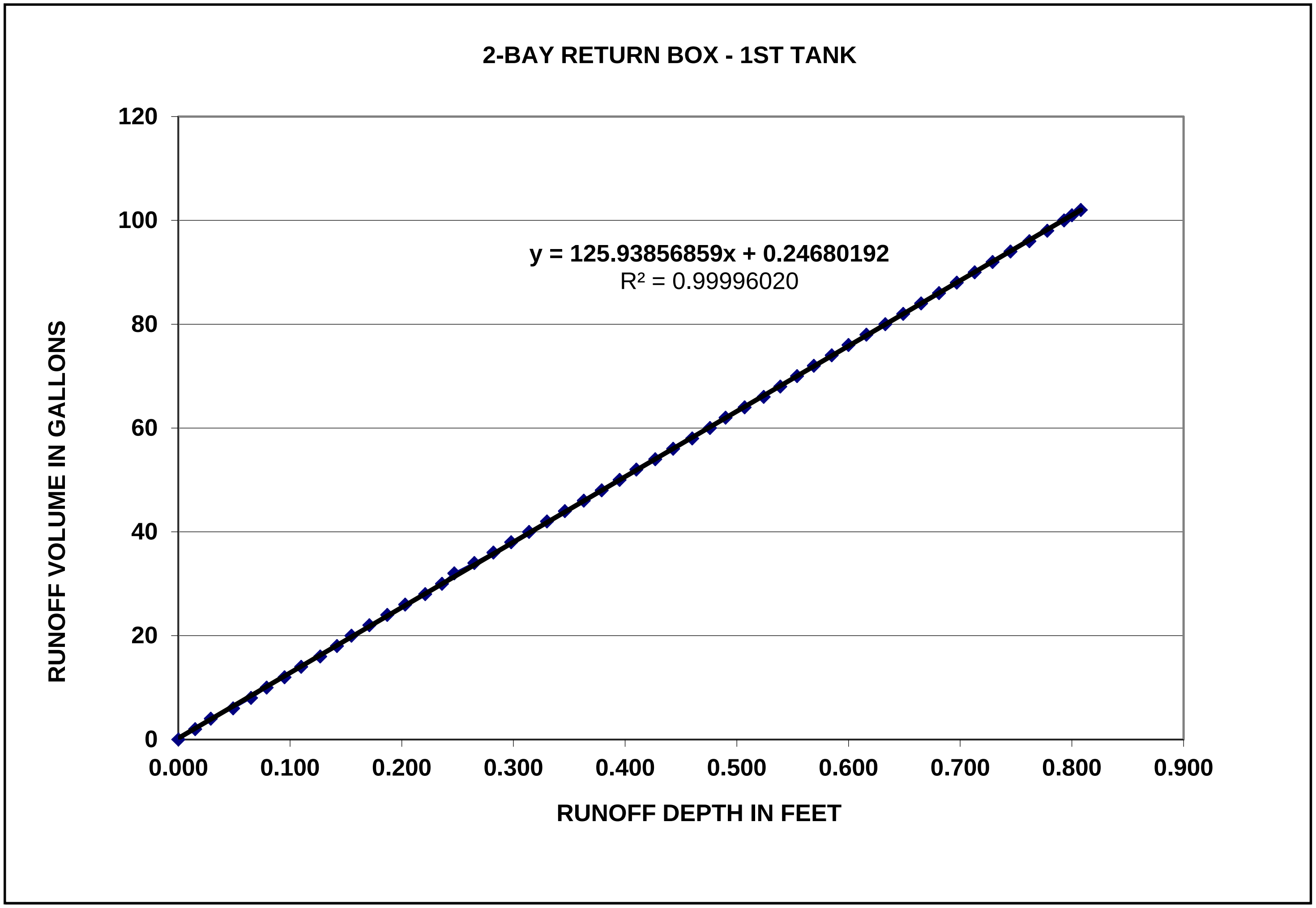

Figure 7. Depth-volume relationships for runoff catchment boxes used in experiments.

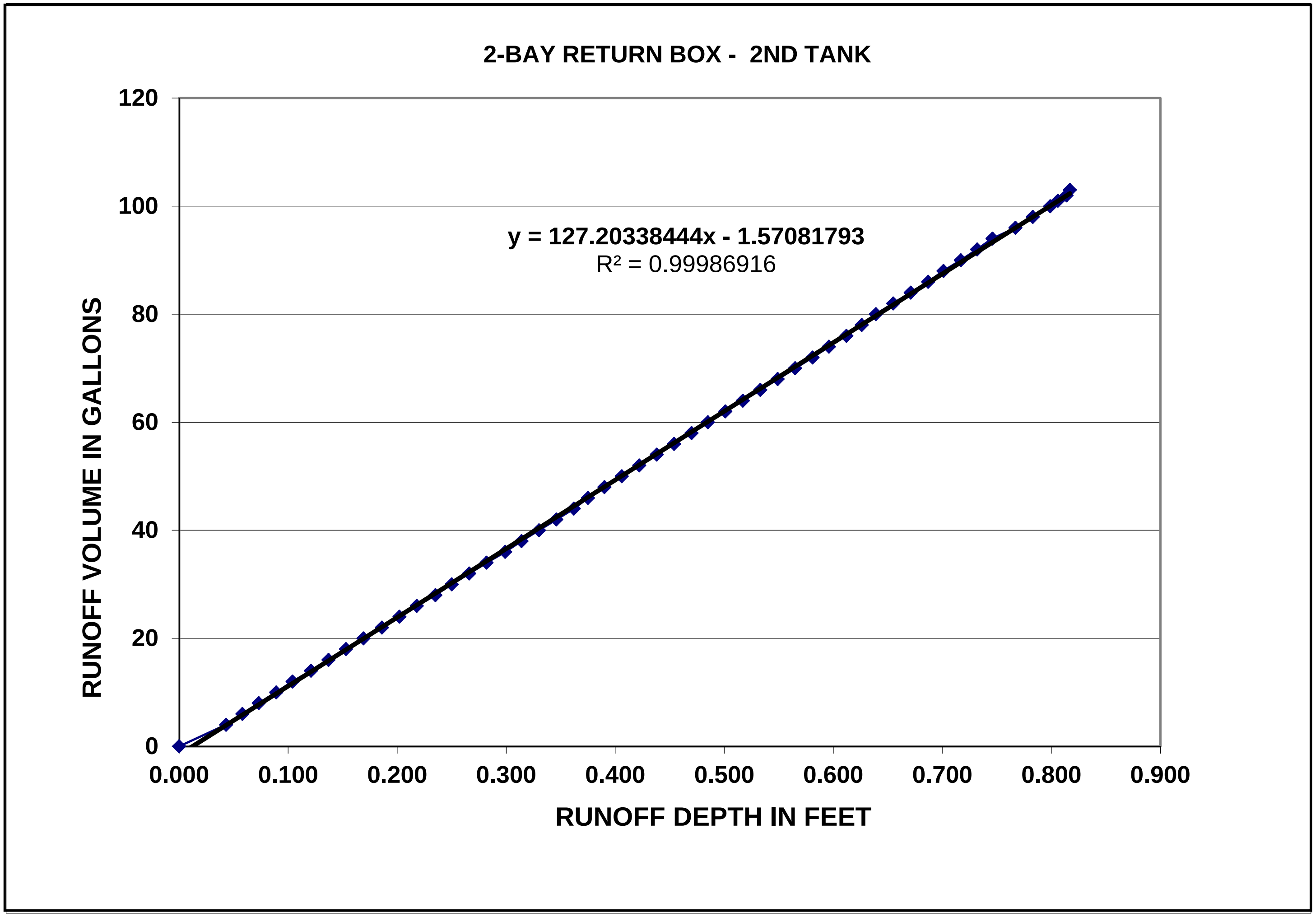

Figure 8. Depth-volume relationships for runoff catchment boxes used in experiments.

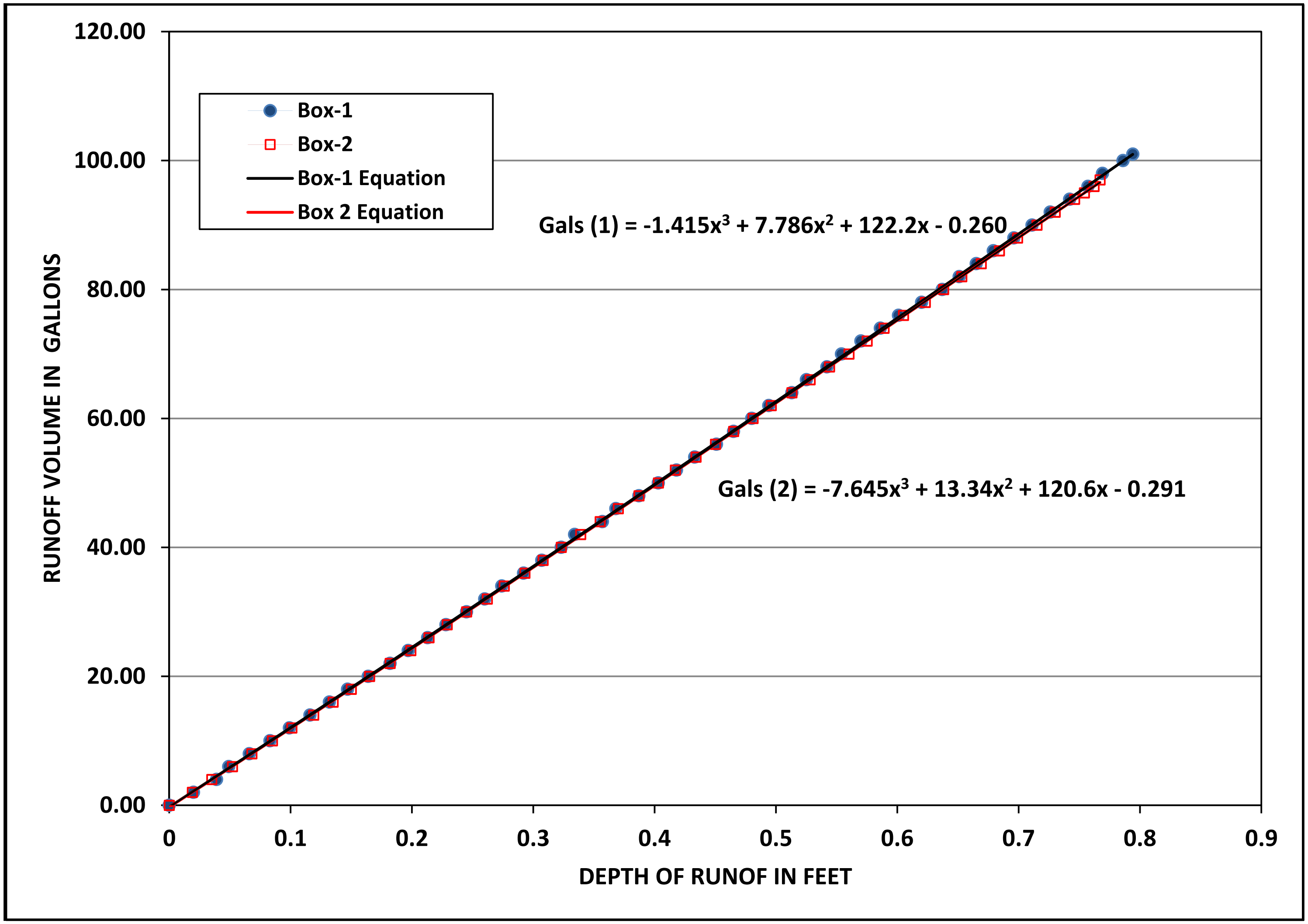

Figure 9. Depth-volume relationships for runoff catchment boxes used in experiments.

4.4 Runoff Coefficients for 25-Year, 50-Year, 100-Year Frequency 1-Hour Events

According to the UDFCD, very intense rainfall in the Denver area results from convective storms or frontal stimulated convective storms. These types of storms often have their most intense periods that are less than one or two hours in duration. They can produce brief periods of high rainfall intensities. It is these short-duration, intense rainstorms that appear to cause most of the flooding problems in the great majority of urban catchments. According to UDFCD's Urban Storm Drainage Criteria Manual, "An analysis of a 73-year record of rainfall at the Denver rain gage revealed that an overwhelming majority of the intense rainstorms produced their greatest intensifies in the first hour of the storm. In fact, of the 73 most intense storms analyzed, 68 had the most intense period begin and end within the first hour of the storm, and 52 had the most intense period begin and end within the first half hour of the storm."

Using UDFCD findings, for the present study in order to represent intense rainstorms in Denver area, 1 hour duration events were chosen. For these events, runoff coefficients (ratio of rainfall to runoff volume) were determined experimentally by subjecting the model ballasted track segment to selected rainfall events and by measuring the corresponding runoff volumes. Runoff coefficients vary with soil type, rainfall intensity, and antecedent conditions. In general terms, for a given soil type as the soils are saturated the runoff coefficients approach the value of 1 (runoff volume equals to rainfall volume). In the experiments, antecedent conditions were varied to determine the length of ponding (how long before runoff starts?). In the following sections runoff coefficients from 25-year, 50-year, and 100-year storms are determined. As the intensity of rainfall increases, the time to reach saturation decreases and therefore a higher runoff coefficient is expected.

The rainfall depth-duration-frequency for a 25-year, 50-year, 100-year frequency 1 hour events are given in UDFCD's Urban Storm Drainage Criteria Manual. According to UDFCD, the rainfall depths for Denver area and the corresponding inflow discharges into the model rainfall simulator are:

Return Frequency	**Rainfall**	**Model Inflow**
25-Year Frequency	2 in/hr	2.6 gallons/minute (gpm)
50-Year Frequency	2.35 in/hr	3.10 gpm
100-Year Frequency	2.70 in/hr	3.50 gpm

In arriving at the model inflow discharges, the rainfall volume falling onto the 8ft wide by 15ft long model area in 1 hour is computed. This discharge is then converted into gallons per minute. The pressure regulator and valve opening is adjusted to allow the required inflow discharge into the fine-spray nozzles to allow a uniformly distributed rainfall on the model ballasted tracks.

4.5 Runoff Coefficient for 25-Year, 1-Hour Event

The runoff data for the 25-year, 1-hour rainfall event is presented in Table 2 and in Figures 10 and 11. Table 2 presents the variation of runoff depth in the catchment box through time in column 3. These depths are converted to cumulative runoff volumes in column 4. Figure 10 shows the variation of cumulative runoff through the duration of the experiment. An experimental regression curve is passed through the data points given in Figure 10. Runoff rate in gallons per minute is computed by using the regression equation by computing the change in volume every 30 seconds. These experimental discharge values are plotted in Figure 11 along with the inflow discharges into the model.

Model data for computing the runoff data is as follows:

1) Start Time: 0 min
2) End Time: 60 min
3) Line Pressure: 42.5 pounds per square inch (psi)
4) Starting Flow-meter Reading: 154228.7 gallons
5) Ending Flow-meter Reading: 154373gallons
6) Total Inflow Into model: 144.3gallons
7) Inflow Rate: 2.3 gpm
8) Runoff Volume after 60 min: 94.7 gallons
9) Runoff Coefficient: 0.66

Table 2. Runoff data from a 25-year, 1-hour rainfall event.

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
0.0	0.494	0.000	0.000		
0.5	0.494	0.000	0.000		
1.0	0.494	0.000	0.000		
1.5	0.494	0.000	0.000		
2.0	0.494	0.000	0.000		
2.5	0.494	0.000	0.000		
3.0	0.494	0.000	0.000		
3.5	0.494	0.000	0.000		
4.0	0.494	0.000	0.000		
4.5	0.494	0.000	0.000		
5.0	0.494	0.000	0.000		
5.5	0.494	0.000	0.000		
6.0	0.494	0.000	0.000		
6.5	0.494	0.000	0.000		
7.0	0.494	0.000	0.000		
7.5	0.494	0.000	0.000		
8.0	0.498	0.004	0.751		
8.5	0.5	0.006	1.002		
9.0	0.503	0.009	1.380	1.348	0.000
9.5	0.504	0.010	1.506	1.517	0.339
10.0	0.506	0.012	1.758	1.752	0.469
10.5	0.508	0.014	2.010	2.048	0.591
11.0	0.511	0.017	2.388	2.400	0.704
11.5	0.514	0.020	2.766	2.804	0.809
12.0	0.518	0.024	3.269	3.257	0.906
12.5	0.522	0.028	3.773	3.754	0.994
13.0	0.527	0.033	4.403	4.291	1.074
13.5	0.53	0.036	4.781	4.864	1.145
14.0	0.536	0.042	5.536	5.467	1.208
14.5	0.541	0.047	6.166	6.098	1.262
15.0	0.545	0.051	6.670	6.752	1.308
15.5	0.551	0.057	7.425	7.425	1.345
16.0	0.556	0.062	8.055	8.112	1.374
16.5	0.562	0.068	8.811	8.809	1.394
17.0	0.568	0.074	9.566	9.512	1.406
17.5	0.575	0.081	10.448	10.454	1.549
18.0	0.582	0.088	11.329	11.300	1.692
18.5	0.589	0.095	12.211	12.173	1.746
19.0	0.596	0.102	13.093	13.071	1.796
19.5	0.603	0.109	13.974	13.993	1.843
20.0	0.611	0.117	14.982	14.936	1.886

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
20.5	0.618	0.124	15.863	15.898	1.924
21.0	0.626	0.132	16.871	16.877	1.959
21.5	0.633	0.139	17.752	17.873	1.988
22.0	0.641	0.147	18.760	18.881	2.017
22.5	0.649	0.155	19.767	19.902	2.041
23.0	0.657	0.163	20.775	20.932	2.060
23.5	0.663	0.169	21.530	21.969	2.075
24.0	0.669	0.175	22.286	23.013	2.087
24.5	0.6765	0.183	23.231	24.060	2.094
25.0	0.684	0.190	24.175	24.187	2.057
25.5	0.693	0.199	25.309	25.197	2.020
26.0	0.7	0.206	26.190	26.207	2.020
26.5	0.708	0.214	27.198	27.217	2.020
27.0	0.716	0.222	28.205	28.226	2.020
27.5	0.723	0.229	29.087	29.236	2.020
28.0	0.73	0.236	29.968	30.246	2.020
28.5	0.738	0.244	30.976	31.256	2.020
29.0	0.745	0.251	31.857	32.266	2.020
29.5	0.753	0.259	32.865	33.276	2.020
30.0	0.761	0.267	33.872	34.286	2.020
30.5	0.769	0.275	34.880	35.296	2.020
31.0	0.777	0.283	35.887	36.306	2.020
31.5	0.783	0.289	36.643	37.316	2.020
32.0	0.795	0.301	38.154	38.326	2.020
32.5	0.802	0.308	39.036	39.336	2.020
33.0	0.809	0.315	39.917	40.346	2.020
33.5	0.818	0.324	41.051	41.356	2.020
34.0	0.826	0.332	42.058	42.366	2.020
34.5	0.835	0.341	43.192	43.376	2.020
35.0	0.844	0.350	44.325	44.385	2.020
35.5	0.852	0.358	45.333	45.395	2.020
36.0	0.86	0.366	46.340	46.405	2.020
36.5	0.868	0.374	47.348	47.415	2.020
37.0	0.877	0.383	48.481	48.425	2.020
37.5	0.885	0.391	49.489	49.435	2.020
38.0	0.893	0.399	50.496	50.445	2.020
38.5	0.899	0.405	51.252	51.455	2.020
39.0	0.909	0.415	52.511	52.465	2.020
39.5	0.916	0.422	53.393	53.475	2.020
40.0	0.924	0.430	54.400	54.485	2.020
40.5	0.932	0.438	55.408	55.495	2.020
41.0	0.94	0.446	56.415	56.505	2.020

Time (Minutes)	**Point Gauge (Feet)**	**Runoff Depth (Feet)**	**Runoff Volume (Gallons)**	**Computed Vol. (Gallons)**	**Runoff Rate (Gallons/Minute)**
41.5	0.948	0.454	57.423	57.515	2.020
42.0	0.956	0.462	58.430	58.525	2.020
42.5	0.964	0.470	59.438	59.535	2.020
43.0	0.972	0.478	60.445	60.544	2.020
43.5	0.98	0.486	61.453	61.554	2.020
44.0	0.989	0.495	62.586	62.564	2.020
44.5	0.997	0.503	63.594	63.574	2.020
45.0	1.005	0.511	64.601	64.584	2.020
45.5	1.013	0.519	65.609	65.594	2.020
46.0	1.022	0.528	66.742	66.604	2.020
46.5	1.03	0.536	67.750	67.614	2.020
47.0	1.039	0.545	68.883	68.624	2.020
47.5	1.046	0.552	69.765	69.634	2.020
48.0	1.054	0.560	70.772	70.644	2.020
48.5	1.062	0.568	71.780	71.654	2.020
49.0	1.07	0.576	72.787	72.664	2.020
49.5	1.078	0.584	73.795	73.674	2.020
50.0	1.086	0.592	74.802	74.684	2.020
50.5	1.094	0.600	75.810	75.694	2.020
51.0	1.102	0.608	76.817	76.703	2.020
51.5	1.11	0.616	77.825	77.713	2.020
52.0	1.118	0.624	78.832	78.723	2.020
52.5	1.126	0.632	79.840	79.733	2.020
53.0	1.133	0.639	80.722	80.743	2.020
53.5	1.142	0.648	81.855	81.753	2.020
54.0	1.15	0.656	82.863	82.763	2.020
54.5	1.158	0.664	83.870	83.773	2.020
55.0	1.166	0.672	84.878	84.783	2.020
55.5	1.173	0.679	85.759	85.793	2.020
56.0	1.182	0.688	86.893	86.803	2.020
56.5	1.189	0.695	87.774	87.813	2.020
57.0	1.198	0.704	88.908	88.823	2.020
57.5	1.205	0.711	89.789	89.833	2.020
58.0	1.213	0.719	90.797	90.843	2.020
58.5	1.22	0.726	91.678	91.852	2.020
59.0	1.228	0.734	92.686	92.862	2.020
59.5	1.237	0.743	93.819	93.872	2.020
60.0	1.245	0.751	94.827	94.882	1.802
60.5	1.252	0.758	95.708	95.675	1.585
61.0	1.259	0.765	96.590	96.522	1.693
61.5	1.266	0.772	97.471	97.292	1.540
62.0	1.269	0.775	97.849	97.972	1.360

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
62.5	1.274	0.780	98.479	98.547	1.151
63.0	1.278	0.784	98.983	99.005	0.915
63.5	1.28	0.786	99.235	99.330	0.651
64.0	1.283	0.789	99.612	99.509	0.359
64.5	1.284	0.790	99.738		

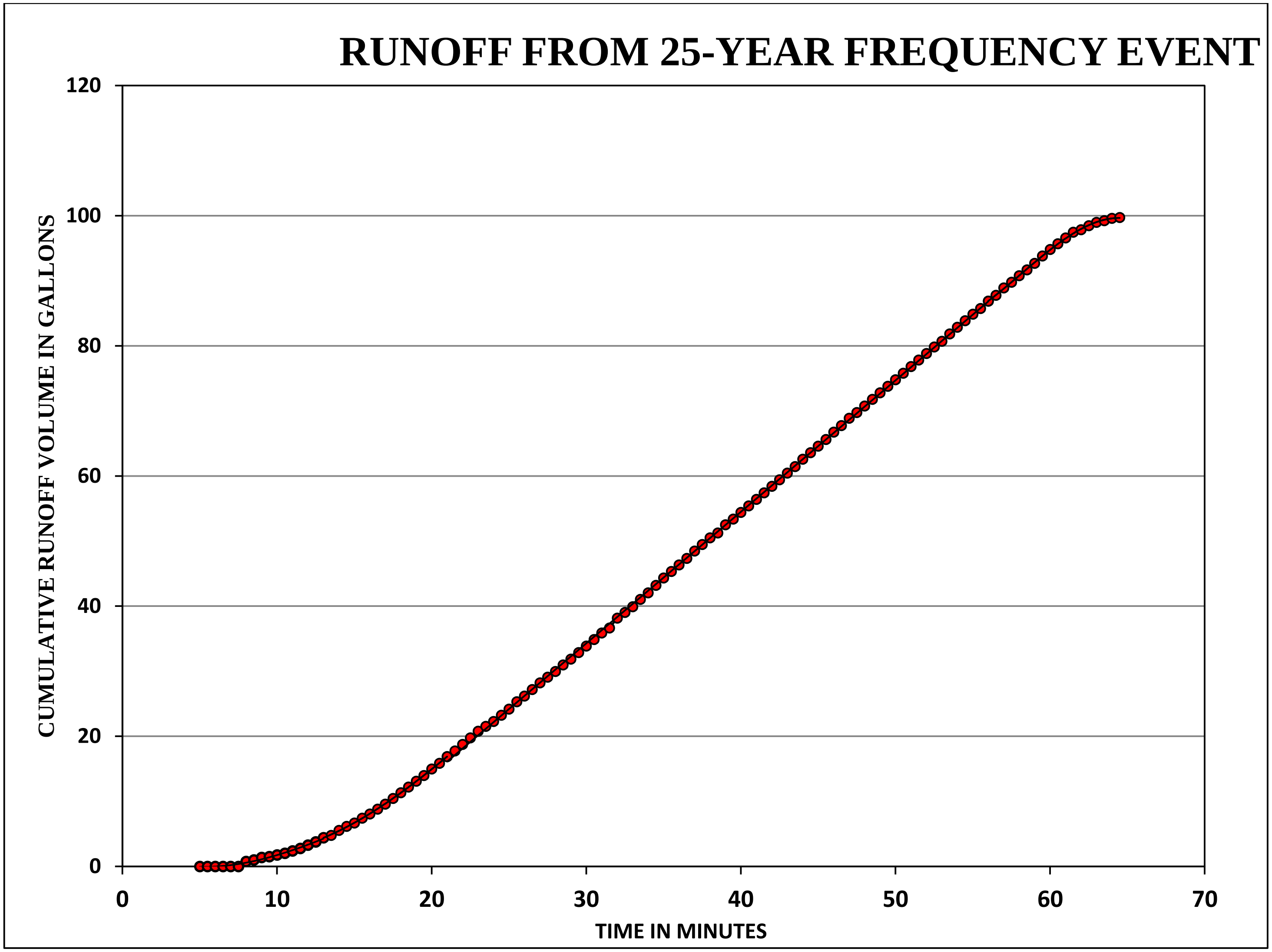

Figure 10. Measured cumulative runoff volumes from a 1-hour, 25-year return frequency rainfall event.

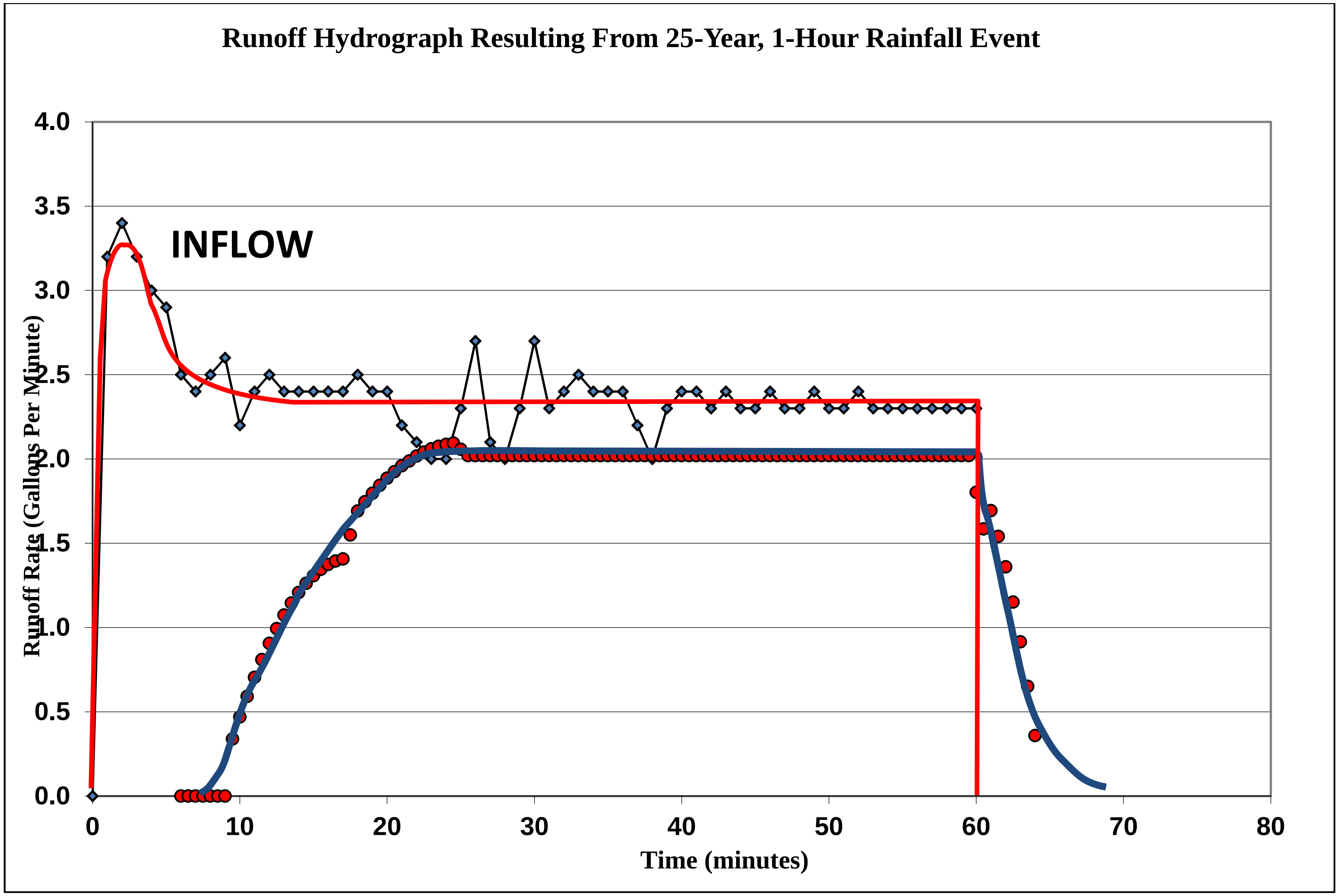

Figure 11. Measured rainfall and runoff hydrographs from a 1-hour, 25-year return frequency rainfall event.

4.6 Runoff Coefficient for 50-Year, 1-Hour Event

The runoff data for the 50-year, 1-hour rainfall event is presented in Table 3 and in Figures 12 and 13. Table 3 presents the variation of runoff depth in the catchment box through time (column 3). These depths are converted to cumulative runoff volumes in column 4. Figure 12 shows the variation of cumulative runoff through the duration of the experiment. An experimental regression curve is passed through the data points given in Figure 12. Runoff rate in gallons per minute is then computed by using the regression equation by computing the change in volume every 30 seconds. These experimental discharge values are plotted in Figure 13 along with the inflow discharges into the model.

Model data for computing the runoff data is as follows:

1) Start Time: 0 min
2) End Time: 60 min
3) Line Pressure: 72 pounds per square inch (psi)
4) Starting Flow-meter Reading: 153845.7.0 gallons
5) Ending Flow-meter Reading: 154033.4 gallons
6) Total Inflow Into model: 187.7 gallons
7) Inflow Rate: 3.13 gpm
8) Runoff Volume after 60 min: 144 gallons
9) Runoff Coefficient: 0.77

Table 3. Runoff data from a 50-year, 1-hour rainfall event.

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
0.0	0.488	0.000	0.000		
0.5	0.488	0.000	0.000		
1.0	0.488	0.000	0.000		
1.5	0.488	0.000	0.000		
2.0	0.488	0.000	0.000		
2.5	0.488	0.000	0.000		
3.0	0.488	0.000	0.000		
3.5	0.488	0.000	0.000		
4.0	0.488	0.000	0.000		
4.5	0.488	0.000	0.000		
5.0	0.488	0.000	0.000		
5.5	0.488	0.000	0.000		
6.0	0.488	0.000	0.000		
6.5	0.488	0.000	0.000		
7.0	0.505	0.017	1.820	1.040	0.790
7.5	0.511	0.023	2.555	1.829	1.579
8.0	0.516	0.028	3.168	2.649	1.640
8.5	0.521	0.033	3.781	3.500	1.701
9.0	0.526	0.038	4.395	4.380	1.761
9.5	0.533	0.045	5.255	5.291	1.821
10.0	0.541	0.053	6.238	6.231	1.880
10.5	0.549	0.061	7.223	7.201	1.939
11.0	0.556	0.068	8.085	8.200	1.998
11.5	0.567	0.079	9.442	9.228	2.056
12.0	0.573	0.085	10.182	10.284	2.114
12.5	0.583	0.095	11.418	11.370	2.171
13.0	0.592	0.104	12.531	12.484	2.228
13.5	0.6	0.112	13.522	13.626	2.284
14.0	0.609	0.121	14.638	14.796	2.340
14.5	0.621	0.133	16.127	15.994	2.396
15.0	0.63	0.142	17.245	17.220	2.451
15.5	0.64	0.152	18.489	18.473	2.506
16.0	0.65	0.162	19.735	19.753	2.560
16.5	0.661	0.173	21.106	21.061	2.614
17.0	0.671	0.183	22.355	22.395	2.668
17.5	0.682	0.194	23.730	23.699	2.609
18.0	0.692	0.204	24.981	25.052	2.705
18.5	0.702	0.214	26.234	26.410	2.717
19.0	0.717	0.229	28.115	27.774	2.728
19.5	0.725	0.237	29.120	29.143	2.738

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
20.0	0.736	0.248	30.503	30.517	2.748
20.5	0.747	0.259	31.888	31.896	2.757
21.0	0.757	0.269	33.148	33.278	2.765
21.5	0.769	0.281	34.662	34.664	2.772
22.0	0.78	0.292	36.051	36.054	2.779
22.5	0.791	0.303	37.442	37.446	2.785
23.0	0.802	0.314	38.835	38.841	2.790
23.5	0.814	0.326	40.356	40.239	2.795
24.0	0.824	0.336	41.625	41.638	2.798
24.5	0.835	0.347	43.022	43.039	2.801
25.0	0.846	0.358	44.421	44.441	2.803
25.5	0.857	0.369	45.821	45.843	2.805
26.0	0.869	0.381	47.350	47.246	2.806
26.5	0.881	0.393	48.881	49.410	2.825
27.0	0.892	0.404	50.286	50.832	2.844
27.5	0.903	0.415	51.693	52.255	2.844
28.0	0.914	0.426	53.101	53.677	2.844
28.5	0.925	0.437	54.510	55.099	2.844
29.0	0.936	0.448	55.921	56.521	2.844
29.5	0.951	0.463	57.847	57.943	2.844
30.0	0.96	0.472	59.004	59.365	2.844
30.5	0.972	0.484	60.548	60.787	2.844
31.0	0.983	0.495	61.965	62.209	2.844
31.5	0.994	0.506	63.383	63.631	2.844
32.0	1.004	0.516	64.674	65.053	2.844
32.5	1.017	0.529	66.353	66.475	2.844
33.0	1.027	0.539	67.646	67.897	2.844
33.5	1.039	0.551	69.199	69.319	2.844
34.0	1.05	0.562	70.624	70.741	2.844
34.5	1.062	0.574	72.180	72.163	2.844
35.0	1.073	0.585	73.608	73.585	2.844
35.5	1.084	0.596	75.037	75.007	2.844
36.0	1.096	0.608	76.598	76.429	2.844
36.5	1.106	0.618	77.899	77.851	2.844
37.0	1.118	0.630	79.462	79.274	2.844
37.5	1.129	0.641	80.897	80.696	2.844
38.0	1.139	0.651	82.202	82.118	2.844
38.5	1.151	0.663	83.769	83.540	2.844
39.0	1.163	0.675	85.337	84.962	2.844
39.5	1.174	0.686	86.776	86.384	2.844
40.0	1.184	0.696	88.086	87.806	2.844
40.5	1.195	0.707	89.527	89.228	2.844

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
41.0	1.207	0.719	91.101	90.650	2.844
41.5	1.218	0.730	92.545	92.072	2.844
42.0	1.23	0.742	94.121	93.494	2.844
42.5	1.241	0.753	95.567	94.916	2.844
43.0	1.252	0.764	97.014	96.338	2.844
43.5	1.263	0.775	98.463	97.760	2.844
44.0	1.274	0.786	99.912	99.182	2.844
44.5	1.285	0.797	101.363	100.604	2.844
45.0	0.504	0.016	102.865	102.026	2.844
45.5	0.504	0.016	104.368	103.448	2.844
46.0	0.504	0.016	105.870	104.871	2.844
46.5	0.504	0.016	107.373	106.293	2.844
47.0	0.504	0.016	108.875	107.715	2.844
47.5	0.54	0.052	110.378	109.137	2.844
48.0	0.549	0.061	111.476	110.559	2.844
48.5	0.559	0.071	112.699	111.981	2.844
49.0	0.572	0.084	114.292	113.403	2.844
49.5	0.581	0.093	115.397	114.825	2.844
50.0	0.591	0.103	116.627	116.247	2.844
50.5	0.602	0.114	117.982	117.669	2.844
51.0	0.612	0.124	119.217	119.091	2.844
51.5	0.623	0.135	120.577	120.513	2.844
52.0	0.634	0.146	121.940	121.935	2.844
52.5	0.644	0.156	123.181	123.357	2.844
53.0	0.654	0.166	124.424	124.779	2.844
53.5	0.664	0.176	125.669	126.201	2.844
54.0	0.675	0.187	127.040	127.623	2.844
54.5	0.686	0.198	128.414	129.045	2.844
55.0	0.698	0.210	129.915	130.468	2.844
55.5	0.709	0.221	131.293	131.890	2.844
56.0	0.718	0.230	132.422	133.312	2.844
56.5	0.731	0.243	134.056	134.734	2.844
57.0	0.742	0.254	135.440	136.156	2.844
57.5	0.752	0.264	136.699	137.578	2.844
58.0	0.764	0.276	138.213	139.000	2.844
58.5	0.775	0.287	139.602	140.422	2.844
59.0	0.786	0.298	140.993	141.844	2.844
59.5	0.799	0.311	142.639	143.266	2.844
60.0	0.81	0.322	144.033	144.688	2.844
61.0	0.833	0.345	146.953	146.782	2.094
62.0	0.85	0.362	149.114	148.854	2.072
63.0	0.864	0.376	150.897	150.608	1.754

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
64.0	0.873	0.385	152.044	152.076	1.468
65.0	0.881	0.393	153.064	153.292	1.216
66.0	0.89	0.402	154.212	154.289	0.997
67.0	0.895	0.407	154.850	155.099	0.811
68.0	0.902	0.414	155.744	155.757	0.657
69.0	0.906	0.418	156.255	156.294	0.537
70.0	0.910	0.422	156.766	156.745	0.451
71.0	0.914	0.426	157.277	157.142	0.397
72.0	0.917	0.429	157.661	157.518	0.376
73.0	0.919	0.431	157.916	157.906	0.388
74.0	0.923	0.435	158.428	158.340	0.434
75.0	0.925	0.437	158.684	158.853	0.512

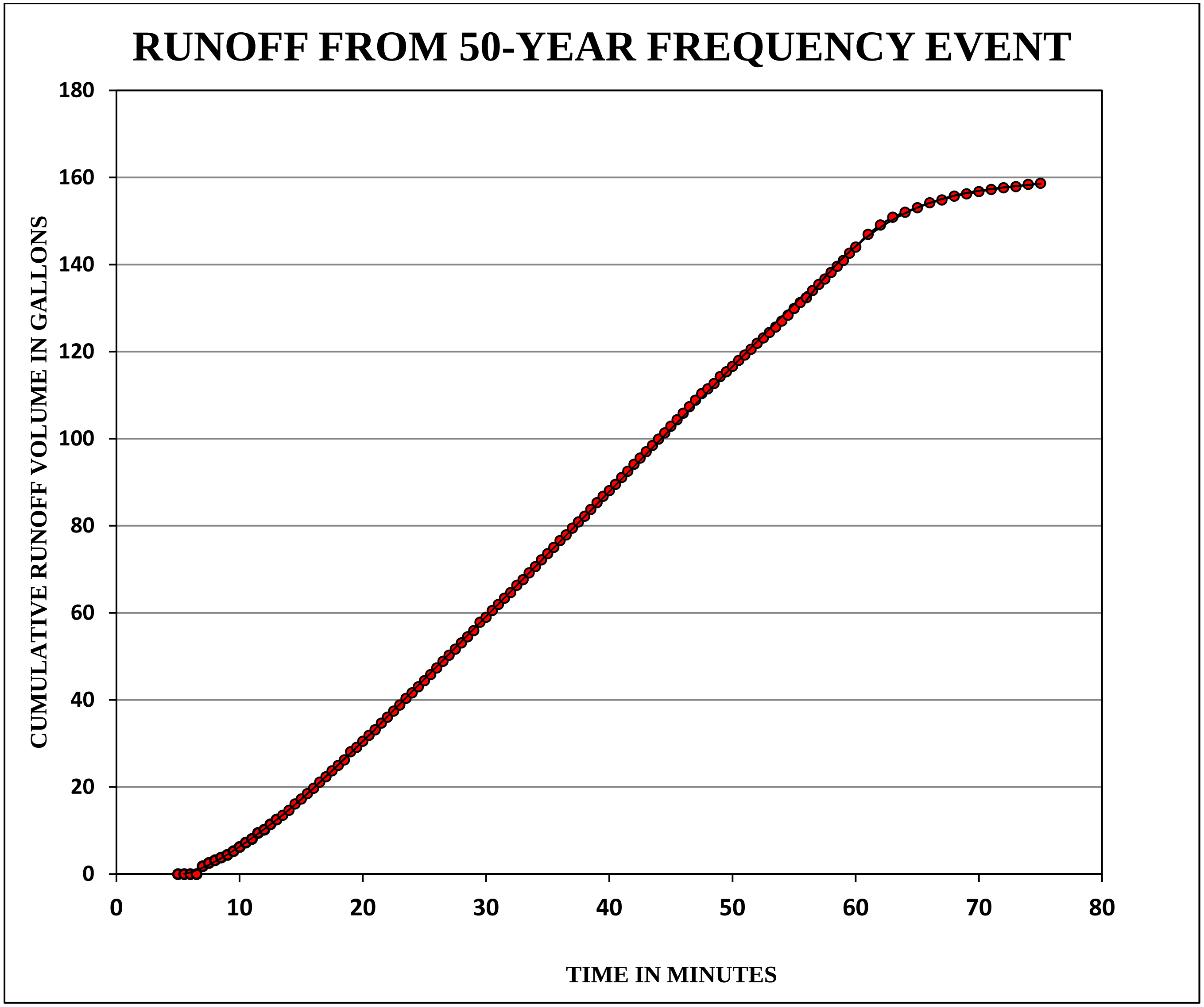

Figure 12. Measured cumulative runoff volumes from a 1-hour, 50-year return frequency rainfall event.

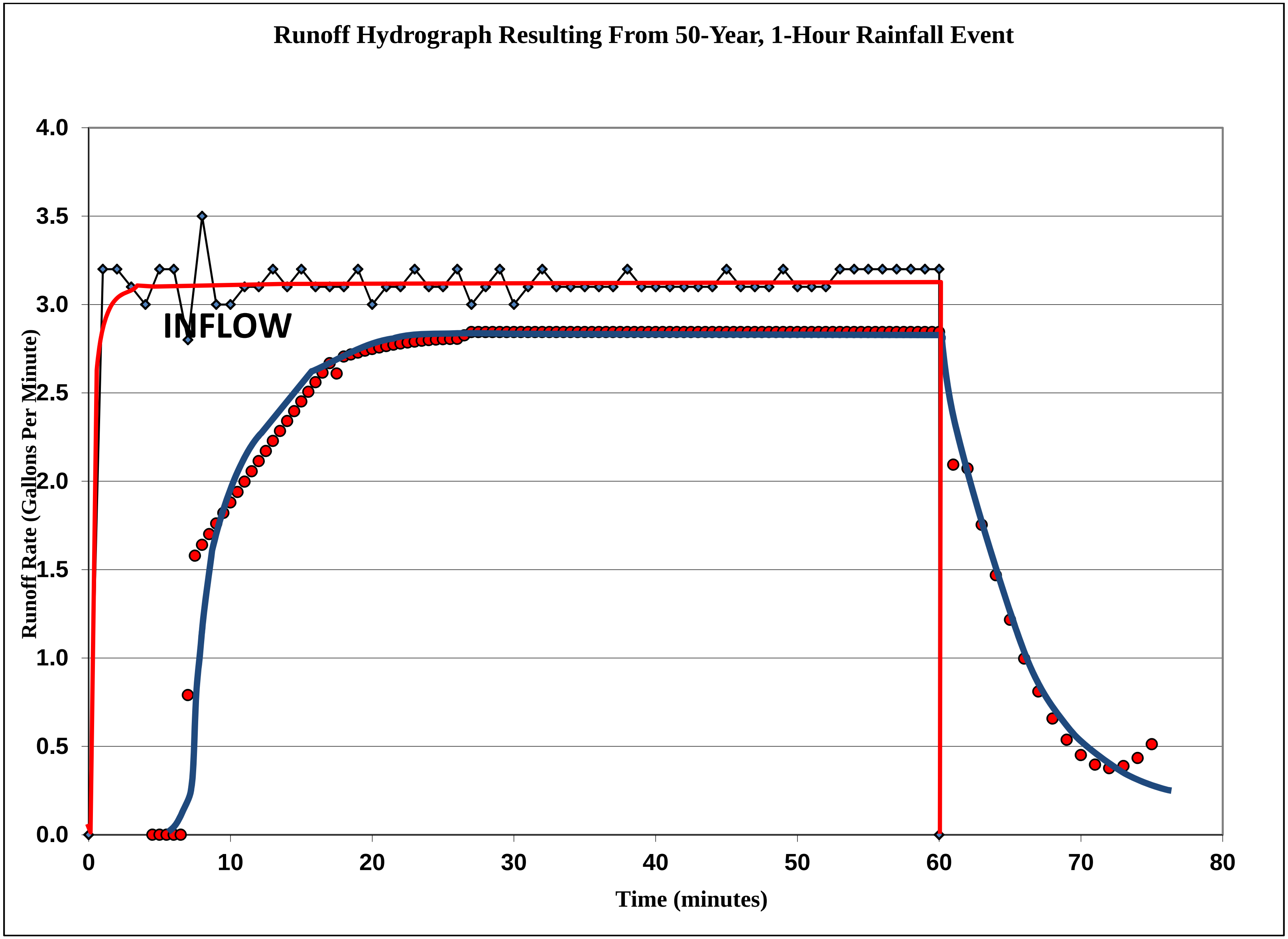

Figure 13. Measured rainfall and runoff hydrographs from a 1-hour, 50-year return frequency rainfall event.

4.7 Runoff Coefficient for 100-Year, 1-Hour Event

The runoff data for the 100-year, 1-hour rainfall event is presented in Table 4 and in Figures 14 and 15. Table 4 presents the variation of runoff depth in the catchment box through time (column 3). These depths are converted to cumulative runoff volumes in column 4. Figure 14 shows the variation of cumulative runoff through the duration of the experiment. An experimental regression curve is passed through the data points given in Figure 14. Runoff rate in gallons per minute is then computed by using the regression equation by computing the change in volume every 30 seconds. These experimental discharge values are plotted in Figure 1**5** along with the inflow discharges into the model.

Model data for computing the runoff data is as follows:

1) Start Time: 0 min
2) End Time: 60 min
3) Line Pressure: 72 pounds per square inch (psi)
4) Starting Flow-meter Reading: 154034.2 gallons
5) Ending Flow-meter Reading: 154228.6 gallons
6) Total Inflow Into model: 194.4 gallons
7) Inflow Rate: 3.25 gpm
8) Runoff Volume after 60 min: 163 gallons
9) Runoff Coefficient: 0.84

Table 4. Runoff data from a 100-year, 1-hour rainfall event (dry antecedent conditions)

Time (Minutes)	**Point Gauge (Feet)**	**Runoff Depth (Feet)**	**Runoff Volume (Gallons)**	**Computed Vol. (Gallons)**	**Runoff Rate (Gallons/Minute)**
0.0	0.494	0.000	0.000		
0.5	0.494	0.000	0.000		
1.0	0.494	0.000	0.000		
1.5	0.494	0.000	0.000		
2.0	0.494	0.000	0.000		
2.5	0.494	0.000	0.000		
3.0	0.494	0.000	0.000		
3.5	0.508	0.014	1.452		
4.0	0.515	0.021	2.310		0.000
4.5	0.52	0.026	2.922	0.586	1.172
5.0	0.527	0.033	3.781	1.912	2.652
5.5	0.535	0.041	4.763	3.244	2.664
6.0	0.542	0.048	5.623	4.581	2.675
6.5	0.552	0.058	6.854	5.925	2.687
7.0	0.562	0.068	8.085	7.274	2.698
7.5	0.571	0.077	9.195	8.629	2.710
8.0	0.58	0.086	10.306	9.990	2.721
8.5	0.59	0.096	11.542	11.356	2.732
9.0	0.6	0.106	12.779	12.728	2.744
9.5	0.612	0.118	14.266	14.105	2.755
10.0	0.621	0.127	15.382	15.488	2.766
10.5	0.632	0.138	16.748	16.876	2.777
11.0	0.643	0.149	18.116	18.270	2.787
11.5	0.655	0.161	19.610	19.669	2.798
12.0	0.6655	0.172	20.919	21.074	2.809
12.5	0.676	0.182	22.230	22.483	2.819
13.0	0.698	0.204	24.981	23.898	2.830
13.5	0.701	0.207	25.356	25.318	2.840
14.0	0.711	0.217	26.610	26.744	2.851
14.5	0.722	0.228	27.990	28.174	2.861
15.0	0.734	0.240	29.497	29.610	2.871
15.5	0.745	0.251	30.880	31.050	2.881
16.0	0.758	0.264	32.517	32.496	2.891
16.5	0.769	0.275	33.904	33.946	2.901
17.0	0.782	0.288	35.546	35.372	2.852
17.5	0.791	0.297	36.683	36.861	2.978
18.0	0.803	0.309	38.201	38.355	2.988
18.5	0.815	0.321	39.722	39.854	2.997
19.0	0.83	0.336	41.625	41.357	3.006
19.5	0.841	0.347	43.022	42.865	3.016

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
20.0	0.852	0.358	44.421	44.377	3.025
20.5	0.863	0.369	45.821	45.894	3.034
21.0	0.875	0.381	47.350	47.415	3.043
21.5	0.887	0.393	48.881	48.941	3.052
22.0	0.899	0.405	50.414	50.471	3.061
22.5	0.912	0.418	52.077	52.006	3.069
23.0	0.923	0.429	53.485	53.545	3.078
23.5	0.936	0.442	55.151	55.088	3.087
24.0	0.947	0.453	56.563	56.636	3.095
24.5	0.961	0.467	58.361	58.188	3.104
25.0	0.971	0.477	59.647	60.494	3.015
25.5	0.982	0.488	61.063	61.957	2.927
26.0	0.994	0.500	62.610	63.421	2.927
26.5	1.005	0.511	64.028	64.884	2.927
27.0	1.015	0.521	65.320	66.347	2.927
27.5	1.03	0.536	67.258	67.810	2.927
28.0	1.043	0.549	68.940	69.274	2.927
28.5	1.055	0.561	70.495	70.737	2.927
29.0	1.067	0.573	72.051	72.200	2.927
29.5	1.078	0.584	73.478	73.663	2.927
30.0	1.089	0.595	74.907	75.127	2.927
30.5	1.1015	0.608	76.533	76.590	2.927
31.0	1.114	0.620	78.160	78.053	2.927
31.5	1.125	0.631	79.593	79.516	2.927
32.0	1.136	0.642	81.027	80.980	2.927
32.5	1.148	0.654	82.593	82.443	2.927
33.0	1.159	0.665	84.030	83.906	2.927
33.5	1.172	0.678	85.730	85.370	2.927
34.0	1.183	0.689	87.169	86.833	2.927
34.5	1.195	0.701	88.741	88.296	2.927
35.0	1.206	0.712	90.183	89.759	2.927
35.5	1.218	0.724	91.757	91.223	2.927
36.0	1.228	0.734	93.070	92.686	2.927
36.5	1.241	0.747	94.778	94.149	2.927
37.0	1.252	0.758	96.225	95.612	2.927
37.5	1.263	0.769	97.673	97.076	2.927
38.0	1.275	0.781	99.253	98.539	2.927
38.5	1.29	0.796	101.231	100.002	2.927
39.0	1.299	0.805	102.418	101.465	2.927
39.5	1.318	0.824	104.928	102.929	2.927
40.0	0.504	0.000	105.507	104.392	2.927
40.5	0.516	0.012	106.086	105.855	2.927

Time (Minutes)	**Point Gauge (Feet)**	**Runoff Depth (Feet)**	**Runoff Volume (Gallons)**	**Computed Vol. (Gallons)**	**Runoff Rate (Gallons/Minute)**
41.0	0.528	0.024	107.539	107.318	2.927
41.5	0.539	0.035	108.874	108.782	2.927
42.0	0.55	0.046	110.212	110.245	2.927
42.5	0.562	0.058	111.675	111.708	2.927
43.0	0.574	0.070	113.141	113.172	2.927
43.5	0.585	0.081	114.489	114.635	2.927
44.0	0.598	0.094	116.085	116.098	2.927
44.5	0.61	0.106	117.561	117.561	2.927
45.0	0.622	0.118	119.041	119.025	2.927
45.5	0.633	0.129	120.400	120.488	2.927
46.0	0.645	0.141	121.885	121.951	2.927
46.5	0.655	0.151	123.125	123.414	2.927
47.0	0.667	0.163	124.616	124.878	2.927
47.5	0.678	0.174	125.985	126.341	2.927
48.0	0.692	0.188	127.730	127.804	2.927
48.5	0.702	0.198	128.979	129.267	2.927
49.0	0.714	0.210	130.480	130.731	2.927
49.5	0.725	0.221	131.858	132.194	2.927
50.0	0.737	0.233	133.364	133.657	2.927
50.5	0.749	0.245	134.872	135.120	2.927
51.0	0.761	0.257	136.382	136.584	2.927
51.5	0.772	0.268	137.768	138.047	2.927
52.0	0.784	0.280	139.283	139.510	2.927
52.5	0.796	0.292	140.799	140.974	2.927
53.0	0.807	0.303	142.191	142.437	2.927
53.5	0.819	0.315	143.710	143.900	2.927
54.0	0.83	0.326	145.105	145.363	2.927
54.5	0.842	0.338	146.628	146.827	2.927
55.0	0.854	0.350	148.153	148.290	2.927
55.5	0.866	0.362	149.679	149.753	2.927
56.0	0.876	0.372	150.952	151.216	2.927
56.5	0.89	0.386	152.736	152.680	2.927
57.0	0.9	0.396	154.011	154.143	2.927
57.5	0.912	0.408	155.543	155.606	2.927
58.0	0.923	0.419	156.948	157.069	2.927
58.5	0.936	0.432	158.609	158.533	2.927
59.0	0.947	0.443	160.016	159.996	2.927
59.5	0.958	0.454	161.423	161.459	2.927
60.0	0.97	0.466	162.959	162.922	2.927
61.0	0.992	0.488	165.778	165.716	2.794
62.0	1.011	0.507	168.214	167.829	2.113
63.0	1.022	0.518	169.624	169.600	1.771

Time (Minutes)	Point Gauge (Feet)	Runoff Depth (Feet)	Runoff Volume (Gallons)	Computed Vol. (Gallons)	Runoff Rate (Gallons/Minute)
64.0	1.034	0.530	171.164	171.064	1.465
65.0	1.042	0.538	172.190	172.259	1.195
66.0	1.049	0.545	173.088	173.219	0.961
67.0	1.055	0.551	173.858	173.982	0.762
68.0	1.059	0.555	174.372	174.582	0.600
69.0	1.064	0.560	175.013	175.056	0.474
70.0	1.068	0.564	175.527	175.441	0.384
71.0	1.070	0.566	175.784	175.771	0.330
72.0	1.073	0.569	176.169	176.083	0.312
73.0	1.077	0.573	176.682	176.412	0.330
74.0	1.078	0.574	176.810	176.796	0.384
75.0	1.080	0.576	177.067	177.269	0.473

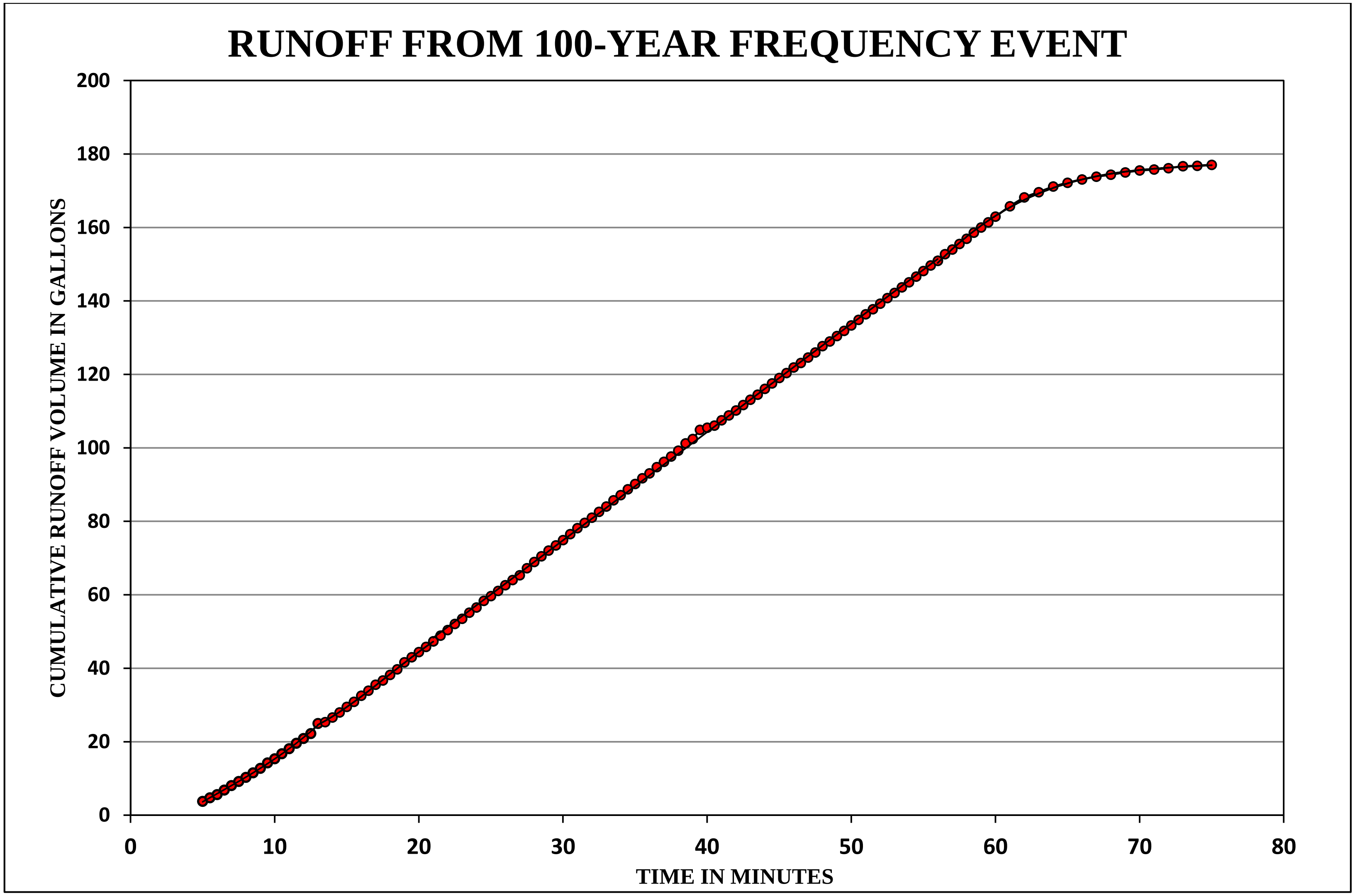

Figure 14. Measured cumulative runoff volumes from a 1-hour, 100-year return frequency rainfall event.

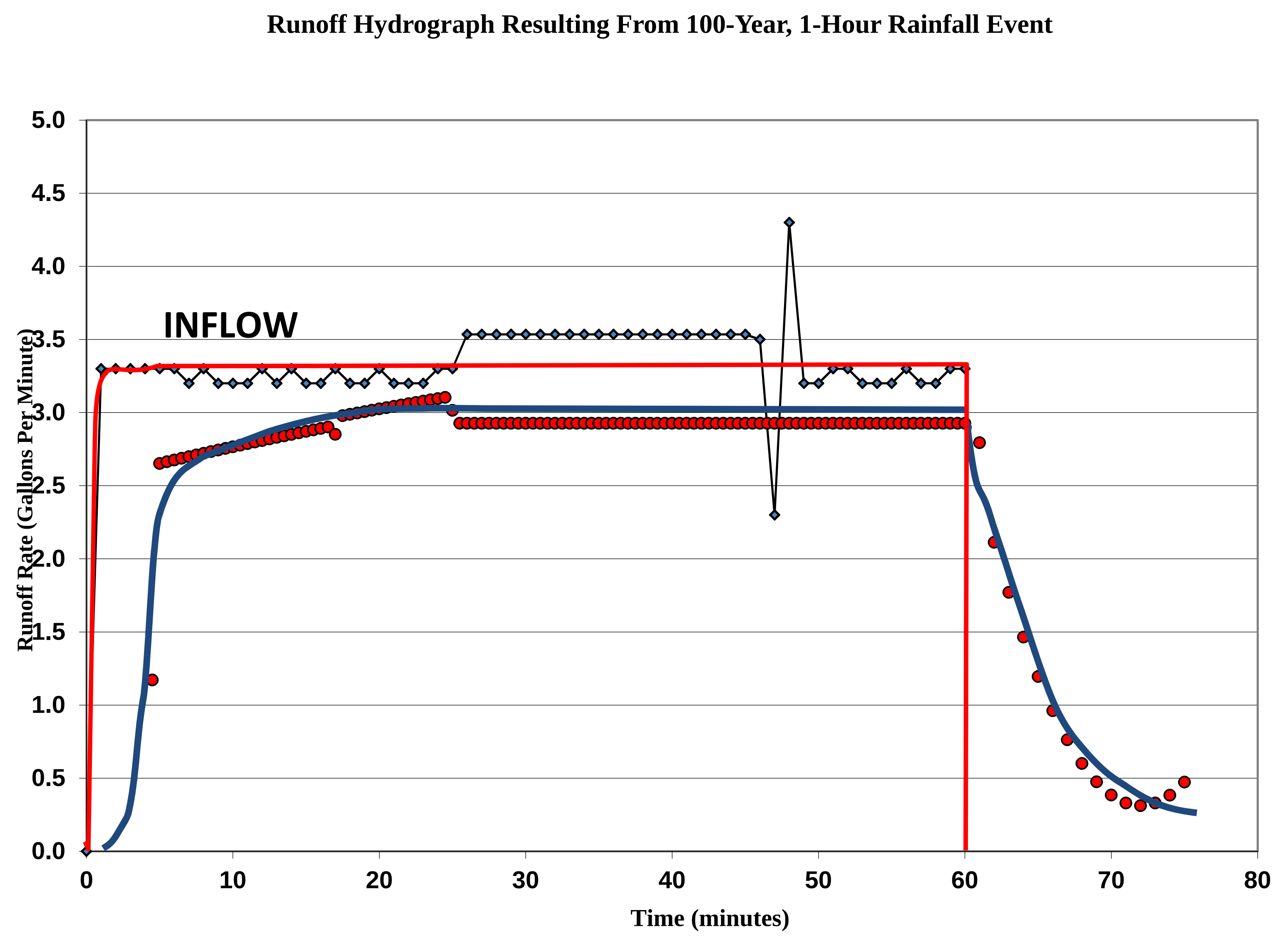

Figure 15. Measured rainfall and runoff hydrographs from a 1-hour, 100-year return frequency rainfall event.

5. SUMMARY

The study entitled "Modeling Ballasted Tracks for Runoff Coefficient C" investigated ballasted tracks to determine runoff coefficients corresponding to rainfall events with different recurrence intervals. In the following sections, the findings for C values are summarized.

4.8 Runoff Coefficients

Tabulated runoff coefficients for railroad yards or areas with gravel surfaces range between 0.2 and 0.4. These coefficients reflect the infiltration potential of such surfaces. However, along ballasted light rail tracks, in order to drain the tracks rapidly, a special design is used. This design aims at reducing soil saturation. Below the ballast and sub-ballast regions, a compacted clay subgrade with 2.5 percent cross-slope is utilized. As a result, for light rail tracks, higher runoff coefficients than the tabulated values for gravel surfaces or railroad yards are expected.

The runoff coefficient experiments resulted in the following values for the targeted 25-yr, 50-yr, and 100-yr return frequencies:

Target Return Frequency	Target Model Inflow	Actual Model Inflow	Actual Return Frequency	Computed Runoff Coefficient
25-year	2.60 gpm	2.30 gpm	13-year	0.66
50-year	3.10 gpm	3.13 gpm	50-year	0.77
100-year	3.50 gpm	3.25 gpm	75-year	0.84

In selecting return frequencies for runoff coefficient experiments, 25-yr, 50-yr, 100-yr frequencies were aimed. Figure 16 shows the variation of model inflows (gpm) and rainfall intensities (in/hr) with return frequencies for the 1-hour rainfall events. As shown in this figure, due to the small variation in model inflows in the laboratory experiments, simulated events corresponded to 13-year, 50-yr, and 75-year return-frequency events. In the regression analysis, these actual return frequencies were regressed with the corresponding runoff coefficients. As shown in Figure 17, the resulting relationship is an exponential relationship in the form of:

$$\text{Runoff Coefficient, } C = 0.46 \text{ Return Frequency}^{0.14}$$

Beyond 10-yr frequency events, since soil saturation occurs sooner, the C values increase rapidly, following a power relationship. The limiting value of C should be set to 0.90.

It is possible to relate the runoff coefficient for lower frequency events by selecting a base factor for 2 to 10 year events, and then applying a multiplication factor. Using a base runoff coefficient of 0.55 for the frequent events, the multiplication factors for 25-, 50-, and 100-year events become:

Return Frequency	Runoff Coefficient	Multiplication Factor
25-year	0.66	1.2
50-year	0.77	1.4
100-year	0.84	1.5

Figure 17 shows the runoff coefficients obtained for frequent events (2-, 5-, 10-year) on the same chart as the 25-, 50-, and 100-year return frequency events.

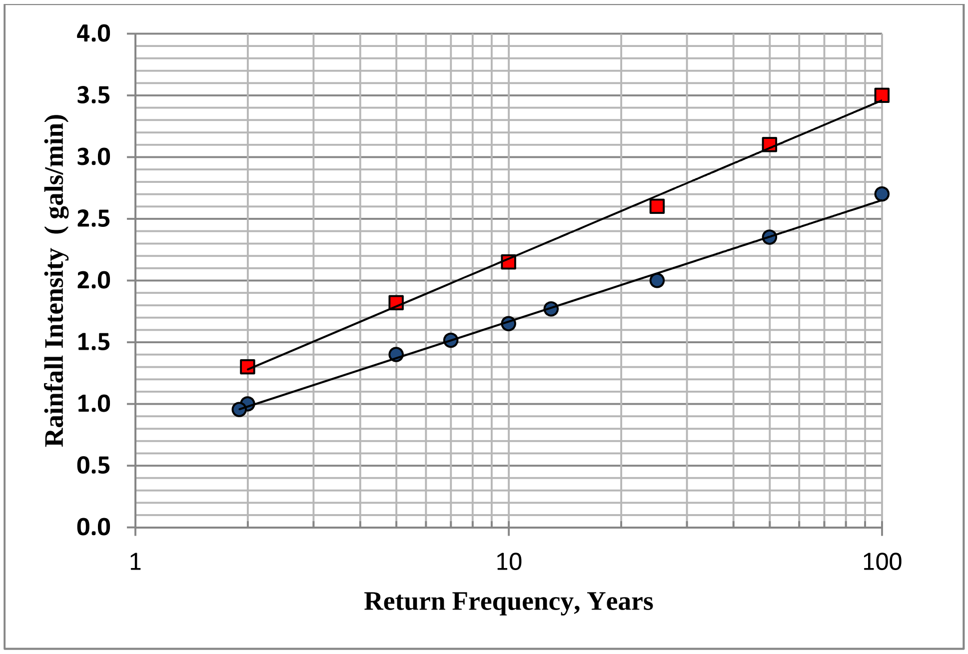

Figure 16. Modeled rainfall intensities for various return-frequency events with 1-hr duration.

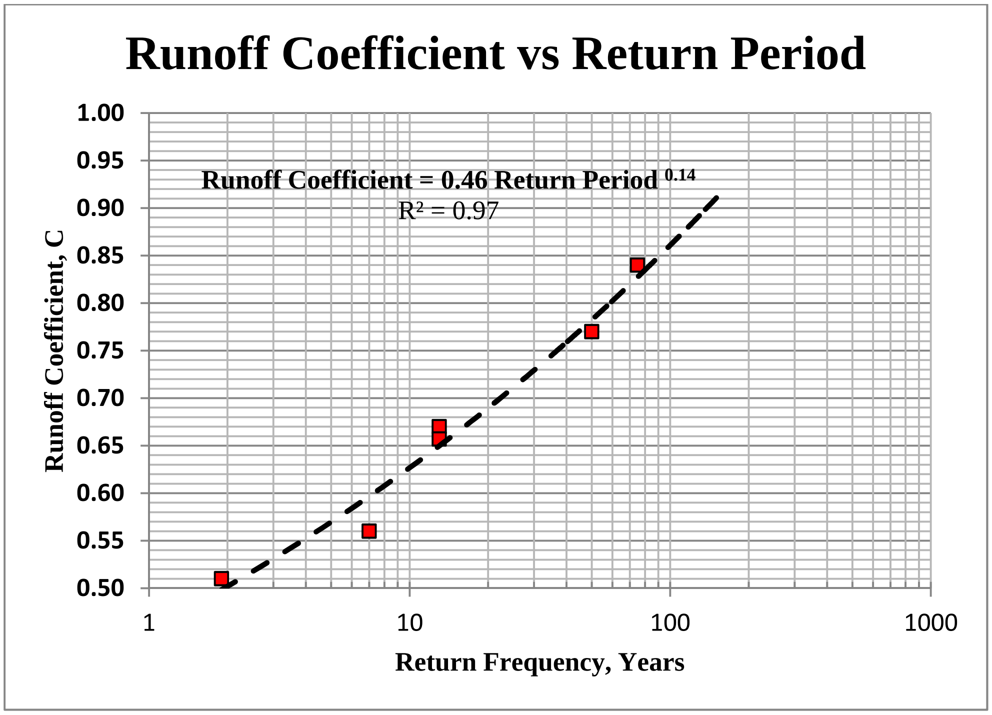

Figure 17. Variation of runoff coefficients with return-period for all experiments.

In the runoff coefficient experiments, the compacted subgrade was simulated by an epoxy-coated plywood surface. This approach would provide for more of the rainfall to be collected thereby resulting in slightly higher C values than would be observed in the prototype. Since the compacted prototype subgrade is subjected to a constant cyclic loading, over a period of 10 to 15 years of light rail operations, this conservatism is expected to affect results minimally.

The lag time experienced from the beginning of the rainfall event to the time when runoff is observed is a function of rainfall intensity and antecedent soil moisture contents of the ballast and more importantly the sub-ballast. Since the ballast is composed of large particles with high porosity, the majority of rainfall is immediately transmitted to the underlying sub-ballast region. In the early stages of the rainfall event, the interstitial space between particles is filled with water displacing the air from the voids. Once the soil is saturated (voids between particles filled by water), runoff initiates. Since the volume of voids in a unit length of the ballasted track is a constant, higher the intensity of the rainfall, faster the voids are filled with water and faster the initiation of runoff. Similarly, higher the antecedent soil moisture contents of the ballasted tracks prior to the rainfall event, smaller the volume of voids to store rainfall and faster the initiation of runoff.

In the runoff experiments, in order to remove the variability of moisture content, a minimum drying period of 7 days was used. For the 25-yr, 50-yr and 100-yr rainfall events, experiments show that initiation of runoff is approximately 9 minutes, 7 minutes, and 6 minutes from the start of event The amount of rainfall supplied to the ballasted tracks corresponding to these lag times are 0.3 in (=2 in/hr x9/60), 0.3 in (=2.35*7/60) and 0.3 in (= 2.8x6/60). In other words, the initial 0.3 inch of rainfall falling on the tracks is retained within the body of the ballasted tracks resulting in no runoff. However, once the soil saturation is reached, ballasted tracks are designed to quickly drain the rainfall. The runoff experiments for the more frequent events (2-yr, 5-yr, and 10-yr return frequencies) show that for the initial 0.5 inch of rainfall, the runoff is very little and mostly retained within the ballasted tracks.

Some watershed applications (e.g. light rail tracks located at the toe region of a vegetated embankment) require estimation of runoff coeffecent for composite areas. Appendix A provides an area-weighted procedure to determine a combined *C* value for Rational Method for composite areas. This method uses tabulated runoff coefficient values for vegetated embankments along with the newly determined C values for ballasted tracks to determine an average *C* value to be used in runoff estimations.

6. CONCLUSIONS

In selecting the rainfall intensity for the Denver area, past storms had shown that vast majority of the storms had their most intense period last for 1 hour. Therefore for the 25-year, 50-year, 100-year return frequency rainfall events, 1-hour duration was chosen.

Conclusions from the study:

1. Runoff resulting from various return frequency rainfall events was determined. A relationship between return frequency and the runoff coefficient, *C*, was developed for Denver hydrology. For the more frequent 2-year, 5-year, 10-year events, the average *C* value is approximately 0.55. For 25-year, 50-year, and 100-year return frequency rainfall events, the *C* value is in excess of 0.55 and is expressed in terms of multiplication factors of this average value.
2. In general, runoff coefficient for ballasted tracks is significantly larger than the previously tabulated values for railroad yards that vary between 0.2 and 0.4. The higher runoff coefficient reflects the design of ballasted tracks to drain rainfall as quickly as possible.
3. The detention time in the ballasted tracks was determined. According to the laboratory study, the detention time is a function of antecedent soil moisture content and rainfall intensity. In general terms, for dry antecedent conditions the initial 0.3 inch-0.4 inch of rainfall is detained in the ballasted tracks. The initial 0.5 inch of rainfall produces only a small amount of runoff. For 25-year, 50-year, and 100-year events, the runoff starts 9 minutes, 7 minutes, and 6 minutes after the start of the event.

REFERENCES

1) American Society of Civil Engineers and the Water Pollution Control Federation, “Design and Construction of Sanitary and Storm Sewers,” 1969.

2) CDOT Drainage Design Manual (2004), Chapter 7.

3) Kuichling, E., “The Relation between the Rainfall and the Discharge of Sewers in Populous Districts,” Transactions, American Society of Civil Engineers, Vol. 20, pp1-56 (1889).

4) Overton, D.E. and Meadows, M.E., “Stormwater Modeling,” Academic Press (1977).

5) Texas DOT Hydraulic Design Manual (2011), http://onlinemanuals.txdot.gov/txdotmanuals/hyd/manual_introduction.htm

6) Texas DOT Hydraulic Design Manual (2011), http://onlinemanuals.txdot.gov/txdotmanuals/hyd/the_rational_method.htm

7) Urban Drainage and Flood Control District, “Urban Storm Drainage Criteria Manual”, 2001.

8) Viessman, W. and Lewis, G.L., “Introduction to Hydrology,” Fifth Edition, Prentice Hall (2003).

9) Young, B. C., “Empirical Determination of Rational Method Coefficients,” Journal of Hydrologic Engineering, ASCE, Vol. 14, No. 12, pp. 1283-1289 (Nov/Dec 2009)

APPENDIX A
ESTIMATING RUNOFF COEFFICENT FOR COMPOSITE AREAS

For areas consisting of ballasted tracks and roadway embankment, the peak discharges can be computed using an area-weighted runoff coefficient determined as shown below.

Figure B-1. Ballasted tracks and roadway embankment.

Ballasted Area

Runoff Coefficient: C_1
Area (acres): A_1

Roadway Embankment

Runoff Coefficient: C_2
Area (acres): A_2

Area-Weighted Runoff Coefficient is:

$$C_{avg} = \frac{A_1\,C_1 + A_2\,C_2}{A_1 + A_2}$$

and,

$$Q_p = C_{avg}\, i \; (A_1 + A_2)$$

Where i=rainfall intensity in in/hr; Q_p= peak discharge in cfs.