HEC-HMS Model Preparation and Calibration for Runoff Simulation; Case Study of the Red Butte Creek Watershed, Utah

Semester Project Report

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CEE 6450- Hydrologic Modeling

May 6, 2016

1. **Introduction**

1.1. HEC-HMS

The hydrologic model HEC-HMS (Hydrologic Engineering Center, Hydrologic Modeling System) is developed by the US Army Corps of Engineers. It is a commonly used software that is designed to simulate the precipitation–runoff processes of dendritic watershed systems (HEC, 2000). HEC-HMS is a lumped model that offers a wide variety of methods for basin loss, channel routing, infiltration modeling and so on, hence the model was used for the project. It is often used in combination with the Geospatial Hydrologic Modeling Extension, HEC-GeoHMS. HEC-GeoHMS is an ArcGIS extension that helps create the input files for HEC-HMS. HEC-GeoHMS was used to prepare input files based on SCS loss and transform method.

1.2. Study Area

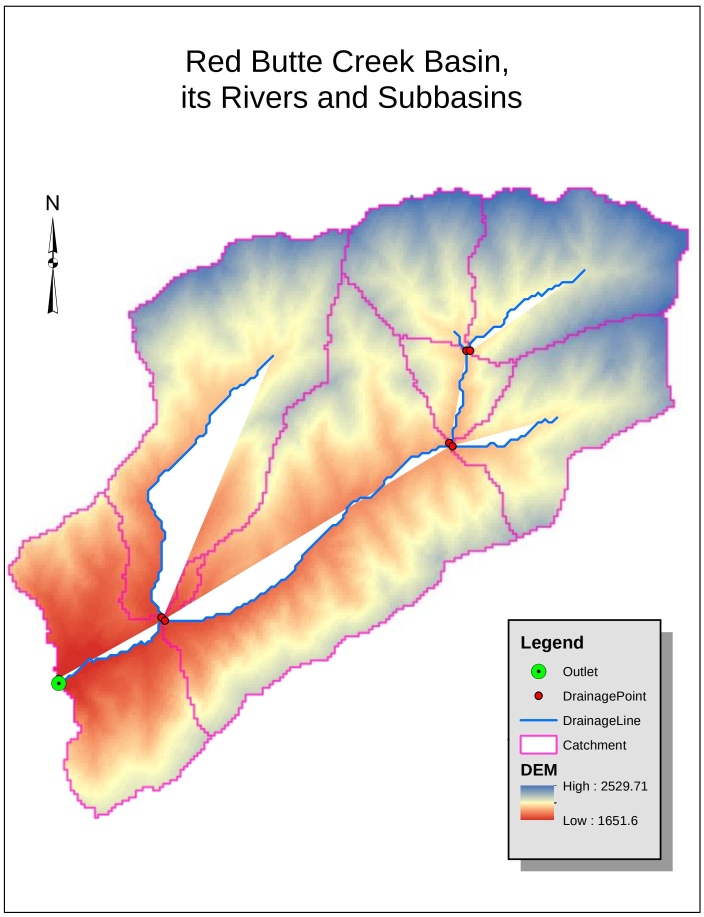

Figure1. Red Butte Creek River basin with its River and subbasins.

Red Butte Creek Basin is a small watershed located in Eastern side of the Salt Lake City. It covers an area of 18.8 km^2 with elevation between 1500 m to 2400 m. The Red Butte Creek (RBC) is a small creek flowing from the watershed, which is especially large at the time of rainfall. Although small, the creek flows thought the watershed into the dense Salt Lake City, hence any flood in the creek can potentially create damages in the downstream urban area. The goal of the project is to create a HEC-HMS rainfall-runoff model to simulate discharge in the creek, thereby helping water resources engineers plan for any flood protection, or other water management issues. The outlet of the watershed is located at lower left part of the watershed as can be seen from Fig.1. The outlet is upstream to a reservoir. The outlet just above the reservoir was chosen because of the proximity of the outlet to a United States Geological Survey (USGS) station with station no: 101722000, which has historical daily flow recordings. The discharge data from the USGS station was used for model calibration.

2. Methodology

2.1. Data Acquisition

2.1.1. Gridded Dataset

A 30-meter grid of USGS Digital Elevation Model (DEM), 30-meter National Land Cover Dataset (NLCD) dataset, 30 m impervious percent gridded data was downloaded using a Python Script (Dahal, 2016) that downloads the data calling the ArcGIS services. These data could also be downloaded from the USDA:NRCS:Geospatial Data Gateway (2016). All of the data was downloaded in 30m resolution to maintain the consistency in data used. Figure 2 contains the dataset for the Red Butte Creek watershed.

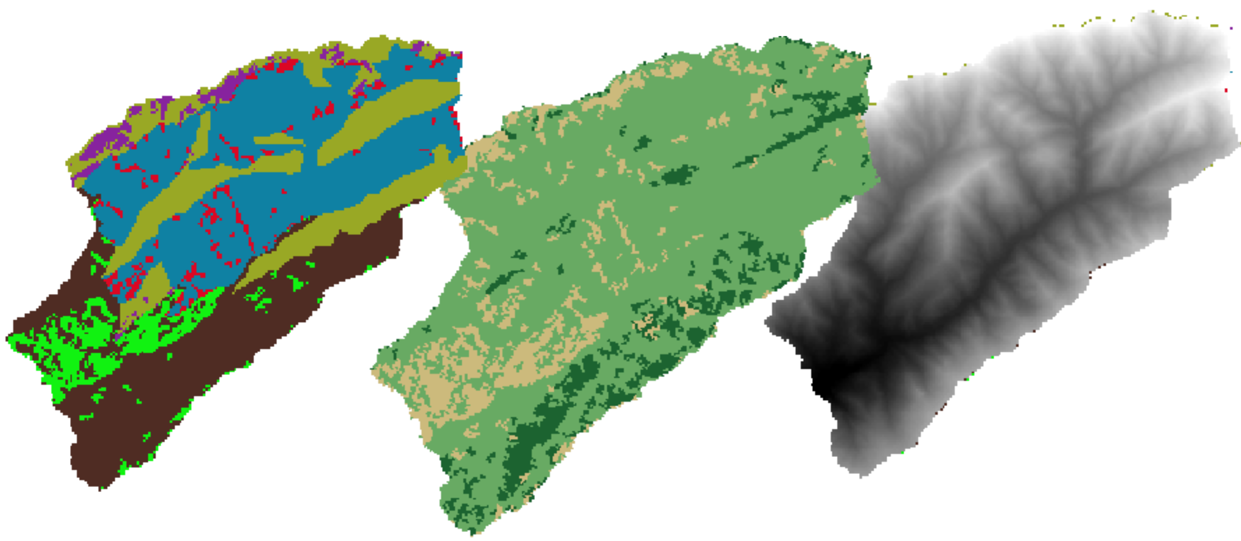

Figure 2. Gridded files for the RBC watershed; CN grid, NLCD land Use and DEM respectively from right

2.1.2. NRCS- Soil Data

The USDA:NRCS:Geospatial Data Gateway (2016) was used to download the National Resources Conservation Service (NRCS) high resolution soil dataset SSURGO (Soil Survey Geographic Dataset). The SSURGO data contains the data required for SCS method such as Hydrological Soil Group (HSG) soil data, which was derived using a Python Script (Dahal, 2016). The HSG soil data along with the NLCD land use data were used to derive CN grid.

Similarly, SSURGO database was used to extract soil texture class located in the region. For each of those class, Rawls et al (1983) lookup table was used to calculate the soil related properties such as Saturated Hydraulic conductivity, suction pressure, saturated soil moisture. Initial soil moisture was approximated somewhere between the field capacity and the effective porosity.

2.1.3. Rainfall / Meteorological Data

The rainfall data from the four GAMUT (Gradients along Mountain to Urban Transitions) rainfall stations, and four other nearby rainfall stations were considered for the study. GAMUT stations are high resolution ecohydrologic observatory to study water (iUTAH GAMUT, 2014). The four GAMUT sites in the watershed are: 1) Red Butte Creek above Red Butte Reservoir Climate (Site Code: RB_ARBR_C), 2) Green Infrastructure Climate (Site Code: RB_GIRF_C), 3) Knowlton Fork Climate (Site Code: RB_KF_C), and 4) Todd's Meadow Climate (Site Code: RB_TM_C). Stations were used to calibrate the model. Also, other rainfall stations were considered because the data form GAMUT sites were marked “Provisional, and subject to revision”. The non-GAMUT climatic stations considered are 1) Bountiful- val verda, 2) City Creek WTP, 3) Salt Lake Triad, 4) Hardscrabble, 5) Lookout Peak, and 6) Louis meadow, derived from Ames, Daniel P., et al (2012).

2.1.3.1. Rainfall Data Variation

The GAMUT climatic stations are fairly new sites that have started recording measurements for only about three years, and the quality of data is marked “Provisional”. Also, the data from other climatic statins seem to vary quite a bit. The measurements from the four GAMUT climatic stations, and from the four nearby climatic stations are shown in the Fig.7 and Fig8 in Appendix B. The mean and max value of rainfall is shown in the tables below, one for GAMUT sites, and one for non-GAMUT sites. This table helps us see the discrepancy in the rainfall data measurements in the six rainfall station located very close to one another. This could be a result of variation in elevation, or difference in microclimate of the region, or inaccuracy in measurement.

Looking at the discharge in the USGS streamflow gage, the climatic stations with very high precipitation did not make sense, in terms of volume balance of the watershed. The high rainfall measured in the stations result in very low rainfall-runoff coefficient, lower than 0.2. Hence, for the project, two climatic stations with lower mean precipitation were considered, Salt Lake Triad from non-GAMUT site, and Green Infrastructure (SiteCode: RB_GIRF) were considered for the model.

Table1: Non GAMUT Climatic station and mean and max precipitation in record over the period of 01/01/2000 to 05/29/2012

Climate Station	Time period	Mean daily precipitation (mm)	Max daily Precipitation (mm)
BOUNTIFUL- VAL VERDA, UT, (GHCN)	01/01/2000 – 05/29/2012	1.651	60.7
CITY CREEK WTP, UT (GHCN)	01/01/2000 – 05/29/2012	1.836	58.2
SALT LAKE TRIAD CTR, UT, (GHCN)	01/01/2000 – 05/29/2012	1.118	30.5
Hardscrabble, Source SNOTEL	01/01/2000 – 05/29/2012	2.877	86.4
Lookout Peak, (SNOTEL)	01/01/2000 – 05/29/2012	3.255	111.8
Louis Meadow, (SNOTEL)	01/01/2000 – 05/29/2012	2.416	81.3

Table2: GAMUT Climatic Station and mean and max precipitation in record over the period of 01/01/2015 to 12/31/2015

GAMUT Climatic Stations	Time Period	Mean Precipitation (mm)	Median Precipitation (mm)	Max Precipitation (mm)
RB_ARRC_C_QC (Above red butte creek climatic site)	1/1/2015 - 12/31/2015	2.15	0.8	43.1
RB_TM_C_QC (Todds Meadow Climate site)	1/1/2015 - 12/31/2016	3.01	0.9	62
RB_KF_C_QC (Knowlton Fork Climate)	1/1/2015 - 12/31/2017	3.81	2.1	83
RB_GIRF (Green infastructure)	1/1/2015 - 12/31/2018	2.00	0.8	34.3

2.1.3.2. Rainfall Comparison to Other Stations

2.2. Model Description

HEC-HMS model was prepared using HEC-GeoHMS, with the final Model schematic shown in the Fig.3. Detail screencast of how the model was prepared is given in Appendix F. The DEM and river shapefile were used to generate most of DEM related data, such as flow direction, flow accumulate, etc. and finally the subbasins. The summary of the steps undertaken in HEC-GeoHMS are listed in Appendix E. The detail screencast of the process is shown in Appendix F.

2.2.1. Subbasin

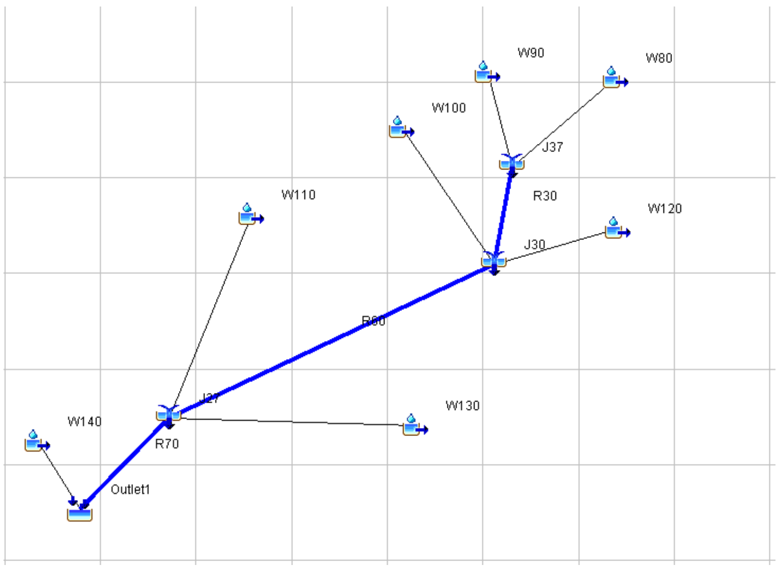

Figure 3. HMS Model Schematic of the Model for the RBC watershed

There are seven subbasin in the model; W80, W90, W100, W110, W120, W130 and W140. The gridded curve number (CN) technique enables spatially distributed infiltration calculations. Infiltration capacity is quantified in a parameter derived by the Soil Conservation Service (SCS) called the CN. The CN is a method for determining storm runoff over an area based on land use, soil and land cover type, and hydrologic soil group (US SCS, 1986). Soil groups are determined based on type and infiltrability of a soil. The infiltration loss method is derived from a set of empirical equations that define the partitioning of rainfall into infiltration and runoff,

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ ----- (1)}$$

$$I_a = 0.2S \quad \text{ ---- (2)}$$

$$S = \frac{1000}{CN} - 10 \text{ ---(3)}$$

Substituting Eq. (2) into Eq. (1) gives

$$Q = \frac{(P - 0.2 * S)^2}{P + 0.8 * S} \text{----- (4)}$$

Where,

Q = runoff in inches
P = rainfall in inches
S = potential maximum retention
Ia = initial abstraction
CN = runoff curve number

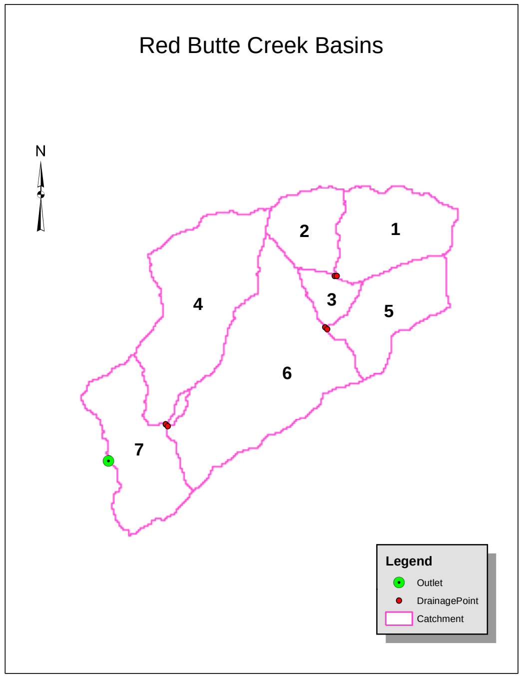

Figure 4. The seven subbasins in the Red Butte Creek watershed

This CN parameter was derived for each grid cell using a script (Appendix D) that combines SSURGO soils data with the National Land Cover Dataset (NLCD) data layer, using Table3 which is a lookup table that maps NLCD land cover to Hydrologic Soil Group (HSG) and CN no. For the Red Butte Creek watershed, the soils are uniformly classified into Hydrologic Soil Group A, B, and C.

However, the land cover in the entirety of watershed is mostly forest and bushes. hence the average value for CN for most subbasin are approximately in the range 60–75. Initial abstraction is a variable parameter that takes into account losses prior to the start of runoff such as interception and depression storage. Evapotranspiration losses are considered negligible for the preliminary model due to several factors: the intensity of the storm being modeled, the continuous saturation of the air, and the resulting assumption that ET volume is negligible compared to runoff volume.

Table 3. Lookup table for NLCD land use and Hydrologic Soil Group (HSG) and CN value

NLCD Land Use Category	Land Use Code	CN value for Hydrologic Soil Group			
		A	B	C	D
Open Water	11	0	0	0	0
Perennial Ice/Snow	12	0	0	0	0
Developed, Open Space	21	57	72	81	86
Developed, Low Intensity	22	63	77	85	88
Developed, Medium Intensity	23	81	88	91	93
Developed, High Intensity	24	89	92	94	95
Barren Land	31	77	86	91	94
Barren Land (Rock/Sand/Clay)	31	77	86	91	94
Deciduous Forest	41	36	60	73	79
Evergreen Forest	42	36	60	73	79
Mixed Forest	43	36	60	73	79
Dwarf Scrub	51	35	56	70	77
Shrub/Scrub	52	35	56	70	77
Herbaceous	72	35	56	70	77
Grassland/Herbaceous	71	49	69	79	84
Sedge/Herbaceous	72	35	56	70	77
Lichens	73	77	86	91	94
Moss	74	68	79	86	89
Hay/Pasture	81	49	69	79	84
Pasture/Hay	81	49	69	79	84
Cultivated Crops	82	49	69	79	84
Woody Wetlands	90	30	55	70	77
Emergent Herbaceous Wetlands	95	30	58	71	78

Table 4. Subbasin characteristics

Subbasin	Area (mi2)	CN	Impervious Percent (%)	Longest Flowpath (m)	Lag time (min)	Downstream	Loss Method	Transform Method
W80	0.88	65.6	1.0	2614	18.4	J37	SCS & Green Ampt	SCS
W90	0.51	69.6	0.0	2454	11.1	J37	"	"
W100	0.22	70.0	1.0	2443	7.89	J30	"	"
W110	1.63	68.4	1.0	2494	28.4	J27	"	"
W120	0.77	70.0	1.0	2293	17.0	J30	"	"
W130	2.15	74.8	0.0	2260	24.7	J27	"	"
W140	1.04	78.4	0.0	2200	10.2	Outlet1	"	"

2.2.2. Loss Method

2.2.2.1. SCS Loss Method

SCS Curve Number method was used as the subbasins' loss method. The SCS method of loss requires data for Curve and Impervious percentage in the basin. The CN for each basin is derived from the CN grid prepared earlier, and the Impervious Percentage grid downloaded using the ArcGIS web services. For RBC watershed, the CN values varies from 65 – 78. The impervious percentage for each watershed is below 1%.

2.2.2.2. Green and Ampt Loss Method

Green Ampt model is a conceptualization of the actual physical processes in which the hydraulic conductivity is assumed to decrease exponentially from the saturated condition, as is often found in real soils. This means that it is less likely to estimate the infiltration better at early time during a storm event. Because of this reason, Green Ampt Loss method was used. The details of Green Ampt values used for each subbasin in the region is given in Appendix A.

2.2.3. Transform Method

The total precipitation that falls in any watershed does not convert as surface runoff, there are different losses such as infiltration, evapotranspiration etc. Only a portion of total precipitation contribute to direct runoff, which is calculated by the Transform method. The transform method used was the SCS unit hydrograph method. This method requires values for Lag Time in minutes. The value is calculated by HEC-GeoHMS, but can also be calculated manually. Lag time is a function of the average CN value for the subbasin, the longest flow path, slope of the basin etc. The equation 5 and 6 shows the calculations of the lag time, in hour.

$$Lag\ time\ (in\ hour) = 0.6 * T_c$$

$$T_c = \frac{l^{0.8}\,(S+1)^{0.7}}{1140\,Y^{0.5}}$$

Where,

L = Lag (in hour)
Tc = time of concentration (hour)
l = flow length (ft)
Y = average watershed land slope (%)
S = maximum potential retention (inch)
= 1000/CN - 10

2.2.4. Baseflow Method

Baseflow can be an important parameter in most rainfall runoff model because it defines a minimum river depth over which additional runoff accumulates. Models that neglect baseflow may underestimate water levels and therefore fail to identify inundated reaches. Baseflow is separated using the Web Based Hydrograph Analysis Tool (WHAT analysis tool) provided by Purdue University. The average monthly summation of the baseflow provided by the tool was considered the baseflow for the outlet point. The total baseflow value per month (table below) was divided into each of the seven subbasins based by using the weighted average of the each subbasin area.

Table5A: Monthly Baseflow separated by WHAT for the outlet for 2015.

Month	Baseflow for different sub-basins for 2015							
	Sub-basin	S1	S2	S3	S4	S5	S6	S7
	Area in percentage	0.122	0.071	0.030	0.227	0.107	0.299	0.144
Jan	0.5855	0.0713	0.0417	0.0176	0.1328	0.0629	0.1749	0.0844
Feb	1.0611	0.1293	0.0755	0.0319	0.2407	0.1140	0.3170	0.1530
Mar	1.0655	0.1298	0.0758	0.0320	0.2417	0.1145	0.3183	0.1537
Apr	1.1980	0.1460	0.0852	0.0360	0.2717	0.1287	0.3579	0.1728
May	3.0310	0.3693	0.2156	0.0910	0.6875	0.3256	0.9055	0.4372
Jun	2.7087	0.3301	0.1927	0.0813	0.6144	0.2910	0.8092	0.3907
Jul	1.2065	0.1470	0.0858	0.0362	0.2737	0.1296	0.3604	0.1740
Aug	0.7606	0.0927	0.0541	0.0228	0.1725	0.0817	0.2272	0.1097
Sep	0.5760	0.0702	0.0410	0.0173	0.1307	0.0619	0.1721	0.0831
Oct	0.6432	0.0784	0.0458	0.0193	0.1459	0.0691	0.1922	0.0928
Nov	0.4770	0.0581	0.0339	0.0143	0.1082	0.0512	0.1425	0.0688
Dec	0.1061	0.0129	0.0076	0.0032	0.0241	0.0114	0.0317	0.0153

Table5B: Monthly Baseflow separated by WHAT for the outlet for 2010 - 2011

Area		Baseflow for different sub-basins for Oct2010-Sep2011						
	Sub-basin	S1	S2	S3	S4	S5	S6	S7
	Area in percentage	0.122	0.071	0.030	0.227	0.107	0.299	0.144
Oct	1.14	0.139	0.081	0.034	0.259	0.122	0.341	0.164
Nov	1.35	0.165	0.096	0.041	0.306	0.145	0.403	0.195
Dec	1.66	0.202	0.118	0.050	0.377	0.178	0.496	0.239
Jan	1.99	0.242	0.142	0.060	0.451	0.214	0.594	0.287
Feb	2.1	0.256	0.149	0.063	0.476	0.226	0.627	0.303
Mar	4.22	0.514	0.300	0.127	0.957	0.453	1.261	0.609
Apr	11.6	1.414	0.825	0.348	2.631	1.246	3.465	1.673
May	24.92	3.037	1.773	0.748	5.653	2.677	7.445	3.594
Jun	23	2.803	1.636	0.691	5.217	2.471	6.871	3.317
Jul	8.15	0.993	0.580	0.245	1.849	0.876	2.435	1.176
Aug	4.51	0.550	0.321	0.135	1.023	0.485	1.347	0.651
Sep	2.77	0.338	0.197	0.083	0.628	0.298	0.827	0.400

2.2.5. Reach

There are three reaches in the watershed model. R30, R60 and R70. The information in the reach section of the model requires information based on which the routing is performed. The model prepared here uses Muskingum method. This method of routing requires values for two Muskingum constants; K (in hour) and X. These values are initially estimated to be 0.6 and 0.2 respectively, but later calibrated using the observed flow to obtain a more precise value.

2.2.6. Meteorological Data

Multiple runs were made using the different meteorological time series from different rainfall stations. Also, different time period of rainfall was used for different runs. The summary of the runs is provided in the table below:

2.2.7. Control Time

There were multiple model runs prepared in the process to obtain a mode that best simulates the rainfall-runoff pattern in the region. As mentioned before, two sources of precipitation data were used; one from GIRF (GAMUT) climatic site, and the other from Salt Lake Triad station were used. The GIRF station was a new one, so we did not want to use data that they measured when they just began operating. Hence, model was run with the precipitation data form 01/01/2015 to 12/31/2015. However, for the Salt Lake Triad station, time period of 01/10/2010 to 30/09/2011 selected.

2.2.8. Discharge Data

The discharge data (daily average flow in CFS) was obtained from the USGS gage 10172200 located very close to the outlet of the HEC-HMS model. Appendix G contains the discharge data used in the model during the calibration phase, and for the comparison of simulated discharge.

2.2.9. Model Calibration

Model was calibrated using the flow data from the USGS station at the outlet of the watershed. The daily average data, which are “Approved” in quality was used to calibrate the model routing parameters (Mushkingum k and x) for the three reaches present in the model.

For model runs that considered SCS Loss method, different value of initial abstraction was tested to calibrate the model. Similarly, for Green Ampt Loss method, different values of initial soil moisture content were considered to calibrate the model. The value was kept as low as the field capacity, and as high as the saturation content (or effective porosity) to calibrate the model.

3. Results and Discussions

3.1. Model Runs

Multiple model runs were completed using different parameters, and different rainfall records, as well as different run period. Two loss methods were accounted for, SCS loss method, and Green Ampt loss method, because SCS loss method gave a poor result, and proper calibration of the model was not achieved. Green Ampt method gave a better result, and hence was adopted in the final calibrated model. The summary of the runs created, and the figure to the results are tabulated below in Table 5.

Table6: Model Run Results Summary

Runs	Precipitation Stations	Control Period	Loss method	Calibrated	Result Figure
Run1	GIRF	01/01/2015 to 12/31/2015	SCS	No	Fig. 5
Run2	GIRF		SCS	Yes	Fig. 5
Run3	GIRF		Green & Ampt	No	Fig. 5
Run4	GIRF		Green & Ampt	Yes	Fig. 5
Run5	SaltLake Triad	01/10/2010 to 30/09/2011	SCS	No	Fig. 6
Run6	SaltLake Triad		SCS	Yes	Fig. 6
Run7	SaltLake Triad		Green & Ampt	No	Fig. 6
Run8	SaltLake Triad		Green & Ampt	Yes	Fig. 6

The results have been shown in the graph below. The blue line represents the simulated discharge at the outlet, while the black line represents the observed flow at the USGS discharge station.

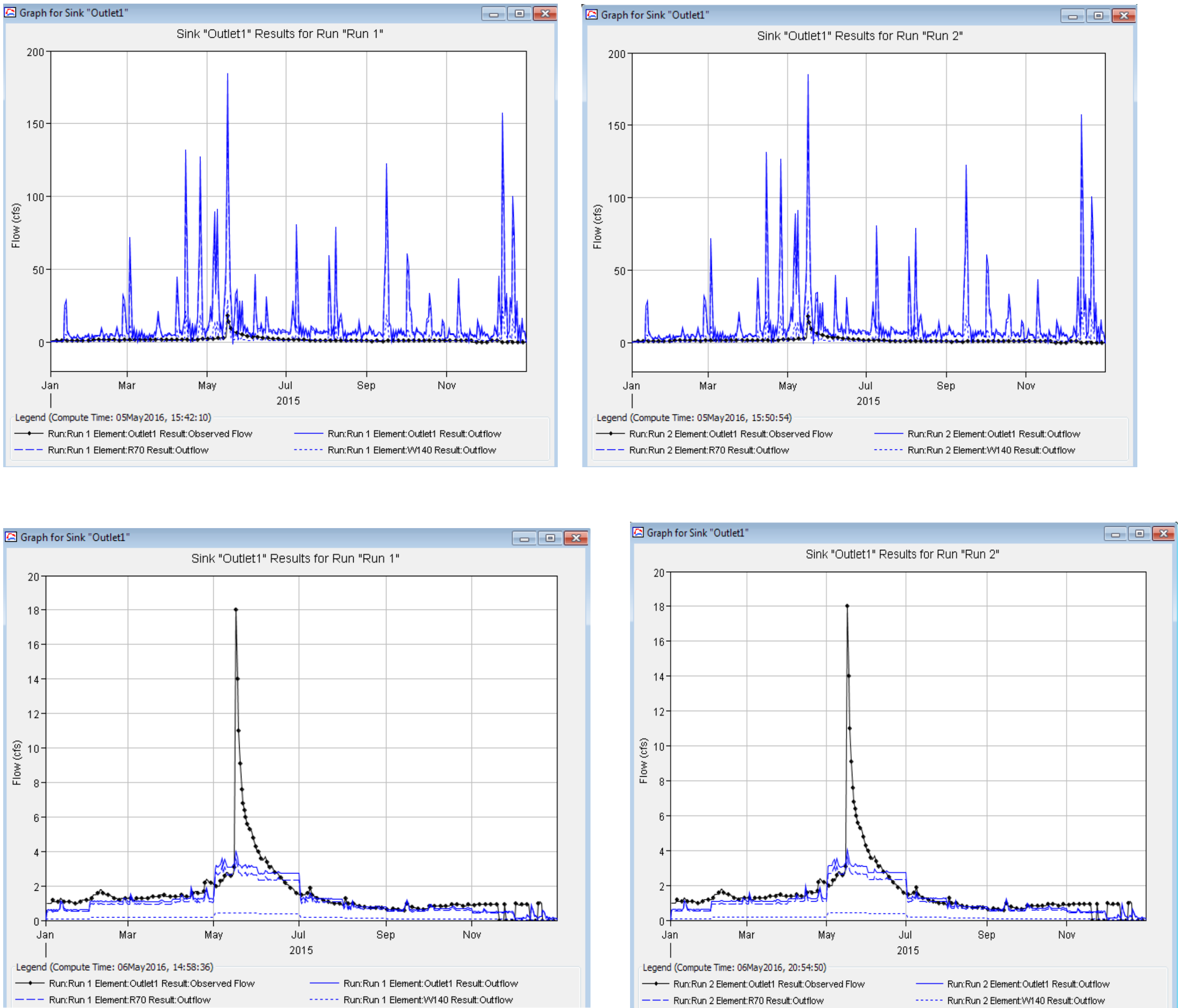

Figure 5. The simulated and observed flow at the outlet using precipitaiton from the Red Butte Green Infrastructure Climate (RB_GIRF_C, iUtah) for time period of Jan01-2015, Dec31-2015

Image Description:

Top Left*: Loss Method:* ***SCS****, Non-calibrated*

Top Right*: Loss Method:* ***SCS****, calibrated*

Lower Left*: Loss Method:* ***Green Ampt****, Non-calibrated*

i: Loss Method: ***Green Ampt****, calibrated*

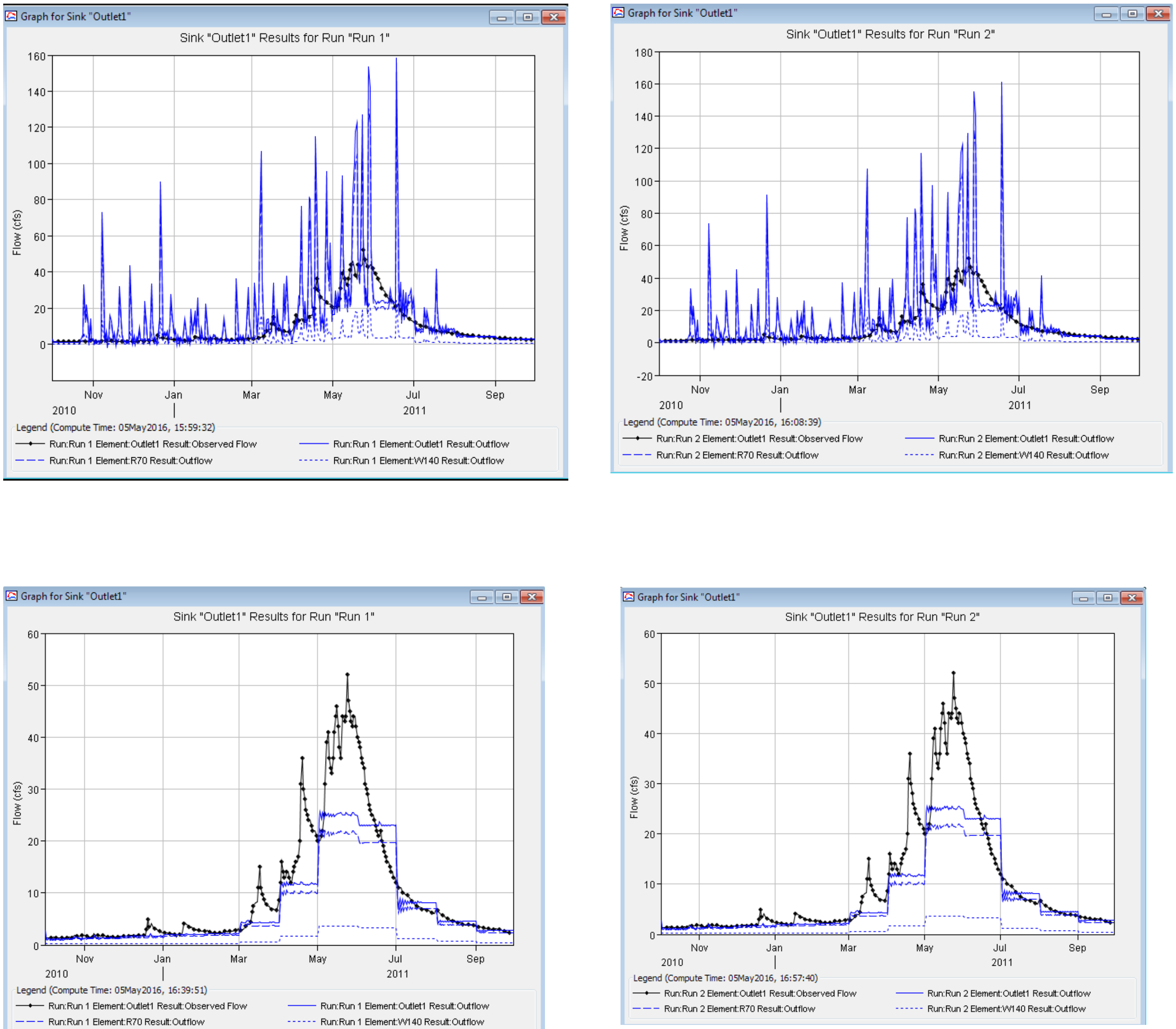

Figure 6. The simulated and observed flow at the outlet using precipitaiton from the Salt Lake Traid for the time period of October 2010 to September 2011.

Image Description:

Top Left*: Loss Method:* ***SCS****, Non-calibrated*

Top Right*: Loss Method:* ***SCS****, calibrated*

Lower Left*: Loss Method:* ***Green Ampt****, Non-calibrated*

Lower Right*:: Loss Method:* ***Green Ampt****, calibrated*

3.2. Public Model Access

All the model, including the final calibrated model can be found in GitHub, the link to the repository being https://github.com/prasanna310/HEC_HMS_RBC. The repository contains the final report of the model, the streamflow data, rainfall data as well as the baseflow separated data. It also contains the step-by-step instruction of how to prepare the model.

4. Conclusion

A HEC-HMS model was prepared for the study region of Red Butte Creek watershed, and calibrated. Rainfall data from 10 different climatic stations were considered, and later two were chosen for the model; Salt Lake Triad and Green Infrastructure climatic sites. The loss method considered were SCS, which gave a poor result, and hence Green and Ampt loss method was considered. Transform method considered was SCS, and the baseflow was considered constant per month, separated using the WHAT analysis tool. The DEM and NLCD Land use data was downloaded using ArcGIS services, from the USGS. The SSURGO database for the area (UT612) was downloaded, and most soil properties required for Green and Ampt method was obtained from it.

The final model simulated flow closely resembled the observed flow. SCS loss method was unsatisfactory for loss accounting. In watershed like Red Butte Creek which is small and covered with thick forest, a proper loss method is required, and Green Ampt method was suitable for the purpose.

Acknowledgement

We would like to express deep thanks to Prof. Dr. Richard Peralta for his constant support, encouragement and guidance throughout the project. His patience, motivation, and immense knowledge has guided us towards a fruitful completion of the project.

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Appendix A. Sub-basin Characteristics

Sub-basin	Area (sq. miles)	Suction (inch)	Saturation	Initial Moisture Content	Conductivity (in/hour)	Impervious (%)
W80	0.87644	7.19	0.388	0.267	0.332	1.0
W90	0.51169	6.29	0.399	0.28	0.373	0.0
W100	0.21597	7.46	0.395	0.28	0.323	1.0
W110	1.6314	7.72	0.394	0.28	0.299	1.0
W120	0.7727	7.42	0.371	0.26	0.429	1.0
W130	2.1486	7.36	0.359	0.25	0.514	0.0
W140	1.0374	9.30	0.369	0.26	0.386	0.0

Appendix B. Rainfall Data

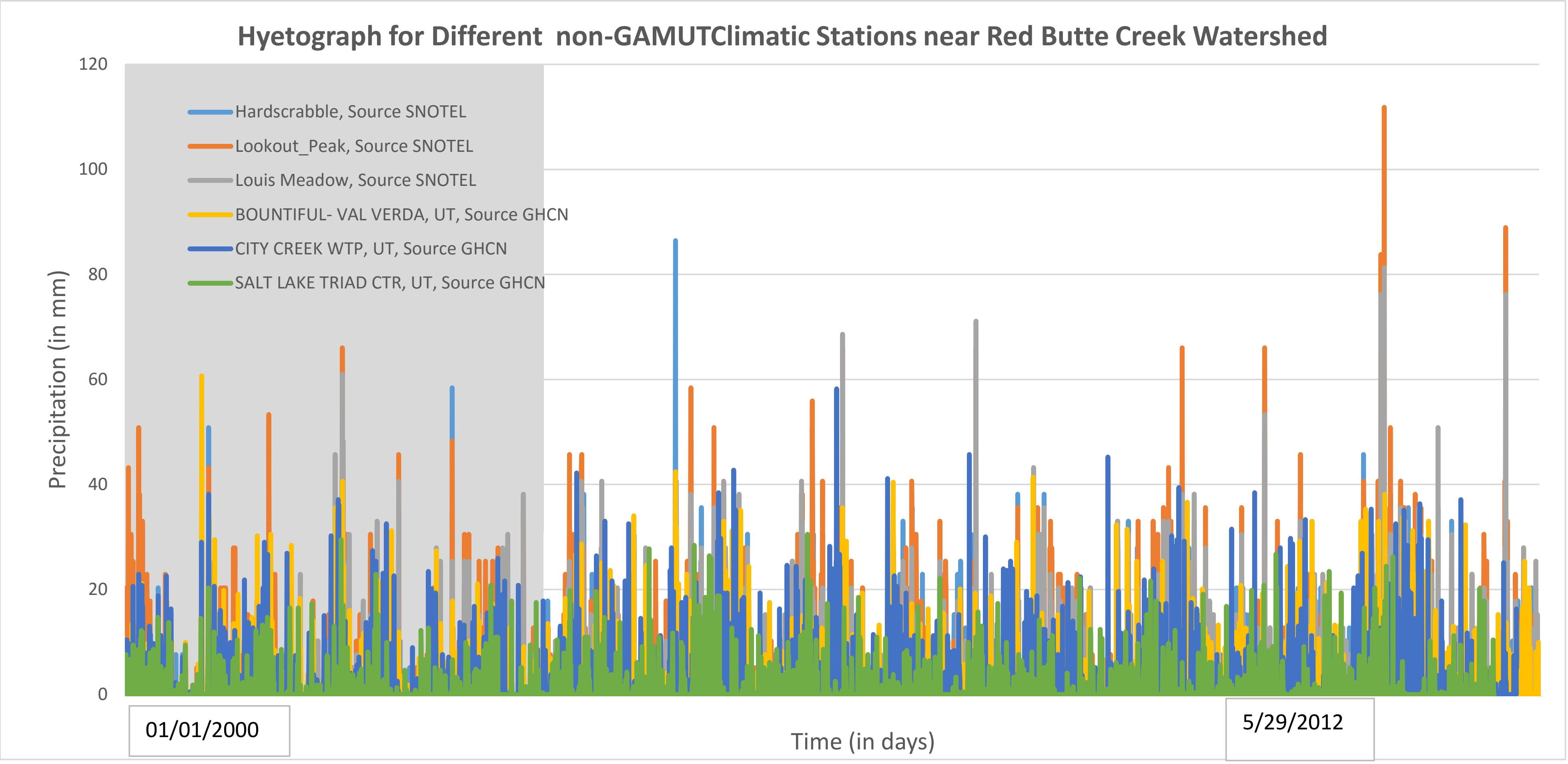

Figure 7. Showing precipitation records for six climatic non-GAMUT stations near the Red Butte Creek Watershed. The figure shows that the Salt Lake Triad Center source gives us the least rainfall among the six, while the Lookout Peak seem to give the largest rainfall.

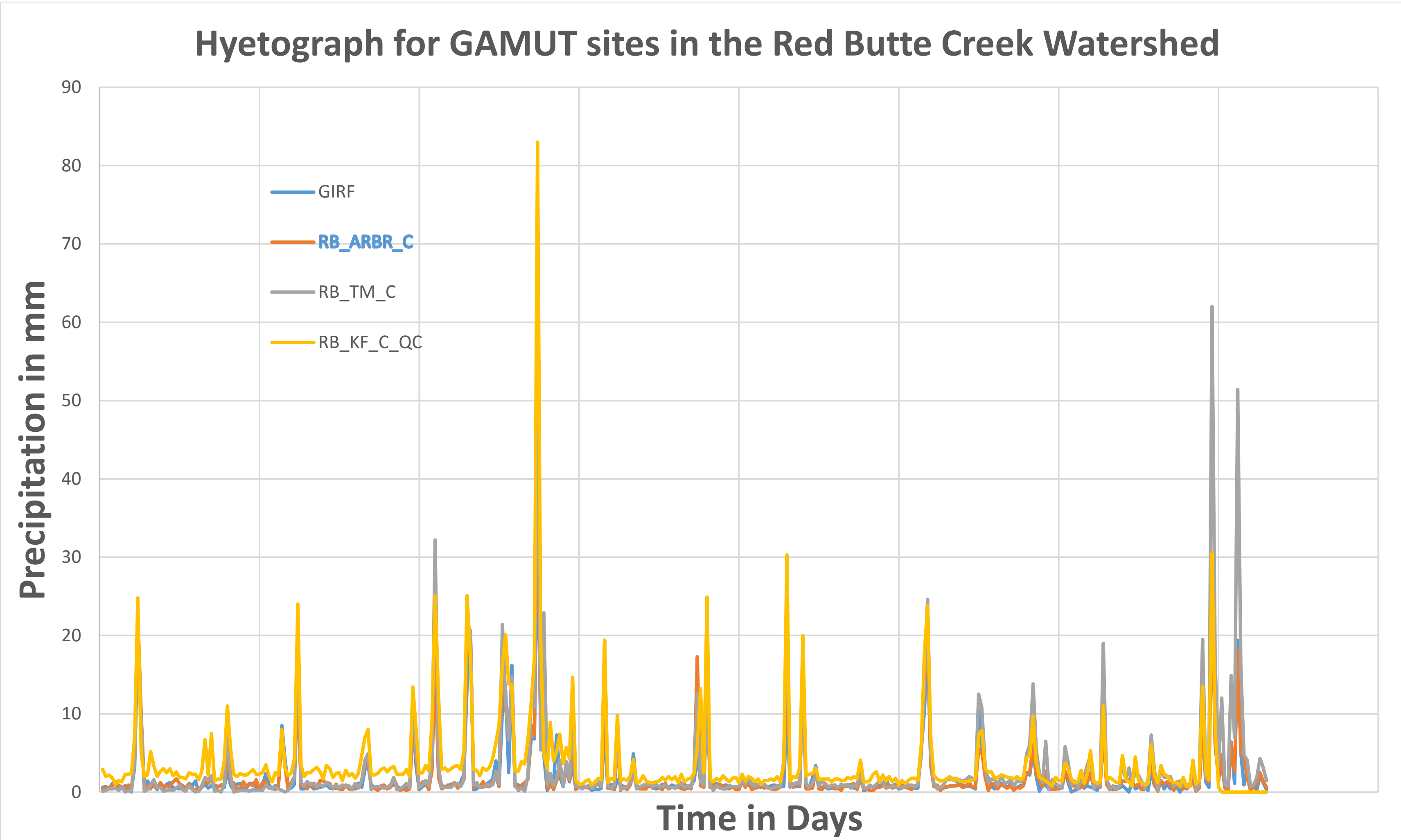

Figure 8. Showing precipitation records for six climatic GAMUT stations in the Red Butte Creek Watershed. The figure shows that the station located in the Green Infrastructure (site code: RB_GIRF) gives the least rainfall among the six, while the Lookout Peak seem to give the largest rainfall.