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Estimating the 100-year Peak Flow for Ungagged Middle Creek Watershed in Northern California, USA

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Abstract This study presents a case study for estimating the 100-year peak flow for Middle Creek Watershed in Northern California. The watershed contains several stream flow gages; however, the precipitation data is only available as daily data, which was not usable form for this study. Thus considering that the watershed to be ungagged. In order to overcome this shortcoming in the hydrologic analysis, other approaches were considered. Therefore, the precipitation point frequency estimates were obtained from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14. The Hydrologic Engineering Center's Hydrologic Modeling System (HMS) was used to create the hydrologic model to estimate the peak flows at key points in the watershed. The purpose of using the HMS model was to predict eh rainfall-runoff analysis for this watershed, which only has steam gage data. Other parameters needed for the HMS model were obtained from various sources as suggested in the United States Army Corps of Engineers (USACE) Central Valley Hydrology Study (CVHS): Technical procedures document. The 100-year flows from the HMS model results were then calibrated/validated by comparing to the 100-year flow frequency curves computed using the Hydrologic Engineering Center's Flood Frequency Analysis (FFA) program, FEMA USACE, and USGS Regression methods. Sensitivity analysis of several of the model parameters was analyzed to determine the results confidence level. The HMS modeled results were in good agreement with the results obtained from the Flood Frequency method and the USGS regression studies. The procedure described herein for developing and validating hydrologic models for ungagged watersheds can be used for other similar ungagged watersheds.

Keywords: *HEC-HMS, partially gagged watersheds, computational methods, flooding*

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1. Background

There is a continuous need to improve and update floodplain mapping to better predict flood risks. The accuracy of hydrologic and hydraulic models can be improved greatly as the ability to estimate the physical parameters for a watershed is improved. Technologies, such as Light Detection and Ranging (LiDAR) and Geographic Information System (GIS) tools, allow for increased spatial accuracy. However, the hydraulic flood models are still only as accurate as their hydrologic inputs. Investigating watersheds without stream flow and/or precipitation data becomes very difficult and lacks accuracy. In order to build and validate a hydrologic model, precipitation, flow and watershed physical characteristics data are all needed. However, not all watersheds are gaged with precipitation and stream instruments. If the precipitation data is not available, precipitation can be estimated using the National Oceanic and Atmospheric Administration (NOAA) precipitation estimates. If stream flow data is available, that data can be used to estimate the expected flows for selected exceedance intervals using the Water Resources Council (WRC) Bulletin 17b method. Additionally, the USGS has developed regional regression equations to estimate peak flows. The peak flow estimates can be compared to the HMS results to validate the hydrologic model. This analysis procedure is documented in United States Army Corps of Engineers (USACE) Central Valley Hydrology Study (CVHS): Ungagged watershed analysis procedures. The methods and procedures from that report are used in the development of the case study described in this study.

The Middle Creek watershed is in the western portion of Lake County in Northern California (about 100 miles north of San Francisco). At the lower end of the watershed there are levees which transport the flood flows around the Town of Upper Lake and discharge into Clear Lake. The watershed is 195 square miles and includes Middle, Scotts, Clover, and Alley Creeks. The watershed is shown in Figure 1.

There are two previous hydrologic studies for the watershed: a study by the USACE in 1956 and a study by the Federal Emergency Management Association (FEMA) in 1976. USACE did not use the recorded stream flow data for Middle, Scott, and Clover Creeks because the data was only available for a period of 8 years (from 1948 to

1956). Instead, USACE used flow frequency data from several nearby streams. Using the recorded peak flows on nearby streams, USACE developed a regional envelope curve of drainage area vs. peak runoff. USACE used this envelope curve to derive flood frequencies for the Middle Creek project streams. The FEMA's Flood Insurance Study (FIS) used a HEC-1 model to determine the peak flows. In this study, the peak flow results were compared with the peak flow results of the previous studies to validate the HMS model developed in the current study.

The records for the precipitation gages within the watershed are maintained by the Western Regional Climate Center (WRCC). The precipitation data for the nearby gages was only available as daily data (WRCC, March 4, 2011). Therefore, the precipitation data could not be used for a precipitation-runoff hydrologic HMS model. Instead, the precipitation point frequency estimates from the NOAA Atlas 14 was used.

There are two stream flow gages in our watershed that were used for validating the model, as shown in Figure 1. The Middle Creek near Upper Lake gage has 15-min peak flow data from 1962-2010 (California Department of Water Resources, Water Data Library. The Scotts Creek near Lakeport gage has annual peak flow data from 1968-2010 (U.S. Geological Survey, National Water Information System).

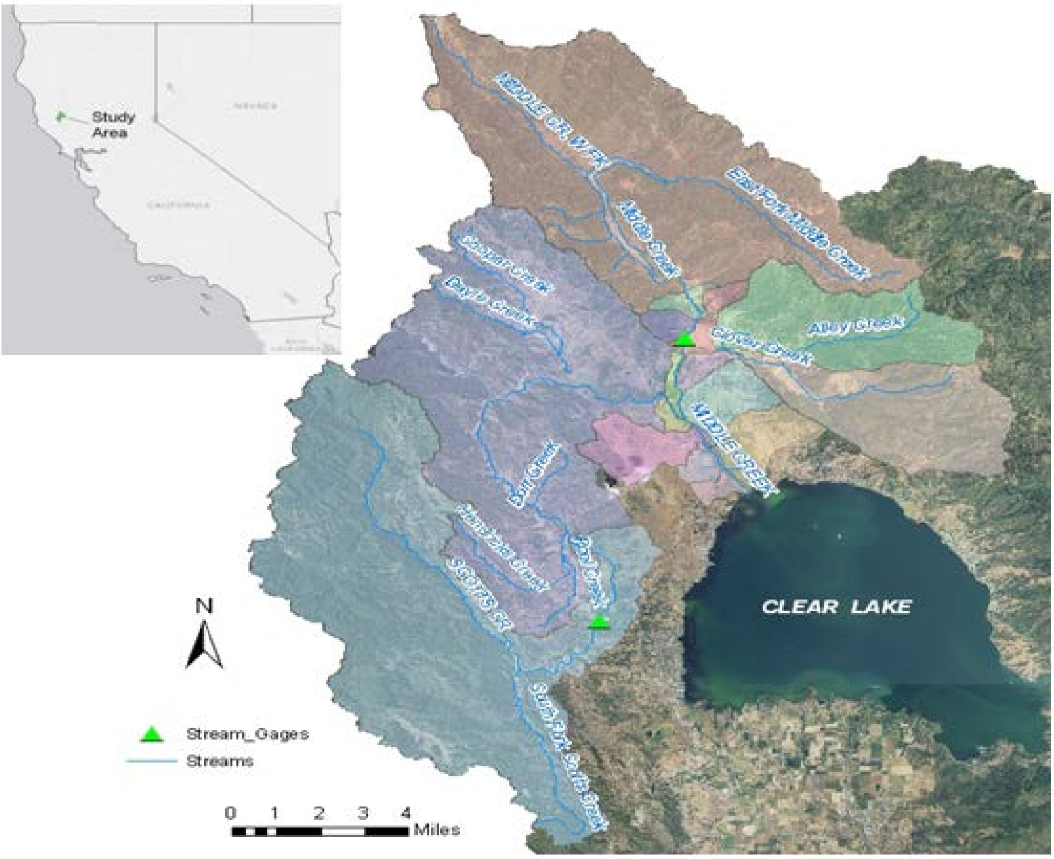

Figure 1. Location of study area, stream gages, and sub-basins

2. Methodology

Based on the objectives of the study and the availability of gaged data, this study will follow the guidance provided in the USACE Central Valley Hydrology Study (CVHS): Ungaged watershed analysis procedures (USACE, 2010). The USACE Hydraulic Engineering Center's (HEC) Hydrologic Modeling System (HMS) program will be used with the NOAA synthetic precipitation data and various physical characteristics of the watershed sub-basins. The HMS model is divided into three sub-models: Hydrologic model (the basin model), the meteorological model, and the control specifications. The following sections describe each of the models and their components.

The developed HMS model will be used to determine the 100-year Flow rate needed to delineate the 100-year flood. This would be a relatively simple task if the precipitation data, stream flow data, and the watershed physical characteristicswereall available. If any of this data is not available, the task becomes more difficult. The current study will attempt to predict the 100-year flow for partially gagged watershed with unavailable precipitation data. Under these circumstances, the results of the 100-year peak flow from the HMS model will be validated with four methods to show that partially gagged watershed hydrologic analysis can still be performed with reasonable accuracy.

2.1. Hydrologic Model (Basin Model)

The basin model consists of the physical modules of the hydrologic model. The inputs for the basin model include: losses, transformation, base flow, and routing. The watershed was subdivided into 16 sub-basins that were hydrologically homogenous in regards to soils and land cover characteristics. The sub-basins also are divided so that the HMS model will output results at crucial analysis points within the watershed, such as at gage stations.

The initial and constant loss model (for losses into the soil matrix as infiltration) will be used for precipitation-runoff modeling of the ungaged watersheds (USACE, 2010). The initial losses were estimated from Table 5-1 of Sacramento City/County Drainage Manual Volume 2: Hydrology Standards (Sacramento City/County, 2006). The initial losses vary depending on the storm recurrence interval. The Soil Survey Geographic (SSURGO) database (U.S. Natural Resources Conservation Service, Soil Data Mart. was used to determine the percentage of each hydrologic soil group for the sub-basins. The constant loss rates were assumed to be the average of the range provided in the HEC-HMS Technical Reference Manual (USACE, 2000). Using ArcGIS, an area for each soil group within the sub-basin was estimated. The soil group areas and infiltration rates were used to calculate the area-weighted constant loss rates for each sub-basin, which were input into the basin model and are shown in Table 1.

Table 1. Soil loss rates for HMS basin model

Sub- Basin	Total Area (sq. mi)	Percentage of Area (%)					Weighted Constant Loss Rate (in/hr)
		Water	A	B	C	D	
1	47.45	0.00	0.22	18.84	39.37	41.57	0.093
2	0.78	0.00	2.62	0.00	66.67	30.72	0.084
3	0.89	0.00	0.00	0.00	60.58	39.42	0.070
4	1.38	0.00	7.04	0.00	58.31	34.64	0.093
5	12.35	0.03	1.62	25.83	9.53	63.00	0.089
6	13.87	0.09	0.36	21.82	28.66	49.06	0.091
7	0.87	0.00	0.00	0.00	93.49	6.51	0.095
8	0.50	0.00	9.82	1.48	54.21	34.48	0.103
9	55.02	0.20	1.09	1.28	11.42	86.21	0.040
10	48.28	0.60	0.33	6.17	17.72	75.77	0.052
11	0.46	1.03	0.00	0.00	14.16	85.84	0.036
12	2.99	0.45	0.00	0.96	45.88	53.16	0.061
13	3.50	0.56	0.00	0.00	33.92	66.08	0.050
14	0.76	12.37	0.00	2.39	7.11	90.50	0.035
15	0.59	19.83	0.00	0.00	0.48	99.52	0.025
16	3.18	1.87	0.00	0.00	32.03	67.97	0.049

The impervious percentage was determined based on National Land Cover Database 2006 (U.S. Geological Survey, National Map Viewer. Most of the watershed is undeveloped and the imperviousness is essentially zero percent.

In this study, an S-graph method, which was developed by the USACE and has been used extensively in many studies in California’s Central Valley (USACE, 2010).The S-graph methodprovides the relationship between the volume of runoff versus the duration. There are different S-graphs (valley, foothill, and mountain) based on the average slope of the stream for each sub-basin (USACE, 2010). The lag time for each sub-basin was computed from the equation (USACE, 2010):

$$T_{lag} = 24n\left(LL_{ca} / S^{0.5}\right)^{0.38} \tag{1}$$

Where T_{lag} is the basin lag time (hrs), n is the basin roughness coefficient, L is the longest flow path length (mi), L_{ca} is the centroidal flow path length (mi), and S is the overall basin slope (ft/mi).The basin roughness coefficient, n, was estimated from Table 7-1 from Chapter 7 of the Sacramento City/County Drainage Manual (SacramentoCity/County, 2006). The basin roughness coefficient is based on the land use and land cover which was determined from the National Land Cover Database. The basin lag time results are shown in Table 2.

Table 2. Sub-basin lag times for HMS basin model

Sub-basin	Manning's n	Total Flow Length,L (mi)	Length to Centroid,L_{ca} (mi)	Basin Slope S (ft/mi)	S-curve Type	T_{lag}(hr)
1	0.10	14.62	6.23	236	FOOTHILL	4.72
2	0.08	1.93	0.87	663	MOUNTAIN	0.68
3	0.09	1.76	0.90	817	MOUNTAIN	0.72
4	0.08	2.65	1.10	624	MOUNTAIN	0.85
5	0.09	6.99	4.05	487	MOUNTAIN	2.37
6	0.09	9.44	5.43	286	FOOTHILL	3.29
7	0.08	1.98	0.96	56	VALLEY	1.14
8	0.08	2.09	1.06	127	VALLEY	1.04
9	0.09	18.84	9.79	123	VALLEY	6.28
10	0.09	16.50	4.95	65	VALLEY	5.21
11	0.09	1.01	0.34	5	VALLEY	1.06
12	0.08	2.88	1.28	314	FOOTHILL	1.06
13	0.09	4.23	2.17	235	FOOTHILL	1.78
14	0.08	1.33	0.48	282	FOOTHILL	0.56
15	0.08	1.22	0.47	180	VALLEY	0.58
16	0.08	4.61	1.77	195	VALLEY	1.57

The flood runoff from the 100-year design storms is likely to be large, and thus the contribution of base flow to the peak runoff is small. Also, the stream flow gage records indicated that the creeks are often dry. Therefore, no base flow contribution was used in the current study.

The USACE (USACE 2001) guidelines for selecting channel routing recommendations were used to select an appropriate reach routing method. The Muskingum-Cunge routing method was selected due its numerical stability and it is an acceptable method for most reach slopes for our study area.

2.2. Meteorological Model

The meteorological model is used to distribute precipitation within the watershed. The NOAA Atlas 14 precipitation point frequency estimates taken at the centroids of each of the sub-basins (National Oceanic and Atmospheric Administration, Precipitation Frequency Data Server) were used. The NOAA precipitation frequency data server outputs the precipitation frequency estimates for durations of 5 minutes to 60 days and for average recurrence intervals from 1-year to 1000-year.

The precipitation estimates were then multiplied by an aerial reduction factors (ARF's) to account for the size of the sub-basins. New aerial reduction factors are being developed by NOAA; however, these new ARF's are not expected to be completed until the spring of 2012 (USACE, 2010). Therefore, the ARF values from the Hydrometereological Report No. 59 (NOAA, 1999) were selected. The ARF's were multiplied by the NOAA precipitation estimates.

The NOAA Atlas 14 data server also provides temporal distributions. The HMS model was ran for three durations (6-, 12-, and 24-hour) and selected the duration producing the greatest peak flow rates. For each duration, there are distributions for the four quartiles and for various cumulative probabilities. The quartiles give separate distributions depending on which quartile of the total duration, the most precipitation occurs during. For example, the first quartile distribution for a 12-hour duration gives the distribution of all the recorded storms where the greatest percentage of the total precipitation fell during the first quarter (e.g. during the first 3 hours). The NOAA Atlas 14 provides a table which shows how many of each quartile-case occurred for each of the 14 different climatic regionsin California. The temporal distribution with the median (50%) cumulative probability of occurrence was used for this study. These precipitation distribution percentages were multiplied by the precipitation estimates that were adjusted by multiplying them by the ARF's.

The precipitation time series was created using the specified hyetograph method for each of the durations (6-, 12-, and 24-hour) to model the 100-year precipitation.

2.3. Control Specifications

The computational time step was chosen so that it adequately captures the runoff peak. Generally, the simulation time step should not exceed 1/6th the time of concentration (T_c) of the smallest sub-basin (CVHS, 2010). The shortest time of concentration is 0.84 hr for sub-basin 14. Also, the minimum time step should be less than that of the precipitation data (USACE, 2010). The NOAA precipitation data that was used has 30 minute time steps for the 6-, 12-, and 24-hour durations. Therefore, a 10-minute computational time-step in HMS model was used.

3. Results

The HMS model was simulated for the three storm events: 6-, 12-, and 24-hour. It was determined that the appropriate precipitation duration was 12 hours, because that storm resulted in the largest summation of the maximum flow rates, as is shown in Table 3.

Table 3. 100-year peak flows for various precipitation durations

Location	6-hour Peak Flow (cfs)	12-hour Peak Flow (cfs)	24-hour Peak Flow (cfs)
Middle Creek Near Upper Lake Gage	10,090	9,140	8,480
Scotts Creek near Lakeport Gage	9,700	11,960	11,980
Clover Creek Upstream of Alley Creek Confluence	4,210	4,230	3,690
Sum	24,000	25,330	24,150

3.1. Model Calibration/ Validation

Calibration refers to the process of adjusting a model so that the results match the historical data. For this study, precipitation calibration of the model was not possible because precise precipitation data was not available to correlate the runoff with recorded precipitation. Four methods were evaluated to perform the calibration (FEMA, USACE, Flood Frequency, and USGS regression). Previous studies from USACE and FEMA were not used for the calibration/validation because they are based on outdated data. Therefore, HMS model was calibrated/ validated indirectly by comparing the HMS results with the flood frequency analysis and the USGS regional regression equations.

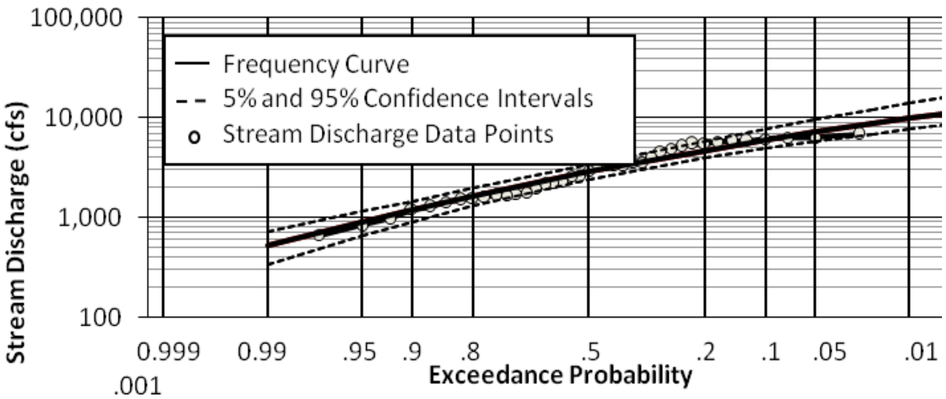

Figure 2. Middle Creek near Upper Lake annual peak flow frequency

The annual peak flows were input into the Hydrologic Engineering Center Flood Frequency Analysis (HEC-FFA) program to generate flow frequency curves. The WRC Bulletin 17b method (WRC, 1982) was followed and a Log-Pearson Type III distribution was used in the computation of the flood frequency curves. The regional skew coefficients and mean square errors were obtained by taking the average of nearby stations' data (Parrett, 2006). The flood frequency curves for Middle Creek and ScottsCreek are presented in Figure 2 and Figure 3, respectively.

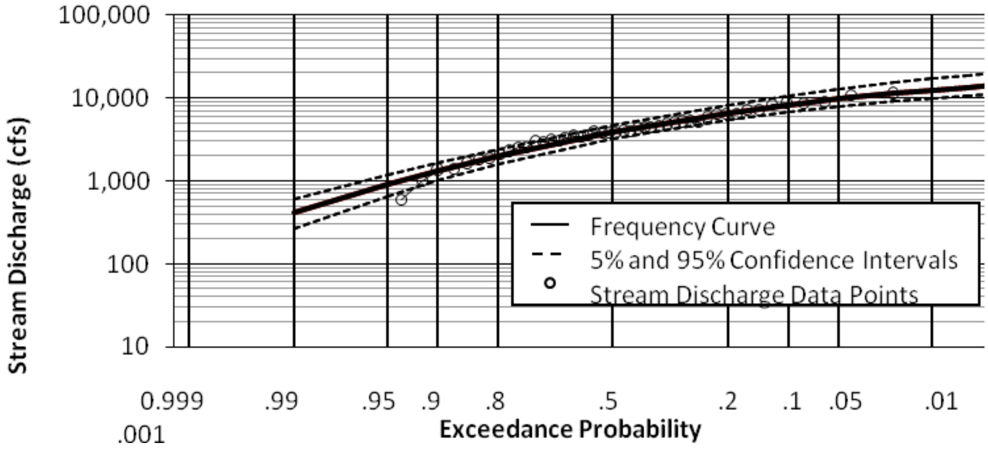

Figure 3. Scotts Creek near Lakeport annual peak flow frequency

The USGS regional regression equation was used to validate the peak flow results from the HMS model. The equation is shown below for the 100-year peak flow (Jennings, 1993):

$$Q_{100} = 9.23A^{0.87}P^{0.97} \quad (2)$$

Where Q_{100} is the 100-year peak flow-rate, A is the drainage area (mi^2), P is the mean annual precipitation (in), and H is the altitude index. The altitude index, H, is defined as the average of altitudes in thousands of feet at points along the main channel at 10 percent and 85 percent of the distances from the site to the watershed divide(Jennings, 1993).

For determining the mean annual precipitation, P, the annual precipitation was obtained for various precipitation gages near the Middle Creek watershed from the WRCC. The annual precipitation was plotted versus the elevation of the gages. From the plot, a regression trend line was developed to estimate the annual precipitation based on the average basin elevation.

Table 4. Peak flows calculated from USGS regression equations

Location	Drainage Area A(mi^2)	Average Annual Precipitation P(in)	USGS Regression Equations Q_{100}(cfs)	HMS Model Q_{100} (cfs)	% Difference
Middle Creek Near Upper Lake Gage Station	49.5	48	11,800	10,910	7.5
Scotts Creek Near Lakeport Gage Station	56.2	51	14,000	12,630	9.8
Clover Creek Upstream of Alley Creek Confluence	13.9	54	4,300	4,650	-8.1

3.2. Sensitivity Analysis

Sensitivity analysis was performed in order to test how sensitive the model results were to changes in the variable parameters. The parameters that have the most uncertainty are the soil loss rates and the Manning's n- values. The each of these parameters was reduced by 20% to test its sensitivity. The results of this analysis are shown in Table 5.

The peak flow rates are more sensitive to the changes in the Manning's n–values than to changes in the soil loss rates. By altering the Manning's n-value, the lag times change drastically. Since this is an ungagged watershed, these parameters cannot be used to calibrate the model. However, the sensitivity of these parameters shows the level of confidence that can be attributed to the HMS model results.

Table 5. Sensitivity analysis of loss rates and Manning's n-values

Location	100-Year Peak Flows from HMS (cfs)	100-Year Peak Flows with Adjusted Soil Loss Rates (cfs)	Percent Change From Original HMS Peak Flows (%)	100-Year Peak Flows with Adjusted Manning's n-values (cfs)	Percent Change From Original HMS Peak Flows (%)
Middle Creek Near Upper Lake Gage	9,140	9,690	+6.0	10,050	+10.0
Scotts Creek near Lakeport Gage	11,960	12,230	+2.3	13,170	+10.1
Clover Creek Upstream of Alley Creek Confluence	4,230	4,400	+4.0	4,520	+6.9
Root Mean Square Error (RMSE)		367		890	

The results of the HMS model were compared to the flood frequency analysis and USGS regression results to show that for ungagged watersheds it is possible to perform accurate hydrologic analysis with reasonable accuracy. The sensitivity analysis of the two parameters that the HMS model is most sensitive to showed that the maximum difference was 10% for all locations. The Root Mean Square Error (RMSE) was calculated for the loss rate and n-value. The calculated RMSE for the loss rate and n-value were 367 cfs and 890 cfs, respectively. Which is reasonable for ungagged watershed given the choice between performing the hydrologic analysis or instrumenting the watershed with rain gages to collect the needed precipitation data then perform the hydrologic analysis. The extra time, cost and effort of installing rain gages and collecting rainfall data might slightly improve the model accuracy but is not warranted.

3.3. Simulated and Estimated 100-Year Flows

The HMS model results with four different methods FEMS, USACE, Flood Frequency, and USGS regression are presented in Table 6. The Middle Creek near Upper lake Gage HMS 100-year peak flow is between the four methods evaluated. The 100-year peak flow for this location is less than the FEMA, USACE and USGS but higher than the Flood Frequency method. The maximum differences between the HMS model results and the four methods evaluated are presented in Table 7. The maximum difference (See Table 7) between the HMS model result and the four methods evaluated for this location is 13%. The maximum difference is observed between the HMS model and the USACE method. The Scotts Creek near Lakeport Gage HMS model 100-year peak flow is less than the FEMA and USGA methods but higher than the USACE and Flood Frequency methods. For this location, the maximum difference (see Table 7) between the HMS model results and four methods evaluated is (-9%). The maximum error is observed between the HMS model and the USGS regression method. The100-year peak flow for Clover Creek Upstream of Alley Creek Confluence is higher than all the four method evaluated. The maximum difference for this location is (-22%).

The FEMA and the Flood Frequency methods resulted in similar Root Mean Square Error (RMSE) of 641 cfs and 674 cfs, respectively. While the USACE and the USGS Regression methods resulted in similar RMSE of 1098 cfs and 965 cfs, respectively. The USGS regression equations are estimated based on the watershed characteristics and the flood frequency curves, which have large ranges of confidence intervals. Based on the nature of estimating the peak flow. The HMS model results are expected to be closer to the results of these two methods. This was confirmed by the results presented in Table 7. As also expect the HMS model results were different than FEMA and the USACE methods.

Table 6. Simulated and Estimated Peak Flow Rates rate From Various models

Location	100-Year Peak Flow Rates (cfs)				
	HMS Model	FEMA Analysis	USACE Analysis	Flood Frequency Model	USGS Regression
Middle Creek near Upper Lake Gage	10,910	11,320	12,400	9,750	11,800
Scott Creek near Lakeport Gage	12,630	13,200	11,500	12,500	14,000
Clover Creek Upstream of Alley Creek Confluence	4,650	3,790	4,300	(No gage data)	4,300
RMSE		641	1098	674	965

Table 7. Comparison of HMS model results with other models

Location	Percent Difference (%)			
	HMS Model Results vs. FEMA Analysis	*HMS Model Results vs. USACE Analysis*	*HMS Model Results vs. Flood Frequency Model*	*HMS Model Results vs. USGS Regression*
Middle Creek near Upper Lake Gage	+3.65	+13	+11.9	-7.5%
Scott Creek near Lakeport Gage	+4.3	+8	+1.0	-9.8
Clover Creek Upstream of Alley Creek Confluence	-22.7	+8	N/A	+8.1

4. Conclusions

This study presented one method for developing 100-year flow rates for an ungaged watershed. The HMS results of this study were compared with four methods that are used by many practitioners. The recently developed methodology by the USACE was followed to study ungagged watersheds. The methodology used various updated datasets such as the NOAA Atlas 14 and USGS regional skew coefficients. The result of the study was favorable as the flow rates simulated by the HMS model were statistically similar to the flow rates obtained from the flow frequency analysis and the flow rates estimated by the USGS regional regression equation. These similar results can allow us to validate a model which otherwise could not be calibrated. The analysis procedure explored in this study can be used for modeling watersheds that have adequate stream flow records but lack applicable precipitation data. A limitation to this procedure is that it only validates the model only for the peak flows. Further studies are needed to validate the model using the extended period simulation analysis using flow time series in the form of hydrograph. Higher error was observed at the low flows for the FEMA method, while, higher error was observed at high flows for the USACE method. The Flood Frequency and the USGS Regression methods were between the FEMA and USACE methods.

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