SIMULATING A CENTURY OF HYDROGRAPHS - MARK TWAIN RESERVOIR

Ann M Midje Banitt, P.E., Hydraulic Engineer
U.S. Army Corps of Engineers, St. Paul, MN
ann.m.banitt@usace.army.mil

Abstract: The Mark Twain Reservoir is located within the Salt River Watershed, in northeastern Missouri. The Salt River watershed encompasses 2,882 square miles and is tributary to the Mississippi River. During the late summer of 2008, the watershed experienced a very large flood, prompting development of a suite of HEC models that could be used to generate 100-year simulations of natural, existing and alternative operation plans for the Mark Twain Reservoir.

The watershed has a very flashy response to large rain events. Land use within the watershed is primarily agricultural. Existing stream gage information was utilized where possible to generate a sequence of runoff hydrographs for a reservoir routing model. To fill in stream gage data gaps, historic precipitation records were used to compute flows. The selected model was HEC-HMS based on a one-hour time interval. Processing the precipitation for the model was a significant task because of the varying degree of gage coverage over the 100-year period. Clark's unit hydrograph parameters were selected as the method of transformation. HEC-HMS Soil loss rate parameters were derived with data extracted from various soil horizons from the SSURGO soil database.

This paper covers the development of inflow sequences from historic data for the reservoir routing model, including the compilation of input data and development and calibration of the HEC-HMS model.

INTRODUCTION

Project Background: The Salt River basin is located in northeast Missouri and has a drainage area of 2,882 square miles. The Salt River enters the Mississippi River at river mile 284.2 just upstream of the town of Louisiana, Missouri. The Clarence Cannon Dam (along with its hydroelectric power plant) went into operation in 1984 and regulates the runoff from the upper 2,400 square miles of the watershed. Below the Clarence Cannon Dam, the Salt River flows 9.5 miles to a secondary Reregulation Dam and then another 50 river miles to its confluence with the Mississippi River.

Evaluation of the pre-project condition, existing and alternative regulation plans for Mark Twain Lake required detailed sequential routings for a 100-year simulation period. MVS specified a period of record as 01January 1908 to 31December 2008, which comprises 101 years of record. Existing stream gage information was used where possible. To fill stream gage data gaps, historic precipitation records were used to compute flows using a rainfall-runoff model, HEC-HMS. The stream gage locations within the Salt River basin are illustrated in **Figure 1**.
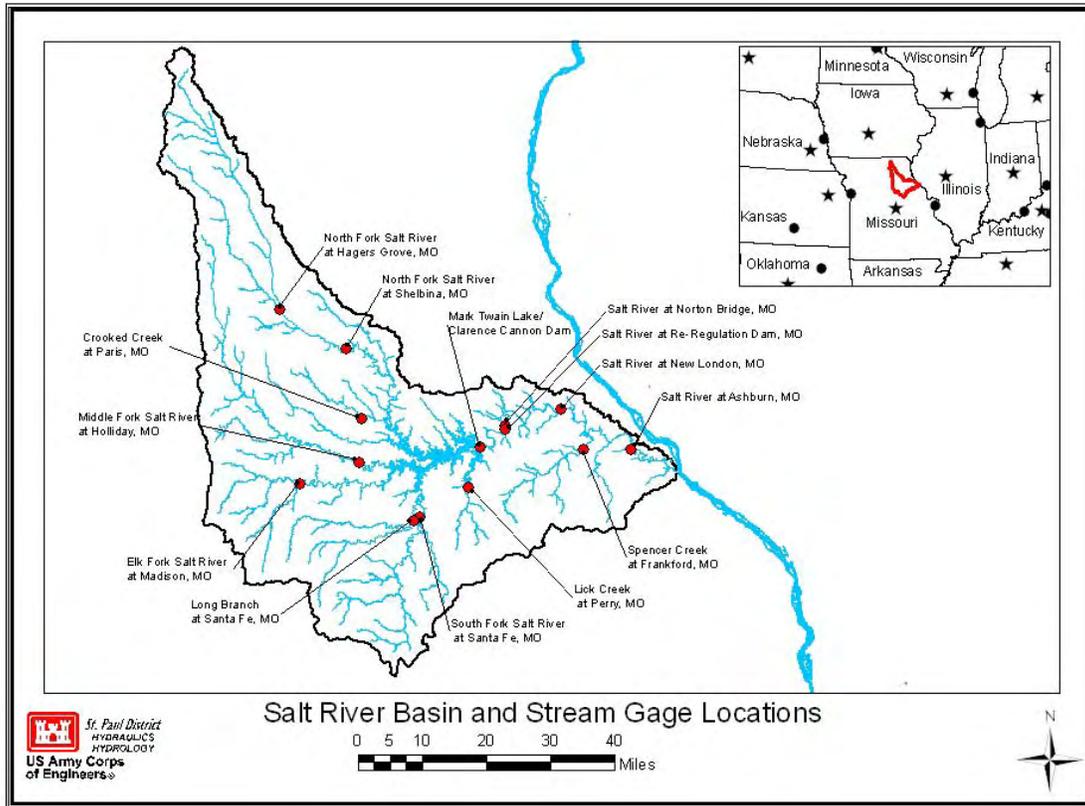
Figure 1 Salt River Basin and Gage Locations

HYDROLOGIC MODEL DEVELOPMENT

The selected hydrologic computer model for this analysis was the U.S. Army Corps of Engineers Hydrologic Engineering Center's rainfall runoff model titled HEC-HMS**.** (USACE HEC 2009b) Historical stream flow data from USGS gages throughout the Salt River Basin and corresponding historic precipitation were utilized to calibrate three summer seasons during the recent period of record. Basin responses to a season of rainfall events were optimized to determine customized timing and shape parameters of the unit hydrograph for each gaged subbasin. Unit hydrograph parameters for ungaged subbasins were computed with a regional equation, developed by HEC (USACE HEC 1996). Using Geographic Information System (GIS) soil coverages, infiltration characteristics were defined for each subbasin.

Watershed Delineation: The delineation of the Salt River Watershed was accomplished with ArcGIS and the Hydrologic Engineering Center's ArcMap GeoHMS application. A 30-meter digital elevation model (DEM) provided by MVS was the foundation for the GIS delineation. The projection of the DEM was Albers Equal Area. The streams definition started at 20,000 cells in the flow accumulation grid. This provided adequate stream definition to all the observed stream gages used in the study. The Salt River watershed size computed through the GIS processing was 2,882 square miles that compared well to other published values for the basin. The watershed was subdivided at USGS and St. Louis District (MVS) stream gage locations. **Figure 2** illustrates the sub watershed delineations and the times of concentrations computed for each.
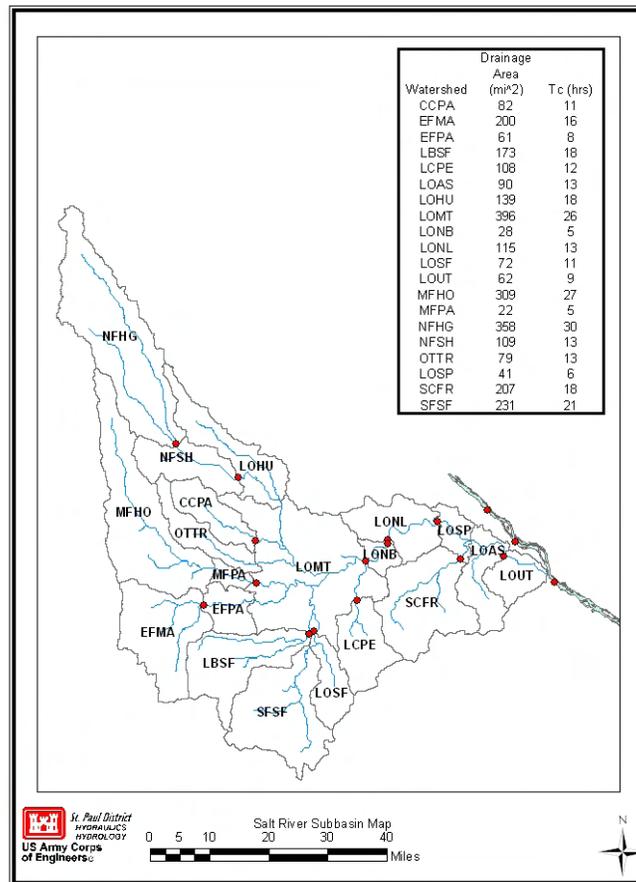
Watershed	Drainage Area (mi^2)	Tc (hrs)
CCPA	82	11
EFMA	200	16
EFPA	61	8
LBSF	173	18
LCPE	108	12
LOAS	90	13
LOHU	139	18
LOMT	396	26
LONB	28	5
LONL	115	13
LOSF	72	11
LOUT	62	9
MFHO	309	27
MFPA	22	5
NFHG	358	30
NFSH	109	13
OTTR	79	13
LOSP	41	6
SCFR	207	18
SFSF	231	21

Figure 2 Salt River Subbasins

Computation Interval: The St. Paul District used a one-hour time interval for the 100-yr simulation. The one-hour time interval is appropriate for this analysis for several reasons. The HEC-HMS model and Unit Hydrograph parameters require enough points on the rising limb of the hydrograph to give adequate definition of the peak. The time of concentration of the smallest subbasin dictated the appropriate time interval. The travel time from the Mark Twain Reservoir to the Mississippi River at Louisiana is only 1-day. Intermediate control points within this reach that the reservoir could operate for, had travel times less than one-day. The watershed exhibits a flashy response to rainfall events. **Figure 3** illustrates how significantly different the hourly discharge hydrographs were from the average daily discharges in both peak magnitude and shape. Using an hourly time increment was necessary to compute the most accurate hydrograph shape and the most accurate depiction of the basin's response to precipitation.

Precipitation Processing: Detailed precipitation records were of key importance for a good calibration of flows in the Salt River Watershed. The basin average precipitation for each subbasin was configured for the entire period of record, 01 Jan 1908 to 31 Dec 2008 using the adopted 1-hour time interval. Continuous recording precipitation stations were identified within and adjacent to the Salt River watershed so that the best possible temporal and spatial weighting could be accomplished during the precipitation processing. For the period prior to August 1948, only daily rainfall records were available.   Hourly precipitation records were available starting

in August 1948. More hourly recording precipitation gages became available as time proceeded, with several additional precipitation gages added by St Louis District starting in 1996.
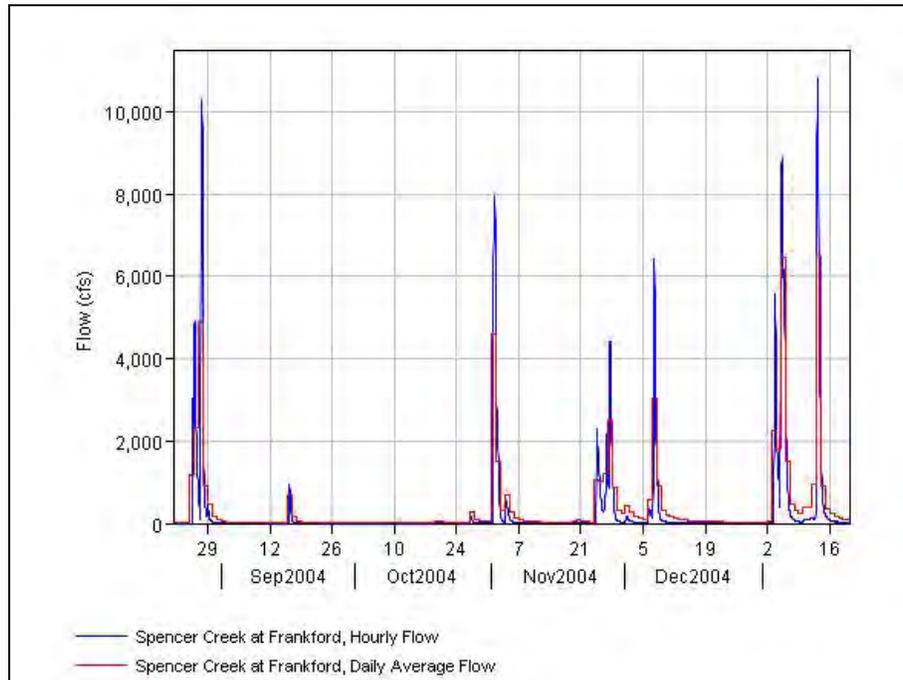

Figure 3 Differences in Daily Versus Hourly Hydrographs

To take advantage of daily precipitation gage data, an hourly distribution was patterned on the daily rain gage depths based on the closest nearby hourly gage, giving regard to the distance from the daily gage and the location of the gages with respect to typical storm tracks over the watershed. The actual time of the daily precipitation reading was noted wherever possible and was used to ensure the best possible timing to pattern the daily precipitation depth with the hourly distribution. Patterning the daily precipitation to an hourly distribution was accomplished with a Microsoft Excel (MS Excel) spreadsheet.

Hourly precipitation data exhibited more on-and-off recording periods than that seen in daily recording gage data. To handle the on-and-off nature of the hourly gages, the HEC GageInterp (USACE HEC 2006) program was used to generate an hourly grid of precipitation data for the Salt River Watershed. For each hour, a grid was created using a Theissen Polygon distribution between all recording precipitation gages. In this way, the precipitation grid automatically accounted for the on-and-off nature of the gages and "filled" the grid with the next nearest gage information when a gage was not operational. The gridded hourly precipitation was written to HEC-DSS.

Prior to 1948, where hourly precipitation records were not available, the daily rainfall totals were distributed in uniform 1-hour increments over the day. Within HEC-HMS the precipitation grids were automatically converted into an average rainfall depth for each subbasin using the grid cells and the subbasin boundaries.

Evapotranspiration: Evapotranspiration is the combination of evaporation from the ground surface and transpiration by the vegetation. It can often account for a significant portion of the water budget in a watershed. The Monthly Average Evapotranspiration method was selected as the preferred method by MVS, to keep the analysis as simplified as possible. The average monthly evaporation rates were taken from the New Franklin 1W climatologic station. (**Table 1**) This station was the closest geographically to all subbasins and had the longest record of 52 years. The evaporation pan coefficient of 0.75 was adopted for all subbasins in the watershed, based on a Missouri Department of Natural Resources Report. (MoDNR 1997) The average monthly evaporation rates and associated pan coefficients were input directly to the meteorologic interface of the HEC-HMS model.

Table 1 New Franklin 1W Monthly Evaporation Rates

Month	Evaporation (inches)
Jan	0.92
Feb	1.61
Mar	3.09
Apr	4.83
May	5.86
Jun	6.69
Jul	7.53
Aug	6.57
Sep	4.79
Oct	3.79
Nov	2.32
Dec	1.35

Within a HEC-HMS continuous simulation, the meteorologic model computes the potential evapotranspiration, and the actual evapotranspiration is calculated for each subbasin based on the soil water limitations.

Infiltration and Soil Moisture: The method selected to track infiltration through the soil column was the Deficit Constant method.   Deficit Constant parameters were derived for each subbasin based on soil parameters from each individual subbasin. Calibrations proved that the deficit constant method produced adequate results, and the more rigorous Soil Moisture Accounting method, that can become very cumbersome to calibrate, was not necessary.

The continuous simulation within HEC-HMS requires soil parameters as input to estimate the infiltration of water into the soil column, and moisture storage capacity. The Natural Resources Conservation Service (NRCS) GIS-based SSURGO Soils data layers were downloaded for each of the 15 counties that are all or partially contained within the boundaries of the Salt River Watershed. Each soil division within SSURGO contains numerous data, including soil components and properties of the individual horizons within each component. The soil types at the soil surface within the watershed are predominantly silt loams. **Figure 4** illustrates the makeup of the soils at the surface.

To further investigate the potential for water infiltration in to the soil column, various tables within the SSURGO database were linked with GIS tools to access the properties of soil layers at various depths below the ground surface. Sample locations were selected at 71 "typical" locations across the Mark Twain watershed. At least 3 locations were selected within each subbasin of the watershed, and more were selected in subbasins where greater variability was observed. The major soil component (minimum 75%) was selected to be representative for each location. The runoff and drainage characteristics for the soils were documented as well as the thickness, wilting water content, available water content, texture, porosity, and saturated hydraulic conductivity of each horizon that the soil contained.
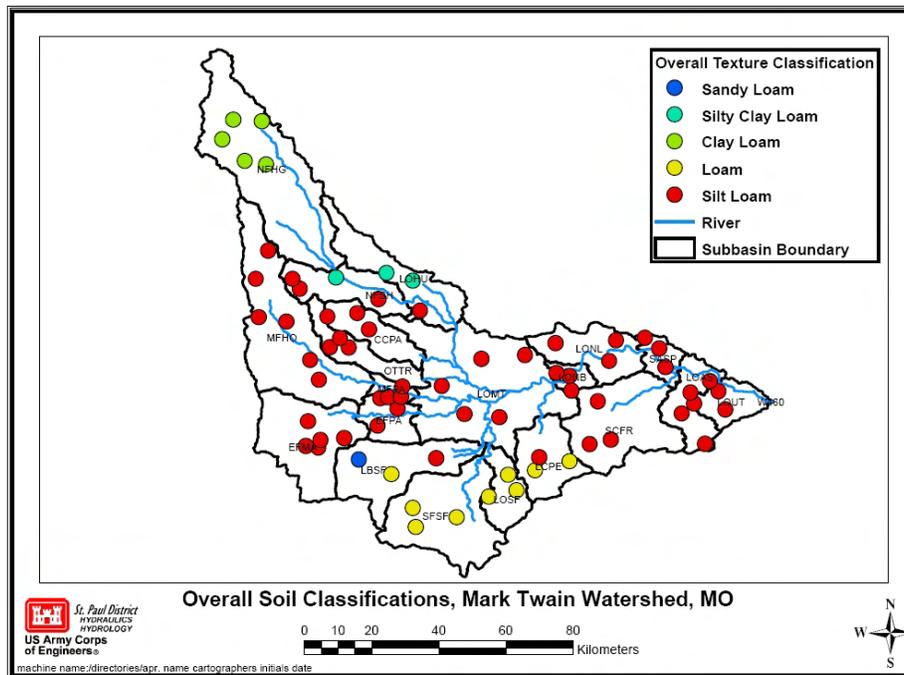

Figure 4 Overall Soil Classifications at the Ground Surface

Through the review of the 71 typical locations and the characteristics of the layers defined within the SSURGO database, it was determined that shallow layers of clay with low hydraulic conductivity lie a short distance below the ground surface. The low hydraulic conductivities of the underlying layer limit the amount of water that can infiltrate into the soil column. **Figure 5** shows the make-up of the layers of limiting hydraulic conductivity. **Table 2** summarizes an "average" value for hydraulic conductivity for the A-horizon and for the limiting layer in the soil column as well as an estimate for the soils capacity to store moisture.
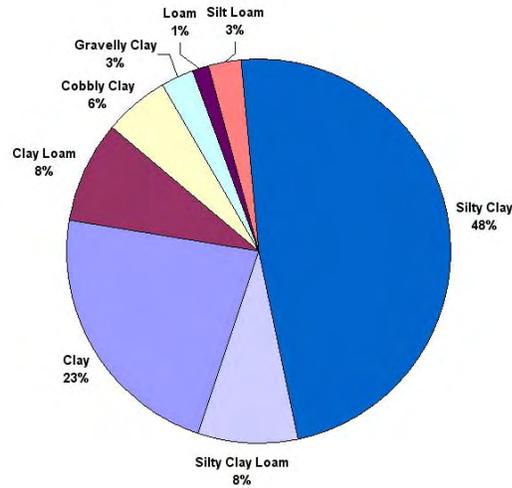
Figure 5 Texture of limiting layer of hydraulic conductivity for Selected Points

Table 2 Soil Properties- Averages of Analysis Points Across Subbasins

	# of points	A horizon depth	A horizon hydr conductivity	Depth to limiting layer	Limiting hydr conductivity	Soil Storage Above Limiting Layer	Soil Storage Above & Including Limiting Layer	Total Storage of Soil Column
		cm	cm/hr	cm	cm/hr	cm	Cm	cm
NFHG	5	14.40	0.90	17.40	0.35	4.56	16.63	37.81
NFSH	4	20.25	0.32	14.00	0.09	3.81	11.70	34.65
LOHU	3	21.67	0.50	18.67	0.11	6.60	15.14	43.68
CCPA	3	21.67	0.50	18.67	0.11	6.60	15.14	43.68
OTTR	3	19.33	0.68	28.67	0.09	9.85	17.98	47.64
MFHO	6	15.83	0.64	17.50	0.14	5.95	15.45	42.40
MFPA	3	12.00	1.11	16.67	0.18	6.12	19.80	50.88
EFMA	5	17.80	0.57	23.20	0.11	7.79	19.97	44.05
EFPA	3	22.00	0.89	26.00	0.08	8.45	19.90	43.37
LBSF	3	20.33	0.68	34.67	0.08	12.17	19.37	52.25
SFSF	3	18.00	0.89	32.00	0.07	10.27	18.54	48.91
LOSF	3	17.00	0.89	31.33	0.08	10.01	18.84	48.08
LCPE	3	20.33	0.68	34.67	0.08	12.17	19.37	52.25
LOMT	5	18.80	0.81	30.40	0.08	10.13	18.78	47.83
LONB	2	24.00	0.68	76.00	0.08	23.17	35.84	53.28
LONL	3	16.00	0.68	69.00	0.10	26.06	38.55	55.98
SCFR	4	17.00	0.68	92.50	0.08	35.04	42.70	58.96
LOSP	3	15.00	0.68	59.00	0.30	22.81	35.32	66.47
LOAS	4	21.00	0.68	62.50	0.08	22.77	28.61	54.00
LOUT	3	14.33	0.68	60.67	0.28	22.52	29.10	66.08

The high percentage of somewhat-poorly-drained to poorly-drained soils within the watershed, and the shallow layers of low hydraulic conductivity clay soils is consistent with the very high runoff characteristics and flashy nature of the observed runoff hydrographs at stream gages in the watershed. The underlying clay layer through the basin limits the vertical movement of water from the surface to the groundwater. Base flow is not sustained during dry periods as can be observed in the stream gage records. Stream flows are highly variable and rapidly increase because of the low permeability of the underlying soil column the steepness of the watershed and the shape of the basin.

Rainfall-Runoff Tranformation
Clark's Unit hydrograph parameters were selected to transform the rainfall into runoff. A multilinear regression equation, developed at HEC during a previous hydrologic study (USACE HEC 1996) was used to predict unit hydrograph parameters for ungaged subbasins. The regional equation used in this study is the following:

$$Tc + R = 0.88*(DA)^{0.338}*(L)^{0.535}$$

Where Tc is Clark's unit hydrograph parameter, time of concentration, R is Clark's storage coefficient,.DA is drainage area and L is the watercourse length. HEC reported an average regional value of R/(Tc+R)=0.44 for the Salt River Watershed. With these two equations and two unknowns, Clark's unit hydrograph parameters were computed for each subbasin. These values were adjusted where gage data was available for calibration.

2.6 Baseflow
The Linear Reservoir baseflow method was used in conjunction with a continuous simulation model to represent the interflow between the ground surface and soil column. It conserves mass within each subbasin. This baseflow model simulates the storage and movement of subsurface flow as storage and movement of water through up to two reservoirs. The initial baseflow is specified for the beginning of the simulations. The groundwater storage coefficient is a time constant in each layer. It is measured in hours and gives a sense of the response time of the subbasin. Increasing the number of groundwater reservoirs increases the attenuation of the baseflow.

In the Salt River Basin, the average monthly baseflow is very small in the watershed due to the low conductivity of the underlying clays and rock. As can be seen in the discharge records within the Salt Basin, the baseflows are not sustained by groundwater inflow during dry weather. There tends to be a relationship between Clark's R, Groundwater coefficient 1 (GW1) and Groundwater coefficient 2 (GW2). In this watershed GW1 was close to Clark's storage coefficient R and the GW2 was approximately two times GW1.

2.7 Hydrologic Routing
The HEC-HMS model required routing parameters to translate subbasin outflow to downstream computation points. Due to the lack of good channel cross section information upstream of Mark Twain Lake, Muskingham routing parameters were adopted from previous studies and adjusted

in the calibration/verification process. **Table 3** shows the routing parameters used within the HEC-HMS model.

Downstream of Clarence Cannon Dam, the time series extracted from the existing condition HEC-HMS simulation were the runoff hydrographs for each of the subbasins. The routing and combination of in-channel flows with incremental local flows was handled within the reservoir routing program.

TABLE 3   HEC-HMS Routing Parameters

Stream	From Location	To Location	Muskingham K	Muskingham X	# Steps
North Fork Salt	HagersGrove	Shelbina Gage	20	0.1	20
North Fork Salt	Shelbina Gage	Hunnewell	24	0.1	24
North Fork Salt	Hunnewell	Mark Twain	9	0.1	9
Crooked Creek	Paris	Mark Twain	9	0.1	9
Otter Creek	Basin Outlet	Mark Twain	9	0.1	9
Middle Fork	Holliday	Paris	15	0.1	15
Middle Fork	Paris	Mark Twain Lake	13	0.1	13
Elk Fork	Madison	Paris	21	0.1	21
Elk Fork	Paris	Mark Twain Lake	10	0.1	10
Long Branch	Santa Fe	Mark Twain Lake	5	0.1	5
South Fork	Santa Fe	Confl w/ LOSF	10	0.1	10
South Fork	Confl w/LOSF	Mark Twain Lake	2	0.1	2
Lick Creek	Perry	Mark Twain Lake	5	0.1	5
Spencer Creek	Frankford	Confl w/ Salt River	5	0.1	5
* Note – Routing reaches on the Salt River below the Clarence Cannon Dam are handled within the reservoir routing program.					

MODEL CALIBRATION

Calibration to Three Seasons: The Salt River Basin HMS model was calibrated to hourly discharges at stream gages within the Salt River Basin. The hourly stages recorded at the MVS stream gages were converted to discharges using the most recent USGS rating curves
The model was calibrated for three summer seasons from recent data period, 1996-2008. During this time period, the modeling benefitted from the densest and finest temporally distributed precipitation gage network and the most detailed stream gaging records within the Salt River Basin. The calibrated events included the summer periods of 2002, 2004 and 2008. The calibrated basins for each year included: North Fork at Hagar's Grove, Crooked Creek at Paris, Middle Fork near Holliday, Elk Fork near Madison, Long Branch at Santa Fe, South Fork at Santa Fe, Lick Creek at Perry, and Spencer Creek near Frankford. **Table 4** summaries the soil parameter limits (as was determined from the SSURGO soil analysis and converted to English units) and the calibrated parameters for each of the calibrated subbasins.

The ratio of R/Tc+R =0.44 (USACE HEC 1996) was computed for the newly adopted calibrated parameters, and it appeared that even with the adjustments through calibration, the ratio of R/Tc+R was still valid.

A CENTURY OF SIMULATED FLOWS

The unit hydrograph parameters for the ungaged basins were computed directly from HEC's regional equation (USACE, HEC 1996). The range of valid soil parameters was bounded by the surface and limiting clay layers properties determined in the soils analysis. The values selected for the model were further informed by the calibrated values for similar, nearby subbasins.

Table 4 Summary of Key Calibration Variables

	Computed.	Measured Values				Calibrated Values				
Basin	Tc(hr),R(hr)	Ksat Upper (in/hr)	Ksat Limitg (in/hr)	Max Def (in)		Tc(hr),R(hr)	Max Def (in)	Const Rate (in/hr)	GW1 Coef (hrs)	GW2 Coef (hrs)
NFHG	30, 23	0.36	0.14	1.80		20, 15	2	0.10	10	20
CCPA	11, 9	0.20	0.04	2.60		11, 10	1.5	0.35	10	20
MFHO	27, 22	0.25	0.05	2.34		24, 20	1.5	0.15	15	30
EFMA	16, 12	0.23	0.04	3.07		16, 12	1.3	0.13	10	20
LBSF	18, 14	0.27	0.03	4.79		14.6,12	1.5	0.10	12	24
SFSF	21, 16	0.35	0.03	4.04		22. 17	2	0.10	15	30
LCPE	12, 9	0.27	0.03	4.79		12, 10	1.5	0.10	5	10
SCFR	18, 14	0.27	0.03	13.80		12.5,10	2.5	0.20	5	10
Tc – Clark's Time of Concentration (hrs)										
R – Clark's Storage Coefficient (hrs)										
Ksat Upper – Saturated Hydraulic Conductivity of the upper soil surface (in/hr)										
Ksat Limitg- Saturated Hydraulic Conductivity of the limiting soil layer (in/hr)										
Max Def – Volume moisture deficit of the soil column (porosity-wilting point) (in)										
GW1 – Groundwater storage coefficient 1 (hrs)										
GW2 – Groundwater storage coefficient 2 (hrs)										

Two separate HEC-HMS runs were made to simulate the existing condition 101 year period of record requested by MVS. The earliest period, January 1908 through August 1948, the daily precipitation records were used to construct a precipitation grid with the daily depths distributed uniformly over the hours in the day. A second simulation was made for August 1948 through December 1986. The two existing condition simulations were overlapped by 2 months to ensure that the model results were consistent and unbiased by the initial conditions in the later model.

The performance of the HEC-HMS model for the Salt River Basin was assessed by visual evaluation of the time series data as well as by computation of the Nash-Sutcliffe Coefficient, also referred to as the efficiency index (E_{NS}), for the recent period of record (1996-2008) where hourly discharges were measured. In the following equation for the Nash-Sutcliffe Coefficient (Dingham), the hourly time series of $i=1,2,...,N$, measured hourly discharges Q_i, simulated hourly discharges $Q^\wedge_i$ and m_Q, the average hourly observed discharges for the period of analysis.

$$E_{NS} = R_{NS}^2 = 1 - \frac{\sum_{i=1}^{N} \left(Q_i - \hat{Q}_i \right)^2}{\sum_{i=1}^{N} \left(Q_i - m_Q \right)^2}$$

A Nash-Sutcliffe efficiency index of 1.0 indicates a perfect fit of the model's simulation to the observed data series. The Nash Sutcliffe efficiency index is affected by sample size, outliers, magnitude bias and time-offset bias. The eight gaged subbasins with hourly discharge records (1996-2008) had efficiency indexes ranging from 0.50 to 0.64. Chung et al. (1999, 2002) used standards of efficiency index > 0.3 with EPIC simulations to determine if the model results were satisfactory.   Green et al. (2006) set the criteria of the efficiency index to 0.4.

The results from the HEC-HMS model filled in actual stream gage data gaps.   Although the models were calibrated to historic rainfall events, the simulation was ultimately used to assess reservoir operation rules, and did not need to reproduce the historic events exactly. Given the spatial and temporal distribution of the reconstituted rainfall events, the varying synchronization between the measured rainfall and runoff records, the flashy nature of the runoff hydrographs in the basin and the possibility of backwater effects at some gage locations, the range of Nash Sutcliffe efficiency indexes suggest excellent results are accomplished with this HEC-HMS model of the Salt River Basin for the purposes of the study.

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