Derivation of Watershed Modeling Parameters for use in a Drainage Design Manual for Lake Tahoe Basin, California-Nevada

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Executive Summary

- The purpose of this report is to:1) apply the results of statistical software developed under the Corps' SWWRP R&D program for a case study in the Lake Tahoe basin; and, 2) to use these results to provide watershed model precipitation-runoff model parameters for use in developing a drainage design manual for the Lake Tahoe Basin. The statistical software developed was used to estimate peak flow frequency curves for gage basins and regional regression flow frequency estimates for ungaged basins.

- The drainage design manual needs to address a range of watershed drainage areas and land uses within the Lake Tahoe Basin. Of these, the urban drainage problem for watersheds between elevations 6200-7000 feet easily present the most common design problem. Unfortunately, the gaged watersheds drain a much greater elevation range (see figure 1.1). No gages specifically measure runoff from the urban watersheds within the basin. Consequently, the focus of this investigation will be on developing watershed model parameters for these lower elevation watersheds.

- Given the data available and the standard practice by the engineering community, event oriented watershed models (e.g., see HEC-1, HEC, 1990 or TR-55, NRCS, 1986) were selected for use in addressing the drainage design problem. The problem with applying the event oriented approach is selecting the various inputs and parameters (hypothetical design storms, antecedent conditions (snow pack and soil moisture), loss rates and routing parameters) that need be combined to obtain a particular design flow (e.g., the 100-year peak discharge).

- The following strategy was undertaken to develop the modeling information needed for a manual.

    - Watershed models were developed and calibrated to observed runoff for the gaged watersheds;

    - Template design storms were used in calibrating snow melt and loss rates to reproduce estimates of the peak 100-year and 2-year discharges obtained from either a frequency analysis of gage annual peak flows or from regional regression equations. (A template design storm is an actual event proportioned to have a specific precipitation depth obtained from depth-duration frequency curves)

    - The 100-year and 2-year peak flows were obtained from these for low-elevation sub-basins (elevation spanning 6200-6700 feet) that were elements of the calibrated models.

    - The 100-year and 2-year discharges for these low-elevation sub-basins were then used to calibrate effective loss rates in simulations of standard 24hour duration hypothetical storms derived from depth-duration-frequency analysis.

- The HEC-1 model was modified to better calibrate model parameters to the precipitation snowmelt runoff for the observed events. The modifications involved modifying the loss rates methods to allow for initial losses of snowmelt. Additional output was created so that the representation of snow pack melt recorded by snow course measurement could be used in the calibration process.
- HEC-1 watershed models were formulated for gages using 500 foot increments in elevation. This allowed the model simulation to reasonably represent the change with elevation of initial snow pack condition at the beginning of the storm event, the representation of temperature effect on precipitation phase and the distributed response of the watersheds.
- Model calibration results were obtained for the 01 January 1997 and the 24 March 1998 events. These two events are, respectively, characteristic of about a 100- and 2-year event.
- Results of the calibrations were somewhat mixed at the gages where data was available. In general, the simulated and peak discharges agreed within a few percent. However, the hydrograph reproduction was mixed. The following figure shows on of the better reproductions

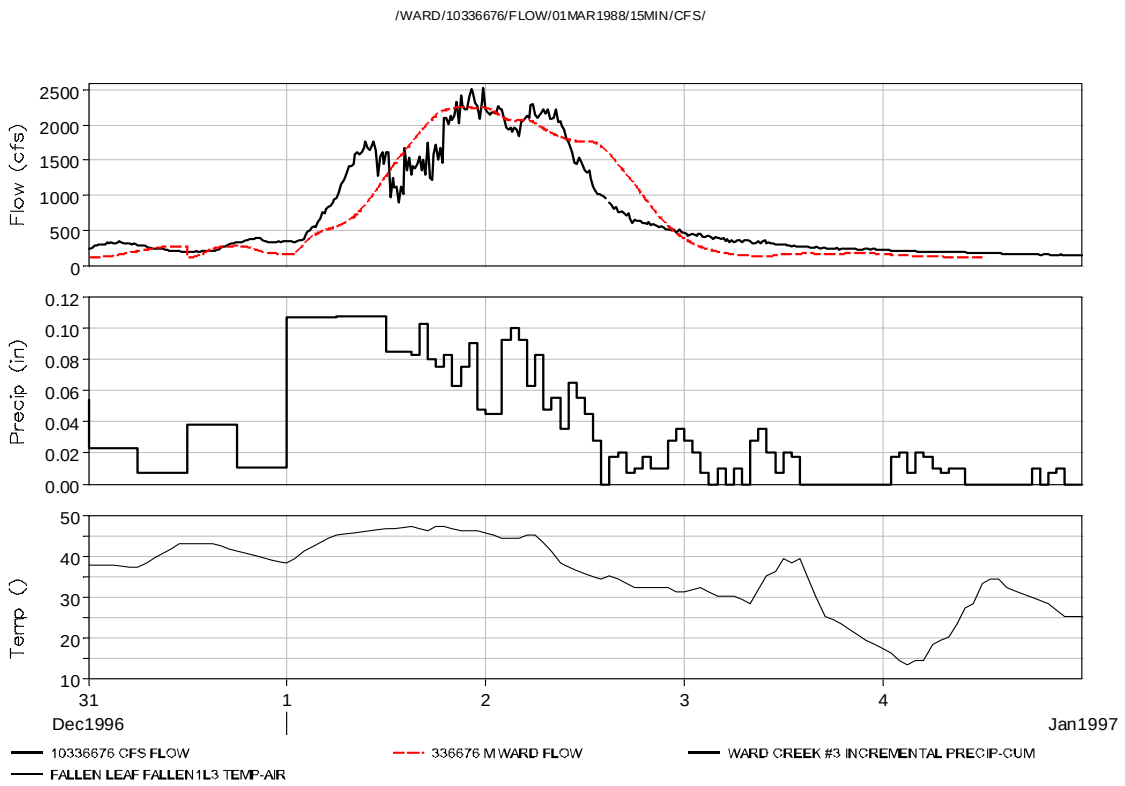

Figure: 01 January 1997 event Ward Creek reproduction

- Template design storm events were constructed to reproduce 100-year and 2-year discharges predicted by flow-frequency and regional-regression equations at the watershed gages. The value of these template events is that the coincidence between

antecedent conditions (snow pack) for actual storm events is preserved. The following figures show the template precipitation pattern used for the 1997 event.

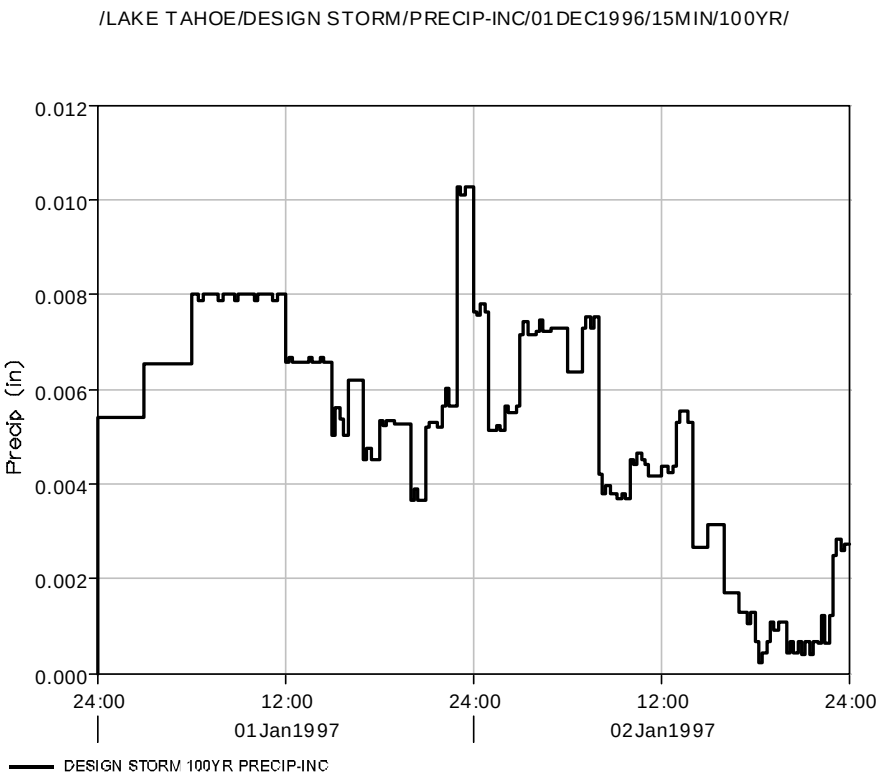

Figure: Dimensionless 100-year template event based on an average 01 January 1997 storm

- The simulation of the template events allowed the estimation of 100 and 2-year return interval peak flows for the low-elevation (6200-6700 feet) sub-basins in the models. The following table presents example loss rate calibrations for the 01 January 1997 event. Note that sub-basin 1 in the table indicates the lowest elevation sub-basin.
- The template design events results for the lowest elevation sub-basins were used to formulate hypothetical events and calibrate loss rates to reproduce the 100 and 2-year discharges estimated for the lowest model sub-basins. The results of the analysis indicated that for a NOAA14 24hour storm depth, an average depth-duration relationship derived from actual storm events together with the loss rates in the table below are appropriate for simulating design flows for open areas. **The loss rates are effective values which are intended to account for the effects of snow melt that would be associated with the storm event.**

Table: Simulation loss rates used to estimate 100-year peak quantiles

basin	USGS ID	sub-basin	area	[1]initial	[2]constant
Upper Truckee	10336610	3	7.83	1.00	0.27
		2	6.32	0.50	0.21
		[3]1	13.9	0.00	0.21
General Creek	10336645	3	2.1	1.00	0.28
		2	1.8	0.00	0.26
		1	2.02	0.00	0.26
Ward Creek	10336676	3	2.41	3.00	0.05
		2	3.05	2.50	0.05
		1	1.87	0.00	0.05
Incline Creek	10336700	3	1.53	0.00	0.38
		2	1.1	0.00	0.40
		1	0.82	0.00	0.37
Third Creek	10336698	3	0.24	1.50	0.38
		2	0.32	0.00	0.40
		1	0.3	0.00	0.37
Trout Creekk	10336780	3	4.21	1.50	0.22
		2	4.2	0.00	0.29
		1	7.18	0.00	0.30

[1](inches), [2](inches/hour), [3]lowest elevation sub-basin

Table: Recommended constant loss rates (in/hr) for open areas between elevations (6200-6700 feet)

Watershed	100-year	2-year
Upper Truckee	0.2	0.1
General	0.2	0.1
Ward	0.05	0.1
Incline	0.3	0.1
Third	0.3	0.1
Glenbrook	0.3	0.1
Trout	0.3	0.1

- Application of the calibration results to an urban watershed is complicated by the difference in response characteristics of open areas. Because of this difference, the recommendation is to use different type storm events for open and impervious surfaces.
    - The average storm depth-duration relationships and effective loss rates used to reproduce the 100 and 2-year flow in the watershed model simulations are recommended for application to open areas.
    - The average storm depth-duration relationships used for open areas peak 5 minute to 1 hour precipitation intensity is much less than indicated by either the

NOAA14 depth-duration-frequency relationships or NRCS hypothetical 24-hour storms. A reasonable approach to simulating design flows from impervious areas would be to use the NRCS type 1A depth-duration relationship combined with some average melt rates derived from the watershed model calibration effort.

- Note that the calibration effort focused on estimating loss rates and developing hypothetical storms, but not on routing parameters. Routing parameters derived from the calibration of watershed models are for relatively large basins. These parameters do not provide any insight into the routing parameters needed for smaller urban watersheds. Rather guidelines provided in TR-55 (NRCS, 1986) need to be considered.

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References:

Bonnin, Geoff, 2003. Personal communication, NOAA-14 atlas precipitation, unpublished data, NOAA, Silver Spring, Maryland. For published data see: http://www.nws.noaa.gov/oh/hdsc/current-projects/project.html

HEC, 1990: HEC-1 Flood Hydrograph Package User's Manual, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA. http://www.hec.usace.army.mil/

Jeton, A.E., 1999, Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4110, 61p.

NRCS, (formerly, SCS) 1986. Urban hydrology for small watersheds, Technical report no. 55, Natural Resources Conservation Service (formerly Soil Conservation Service), Washington, D.C.

SPK, 2005. Investigation of Regional Regression Equations for Flow Duration, Peak and Annual Maximum Flow, and Low-flow Frequency Curves for the Lake Tahoe Basin, prepared for the Lake Tahoe Storm Water Quality Investigation Committee, Sacramento District, U.S. Army Corps of Engineers.

NOAA, 2004. Precipitation frequency analysis of the United States, Volume 1: Semiarid Southwest (Arizona, Southeast California, Nevada, New Mexico, Utah) Geoffrey M. Bonnin, Deborah Todd, Bingzhang Lin, Tye Parzybok, Michael Yekta, David Riley, National Oceanic and Atmospheric Administration, Silver Spring, Maryland. http://www.nws.noaa.gov/oh/hdsc/current-projects/project.html

United States Geological Survey (USGS), 2005. Personal communication Robert Bostic (rebostic@usgs.gov), Gerald Rockwell (glrock@usgs.gov). Short interval USGS stream flow data, Carson City, NV.

United States Geological Survey (USGS), 2004. Water Resources of the United States, Web Data Base, http://water.usgs.gov/.

Personal communication, Dan Greenlee, Hydrologist, Snow Survey Program Manager, 775-784-5878 ext.151, dan.greenlee@nv.usda.gov, www.nv.nrcs.usda.gov/snow)

1 Introduction

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The drainage design manual needs to address a range of watershed drainage areas and land uses within the Lake Tahoe Basin. Of these, the urban drainage problem for watersheds between elevations 6200-7000 feet easily represents the most common design problem. Unfortunately, the gaged watersheds drain a much greater elevation range (see figure 1.1). No gages specifically measure runoff from the urban watersheds within the basin. Consequently, the focus of this investigation will be on developing watershed model parameters for the lower elevations of the gaged watersheds.

Given the data available and the standard practice by the engineering community, event oriented watershed models (e.g., see HEC-1, HEC, 1990 or TR-55, NRCS, 1986) were selected for use in addressing the drainage design problem. The problem with applying the event-oriented approach is selecting the various inputs and parameters (hypothetical design storms, antecedent conditions (snow pack and soil moisture), loss rates and routing parameters) that should be combined to obtain a particular design flow (e.g., the 100-year peak discharge).

The following strategy was undertaken to develop the modeling information needed for a manual.

- Watershed models were developed and calibrated to observed runoff for the gaged watersheds;
- Template design storms were used calibrated to estimates of the peak 100-year and 2-year discharges obtained from either a frequency analysis of gage annual peak flows or from regional regression equations. (A template design storm is an actual event proportioned to have specific precipitation depth obtained from depth-duration frequency curves)
- The 100-year and 2-year peak flows were obtained from these for low-elevation sub-basins (elevation spanning 6200-6700 feet) that are elements of the calibrated models.
- The 100-year and 2-year discharges for these low-elevation sub-basins were then used to calibrate loss rates in simulations of standard 24hour duration hypothetical storms derived from depth-duration-frequency analysis.

These calibration results can then be used to recommend modeling parameters for a drainage design manual.

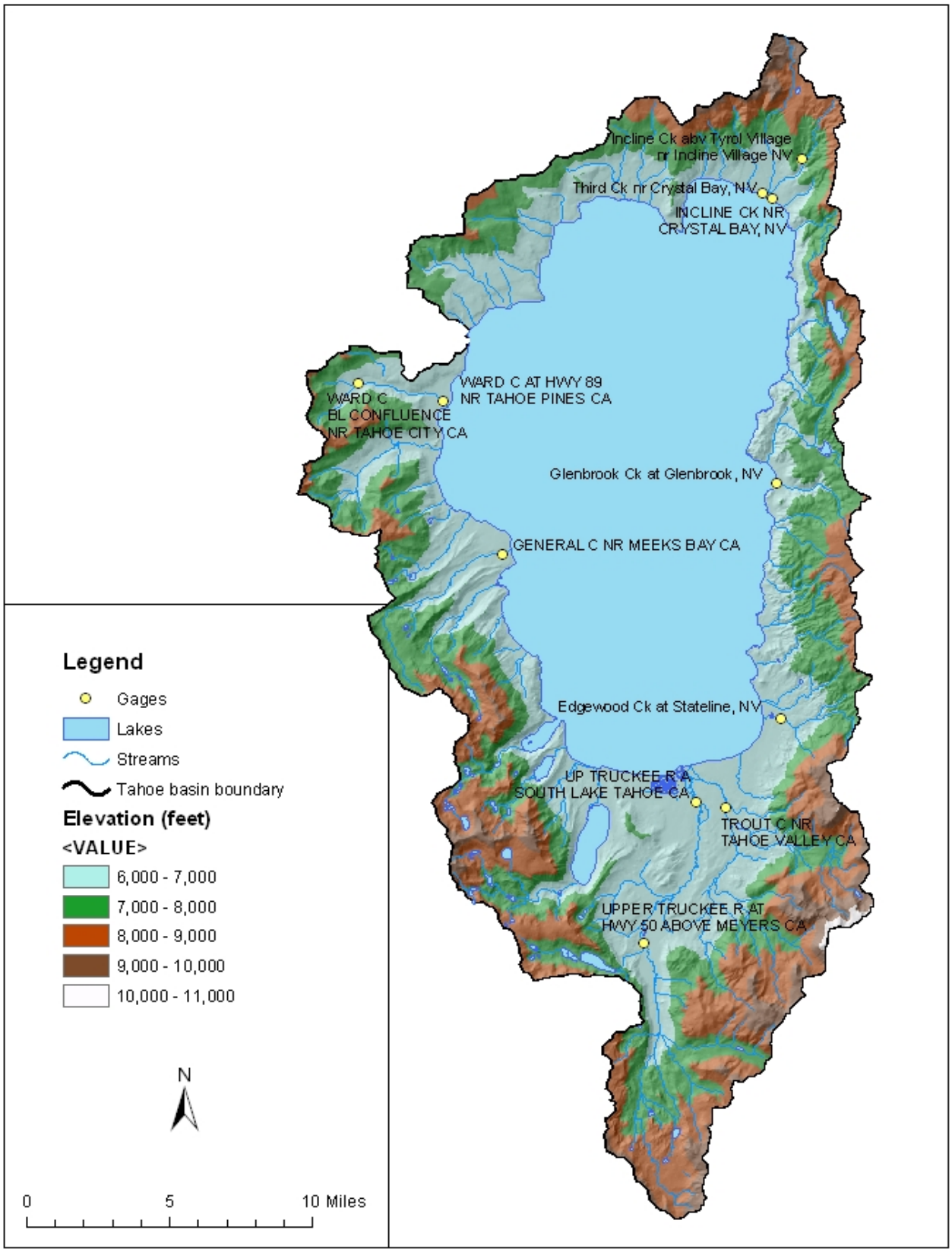


Figure 1.1: Gaged Lake Tahoe Watersheds

Note that most of this discussion has focused on estimating loss rates and developing hypothetical storms, but not on routing parameters. Routing parameters derived from the calibration of watershed models are for relatively large basins. These parameters do not provide any insight into the routing parameters needed for smaller urban watersheds. Rather guidelines provided in TR-55 (NRCS, 1986) need to be considered.

Section 2 describes the database available for calibrating watershed models to gage information. The watershed model development approach using a modified HEC-1 model is described in Section3. Sections 4 and 5 give the details of calibrating watershed models to the 01 January 1997 and 24 March 1998 storms. The determination of the 100-year and 2-year peak discharges for low-elevation sub-basins (6200-6700) feet using template design storms is described in Section 6. Section 7 provides the results of estimating effective loss rates needed to reproduce these estimates of the 100-year and 2-year peak flows by simulating hypothetical storms. Section 8 provides recommendations for using these results to estimate design discharges for urban watersheds.

2 Database

Watershed model simulation of hydrographs generally requires short interval information (hourly) or less. In the case of Lake Tahoe basin, short interval measurements of temperature are also desirable. Table 2.1 shows that the NRCS SNOTEL Data Network has significant amounts of break point (short interval) precipitation data and max-min temperature data but a limited amount of break-point hourly temperature data. Table 2.2 list the gages and Figure 2.1 shows the locations where 15-minute interval stream flow measurements are available.

The value of the data for simulating hydrographs is limited by the availability of short interval temperature data. An attempt to use this max-min data for event simulation was made by trying to model the diurnal variation of temperature from historic patterns. Ratios shown in Table 2.3 were determined from the patterns and applied using the following formulas:

thourly = tmax1 + ratio(tmin2-tmax1) Time 1:00 – 6:00

thourly = tmin2 + ratio(tmax2-tmin2) Time 7:00 – 15:00

thourly = tmin3 + ratio(tmax2-tmin3) Time 16:00 – 24:00

Figure 2.2 shows an example of estimated diurnal variation of temperature using the inferred patterns. However, figure 2.3 show the ineffectiveness of the inferred diurnal temperature variation in comparison to actual short interval temperature. This comparison basically shows that inferred temperature variation from max-min temperature data is not particularly useful for simulating runoff hydrographs. Simulating runoff hydrographs requires being able to distinguish the phase of precipitation, and only having max-min temperature makes this very difficult. This lack of short interval temperature record limits the period of record where hydrographs can be selected for calibrating watershed models.

Table 2.1: Precipitation, temperature and snow water equivalent gages (obtained from NRCS (formerly SCS), 2004c.

Gage	Elevation (ft)	[1]Lat	[2]Long	[3]T	[4]SWE	[5]POR	[6]Source
Echo Peak	7670	38.84903	120.07850	x	x	1979-2004	SNOTEL
Fallen Leaf Lake	6236	38.93405	120.05457	x	x	1979-2004	SNOTEL
Hagan's Meadow	7776	38.85185	119.93742	x	x	1979-2004	SNOTEL
Heavenly Valley	8582	38.92433	119.91647	x	x	1979-2004	SNOTEL
Marlette Lake	7880	39.16395	119.89672	x	x	1979-2004	SNOTEL
Rubicon #2	7689	38.99920	120.13032	x	x	1980-2004	SNOTEL
Squaw Valley	8029	39.18998	120.26475	x	x	1979-2004	SNOTEL
Tahoe City Cross	6797	39.17162	120.15362	x	x	1980-2004	SNOTEL
Ward Creek #3	6655	39.13562	120.21763	x	x	1979-2003	SNOTEL
Glenbrook	6350	39.16700	120.13300	x		1948-2001	NOAA
Tahoe City	6240	38.84903	120.07850	x		1931-1999	NOAA

[1]Latitude [2]Longitude [3]Max-Min Daily Temperature [4]Daily Snow Water Equivalent
[5]Period of record break point interval data (reports precipitation as it occurs at short intervals (as small as a minute increment), **period of record for hourly temperature data 1997-2004**.

Table 2.2: Stream gages (United States Geological Survey (USGS), 2005.

USGS ID	Description	[1]latitude	[1]longitude	[2]area	[3]elevation
103366092	Upper Truckee River at Highway 50 above Meyers, CA	38.8485186	-120.0271275	34.28	6310
10336610	Upper Truckee River at South Lake Tahoe, CA	38.92240778	-119.9915706	54.9	6229
10336645	General Creek near Meeks Bay, CA	39.05185194	-120.1185208	7.44	6250
10336674	Ward Creek below Confluence near Tahoe City, CA	39.14074	-120.2121378	4.96	6600
10336676	Ward Creek at Highway 89 near Tahoe Pines, CA	39.13212917	-120.1576914	9.7	6230
10336698	Third Creek near Crystal Bay, NV	39.2404633	-119.9465775	6.02	6234
103366993	Incline Creek above Tyrol Village near Incline Village, NV	39.25879694	-119.9232439	2.85	----
10336700	Incline Creek near Crystal Bay, NV	39.24018556	-119.9449106	6.69	6247
10336730	Glenbrook Creek at Glenbrook, NV	39.08740806	-119.9399056	4.11	6240
10336760	Edgewood Creek at Stateline, NV	38.96601917	-119.937125	5.61	6280
10336780	Trout Creek near Tahoe Valley, CA	38.91990778	-119.9724036	36.7	6229

[1]Decimal degrees
[2]Drainage area in square miles,
[3]Gage elevation (feet)

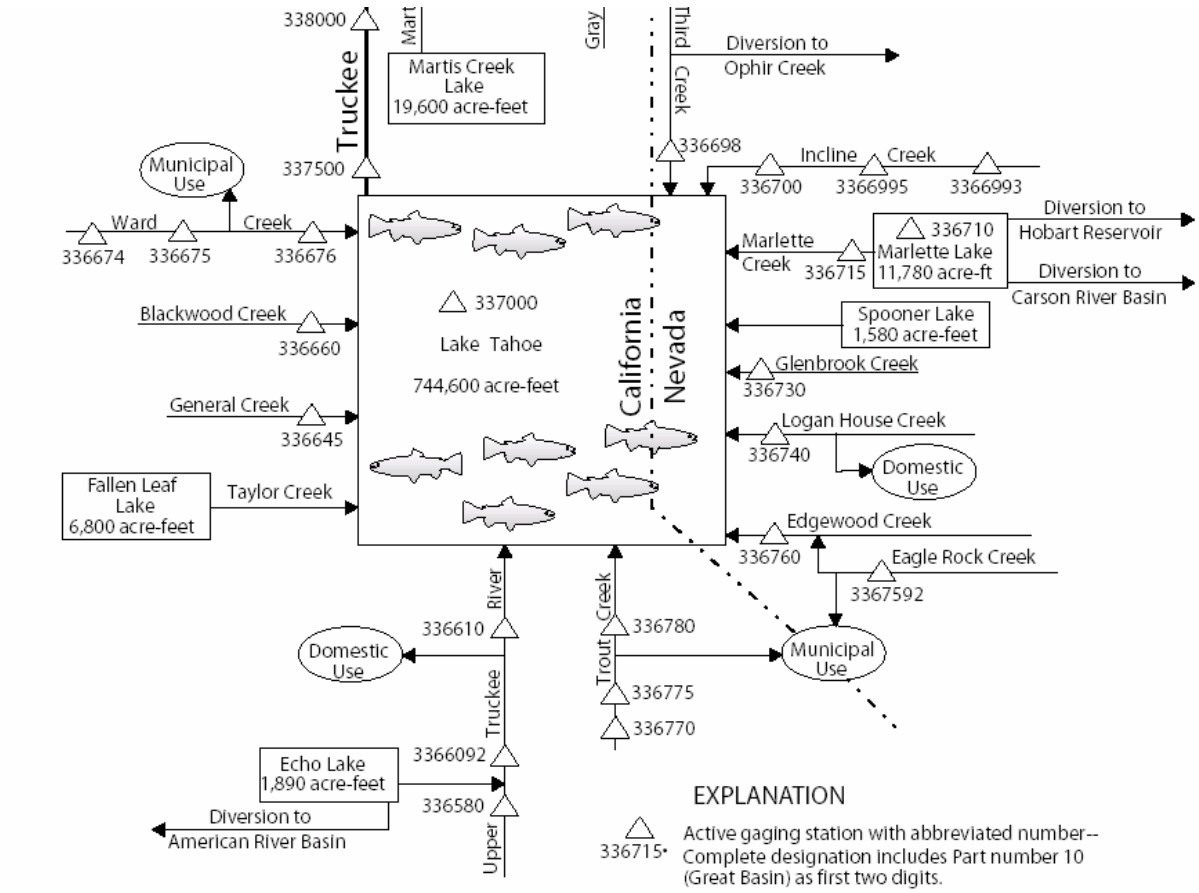


Figure 2.1 Stream gage schematic
(from: Steven N. Berris, E. James Crompton, Joseph D. Joyner, and Roslyn Ryan, 2002. Water Resources Data, Nevada, Water-Data Report NV-02-1, U.S. Geological Survey, Department of Interior, pg. 251.)

Table 2.3 Diurnal temperature pattern, fraction of daily max-min temperature difference

hour	dec/jan	mar	may/jun
first day max second day min temperature			
1:00	0.06	0.23	0.09
2:00	0.06	0.15	0.07
3:00	0.06	0.08	0.05
4:00	0.04	0.00	0.05
5:00	0.02	0.00	**0.00**
6:00	**0.00**	**0.00**	0.14
second day max and min temperature			
7:00	0.20	0.14	0.29
8:00	0.40	0.29	0.43
9:00	0.60	0.43	0.57
10:00	0.80	0.57	0.71
11:00	1.00	0.71	0.86
12:00	1.00	0.86	1.00
13:00	1.00	1.00	1.00
14:00	1.00	1.00	1.00
15:00	**1.00**	**1.00**	**1.00**
third day max second day min temperature			
16:00	0.89	0.92	0.91
17:00	0.78	0.85	0.82
18:00	0.67	0.77	0.73
19:00	0.56	0.69	0.64
20:00	0.44	0.62	0.55
21:00	0.33	0.54	0.45
22:00	0.22	0.46	0.36
23:00	0.11	0.38	0.27
24:00	0.06	0.31	0.18

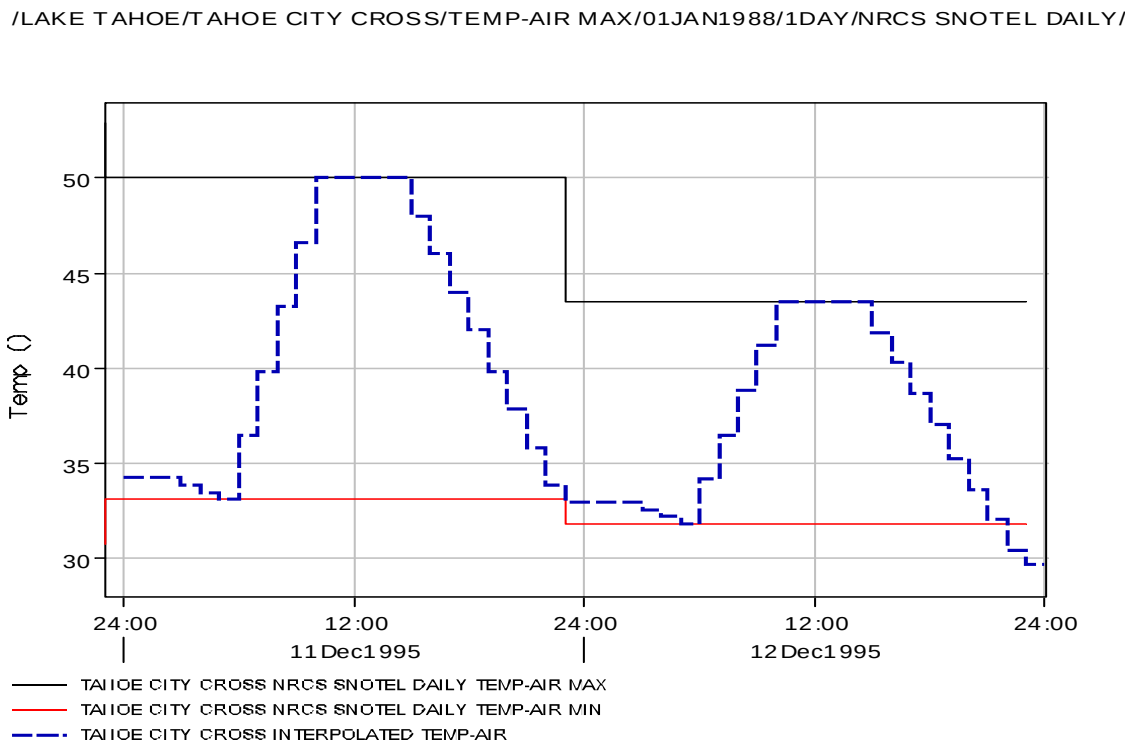


Figure 2.2: Estimated diurnal variation of temperature

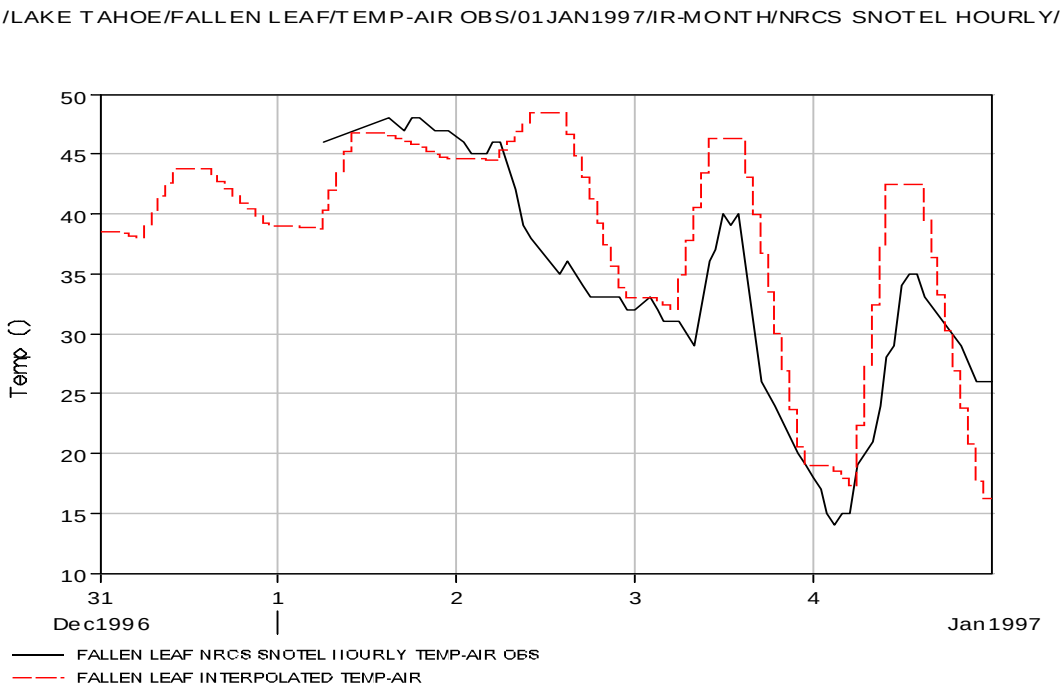


Figure 2.3: Comparison of observed short interval temperature to estimated diurnal variation

3 Watershed model development

3.1 Introduction

The HEC-1 watershed model (HEC, 1990) software was used to simulate precipitation-runoff. The purpose of this section is to describe the development of the HEC-1 watershed models used to simulate runoff in the Lake Tahoe Basin. Section 3.2 describes the modification of the HEC-1 model needed to adequately model snow-melt affected flood runoff from the basin. The segmenting of each the watershed into HEC-1 sub-basins is described in section 3.3.

3.2 HEC-1 model modification

The HEC-1 model watershed snowmelt and loss rate methods assume that the antecedent snow pack is ripe, that is any increment of heat during the storm will melt snow pack for runoff. This is useful for simulating design events but not for simulating observed events with either the degree-day or energy-budget methods. This is particularly true when the snow pack condition can change significantly with elevation, as in Lake Tahoe.

The HEC-1 model loss rate algorithms were altered to better allow the change in snow pack condition to be better simulated when using the degree-day method. This was done by dispensing with the snowmelt loss rate method and allowing for an initial loss when a snow pack exists. The initial loss was used to both simulate infiltration losses and the refreezing of rainfall in a snow pack that is not ripe. This is particularly important given that at higher elevations in the Tahoe Basin, the snow pack is likely to be able to absorb more rainfall than at lower elevations.

Output capabilities were added to the software so that the snow pack and associated precipitation phase, and melt rates changes as a function of elevation, could be reviewed to see how the algorithm changes the affected the simulation; as well as, compare changes in pack snow water equivalent with those recorded by snow-course and snow-pillow measurements for a particular storm. Table 3.1 and 3.2 provide an example of this modified output.

Table 3.1: HEC-1 modified output, precipitation, rain, snow, loss rates, runoff excess, melt rates

[1]Z789	zone	[2]precip (inch)	snowfall (inch)	rain (inch)	melt (inch)	melt loss (inch)	rain loss (inch)	melt excess (inch)	rain excess (inch)	total excess (inch)	melt rate (in/hr)	[3]melt duration (days)
	1	0.80	0.35	0.45	0.04	0.04	0.45	0.00	0.00	0.00	0.22	1.60
	2	1.91	0.96	0.95	0.06	0.06	0.95	0.00	0.00	0.00	0.17	1.43
	3	5.34	3.38	1.96	0.10	0.10	1.96	0.00	0.00	0.00	0.13	1.12
	total	8.04	4.68	3.36	0.19	0.19	3.36	0.00	0.00	0.00		
Z56	zone	precip	snowfall	rain	melt	melt loss	rain loss	melt ex	rain ex	total ex	melt rate	duration
	1	4.24	1.63	2.61	0.34	0.34	2.51	0.00	0.10	0.10	0.31	2.04
	2	3.66	1.47	2.20	0.22	0.22	2.14	0.00	0.05	0.05	0.27	1.83
	total	7.90	3.10	4.80	0.56	0.56	4.65	0.00	0.15	0.16		
Z4	zone	precip	snowfall	rain	melt	melt loss	rain loss	melt ex	rain ex	total ex	melt rate	duration
	1	7.80	2.54	5.26	0.79	0.78	4.97	0.01	0.29	0.30	0.36	2.17
	total	7.80	2.54	5.26	0.79	0.78	4.97	0.01	0.29	0.30		
Z3	zone	precip	snowfall	rain	melt	melt loss	rain loss	melt ex	rain ex	total ex	melt rate	duration
	1	7.63	2.13	5.51	2.88	2.40	4.19	0.48	1.31	1.80	1.21	2.38
	total	7.63	2.13	5.51	2.88	2.40	4.19	0.48	1.31	1.80		
Z2	zone	precip	snowfall	rain	melt	melt loss	rain loss	melt ex	rain ex	total ex	melt rate	duration
	1	7.41	1.30	6.11	2.52	2.07	4.44	0.45	1.66	2.11	1.01	2.49
	total	7.41	1.30	6.11	2.52	2.07	4.44	0.45	1.66	2.11		
Z1	zone	precip	snowfall	rain	melt	melt loss	rain loss	melt ex	rain ex	total ex	melt rate	duration
	1	7.06	0.88	6.18	3.23	2.63	4.49	0.60	1.69	2.29	1.12	2.88
	total	7.06	0.88	6.18	3.23	2.63	4.49	0.60	1.69	2.29		

[1]HEC-1 sub-basin, [2]Precipitation weighted by fraction of sub-basin, [3]duration of melt

Table 3.2: HEC-1 modified output, end of day elevation zone snow water equivalent (inches)

[1]Z789	[2]zone	1	2	3
[3]day	0	[4]10.00	10.00	10.00
	1	10.10	10.49	10.78
	2	10.51	11.15	12.33
	3	12.49	13.14	14.37
	4	13.09	13.75	14.98
Z56	zone	1	2	
day	0	10.00	10.00	
	1	9.81	9.96	
	2	9.83	10.09	
	3	11.82	12.08	
	4	12.41	12.68	
Z4	zone	1		
day	0	10.00		
	1	9.66		
	2	9.54		
	3	11.36		
	4	11.75		
Z3	zone	1		
day	0	10.00		
	1	8.76		
	2	7.31		
	3	8.92		
	4	9.24		
Z2	zone	1		
day	0	10.00		
	1	8.93		
	2	7.64		
	3	8.47		
	4	8.78		
Z1	zone	1		
day	0	10.00		
	1	8.65		
	2	7.07		
	3	7.40		
	4	7.65		

[1]HEC-1 sub-basin, [2]Elevation zone (500ft increments),[3]End of simulation day,[4]Snow pack snow water equivalent (inches)

3.3 Precipitation runoff methods

HEC-1 represents a watershed as an inter-connected group of sub-basin and routing elements. Precipitation-runoff for each sub-basin was computed using the following methods:

- Precipitation phase, snowfall versus rainfall, was identified given a watershed outlet temperature and the lapse rate per elevation zone. Elevation zones were defined at 500 foot intervals.
- Precipitation for each elevation zone was computed by weighting the gage precipitation by the ratio of the elevation zone area average to the gage 2-year, 24-hour precipitation. This was done to account for the variation of precipitation versus elevation.
- Melt rates were computed based on the degree day method.
- Rain and snow loss rate were computed using the initial and constant loss rate method described in the previous section.
- The NRCS dimensionless unit hydrograph was used to transform runoff excess to discharge.
- An initial flow value was use to simulate base flow. No recession flow was used.

Sub-basin runoff was routed downstream using the Muskingum method.

3.4 Watershed representation

The watershed models for each gage were developed with the overall goal of estimating loss rates for the lower portion of the watershed (between 6200-6700 feet). This was done by segmenting the watersheds based on elevation zone (see figure 1.1 and 3.1). The segmentation with elevation was important for capturing the distributed response of the watershed due to both the change in precipitation volume and phase with elevation, and, the condition of the snow pack (as discussed in section 3.2).

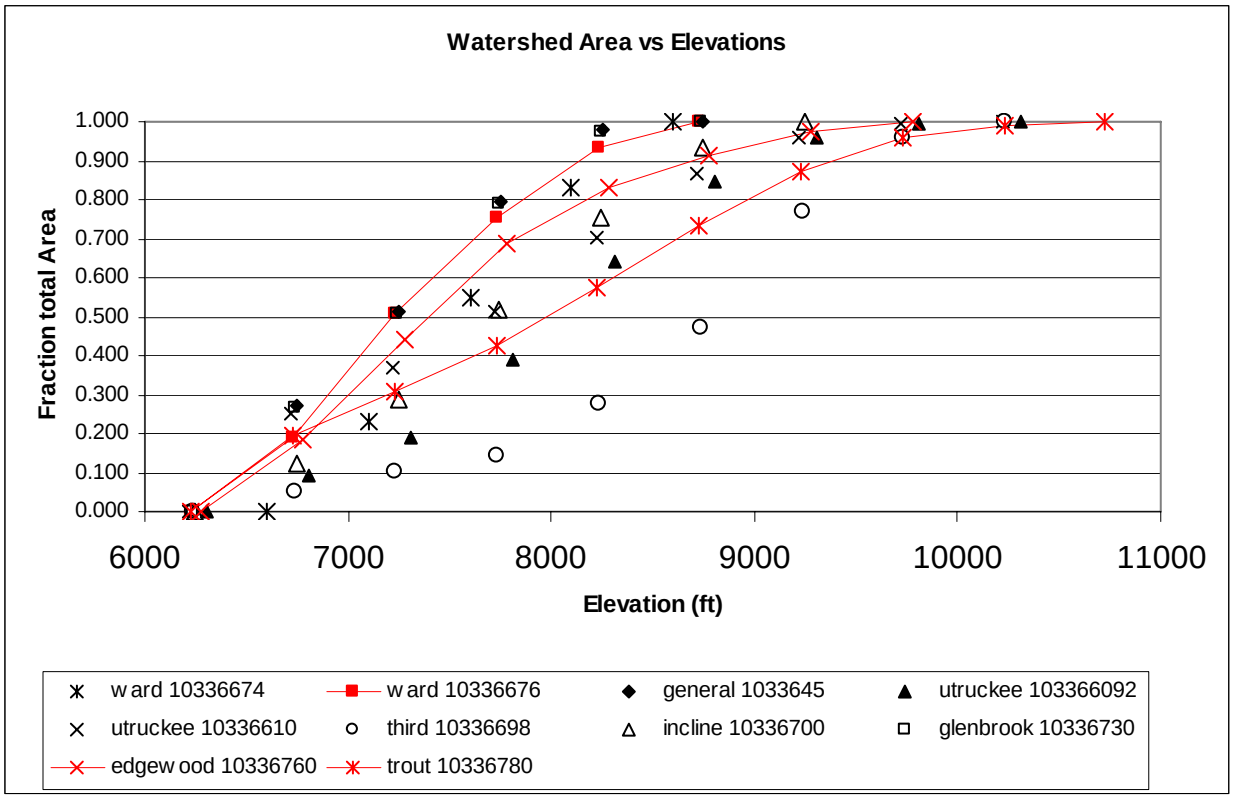


Figure 3.1: Fraction of basin area less than elevation, 500 foot intervals used for application of temperature lapse rate in HEC-1 model

3.5 Calibration strategy

Sources of data for calibrating the watershed model are:

- Short interval (15 minute or less) gage precipitation;
- Short interval (15 minute or less) temperature data;
- Observed short interval (15 minute or less) streamflow;
- Daily snow pack storm water equivalent (SWE);
- Daily streamflow records.

These sources of information are important because, together, the data provides a picture of the distributed response of a watershed.

The calibration procedure used adjusted temperature lapse rates, melt coefficients, loss rates, unit hydrograph lag and the Muskingum K values, to both reproduce the observed watershed outlet hydrograph, approximate the daily SWE, and proportion of observed daily runoff coming from each elevation zone. The approximate nature of the calibration to distributed response was dictated by the daily interval available for SWE values and observed daily runoff. The exact time of day when the SWE measurements were taken is not known, and of course, these

represent only point values. The model simulates basin average SWE for a 500 ft elevation zone. Consequently, the calibration attempted to generally replicate the state of the snow pack indicated by the SWE measurements and the reduction/accumulation of snow over a one-two day period.

Daily gage information was available upstream of watershed outlets at locations where short interval information was not available. This daily data is useful for gaining some approximate measure of the proportion of the total watershed contribution runoff for a particular storm event. This data has limitations in that the daily average flow does not necessarily provide a clear representation of the outflow hydrograph as can be seen from figure 3.2. Consequently, the time varying nature of the distribution of watershed response is not ideally represented by the daily data, but some approximate idea can be obtained by using this data.

In summary, the overall goal of the calibration will be to determine loss rates for the lower watershed elevation zone. These loss rates will be determined by trial and error adjustments of the model parameters; approximately reproducing the observed variation in daily observations of SWE and the distributed nature of the runoff indicated by daily runoff observation upstream of the watershed outlet.

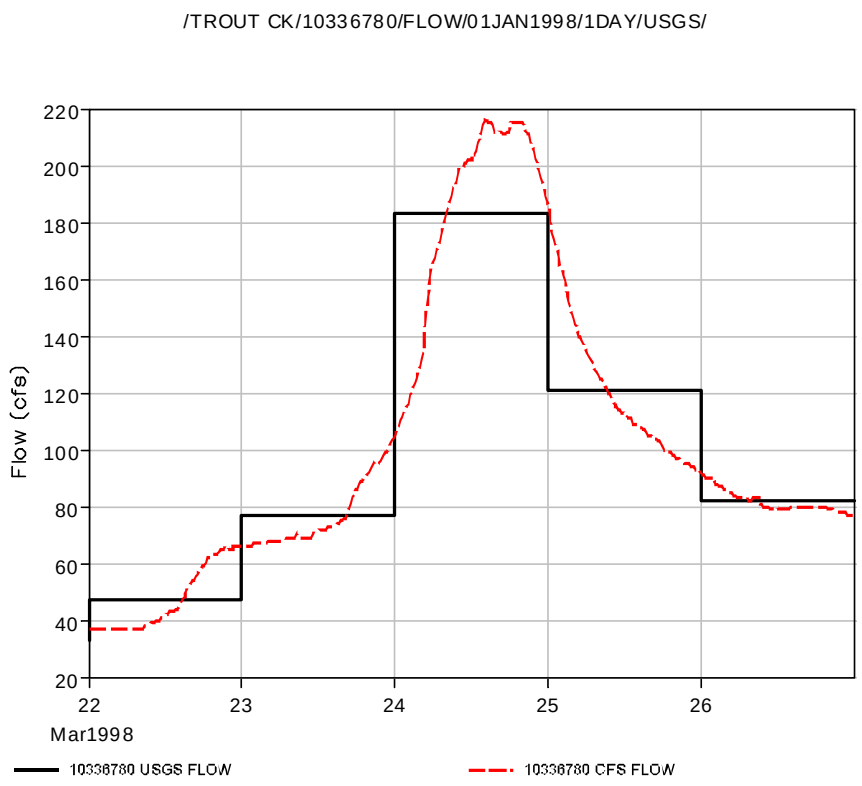


Figure 3.2: Comparison of daily and short interval hydrograph observations at Trout Creek outlet near South Lake Tahoe

4 Calibration 01 January 1997

4.1 Event description

The 01 January 1997 event caused the largest outflow from Lake Tahoe in at least 100-years, clearly a major event. The storm was particularly warm, producing rainfall at relatively high elevations as can be seen by inspecting both the snowfall and SWE data shown in Tables 4.1 and 4.2. Snowfall gages record no snowfall on January 1st, and a small amount on January 2nd at the higher elevation Dagget Pass gage. SWE information shows the relatively high elevation Heavenly Valley (8582 feet) and Squaw Valley (8029) feet gages experience snowmelt on January 1st, but Heavenly Valley begins to accumulate snow pack on January 2nd.

Precipitation was significant and relatively uniform across the watershed as can be seen from inspecting figure 4.1. The relative contribution of precipitation to simulated runoff at various elevations will depend greatly on the observed temperature and laps rate used in the watershed models.

Estimating both melt rates and temperature lapse rates occurring over a watershed for a storm from gage data is difficult because: 1) the data only represents point values; 2) gage exposure differences can bias results; and, 3) the exact time when daily measurements are taken is not known. The melt rates shown in Table 2 are maximum, average two-day and January 2nd (when the peak discharge occurred). The two-day values are perhaps most relevant to assessing target melt rates for simulation given the difficulty in knowing the time of day when the measurements were taken, as well as the difficulty in knowing the net contribution to SWE of precipitation. In any case, the melt rates tend to vary from 1-3 inches/day except for Squaw Valley, which is about 5 inches per day. This very high melt rate for the Squaw Valley gage seems to be anomalous, and could have something to do with the exposure of this gage. A melt rate of this magnitude is not consistent with the volume of runoff observed.

The reduction/accumulation of snow pack over the period of the event shown in Table 4.2 indicates a much greater melt in the western portion of the basin than in the east (see Figure 4.2). Notice that there is a net reduction in snow pack at the relatively higher-eastern Heavenly and Hagan's gage on only January 2nd, but the reduction continues into January 3rd at the Ward Creek and Squaw Valley gages. Examination of this data would also indicate that there is **probably** minimum contribution to runoff from watershed areas above 8500 feet given that the reduction at most gages is less than inch at Heavenly Valley, the effect of lapse rate and the snow conditioning at higher elevations.

Typically, lapse rates should be expected to be between the dry and wet adiabatic values (3-5 ^{o}F per 1000 feet). Comparisons of temperature gage information will show variation from this range for reasons discussed in the first paragraph. Additionally, there can be a lapse rate reversal (colder temperatures at lower elevations) due to the sinking of cold-air that has cooled earlier in the evening, become more dense, and sinking to displace warmer air at lower elevations. This is sometimes referred to as a down valley wind effect, and probably is most prevalent when cloud cover is absent. Table 4.2 shows some estimated lapse rates which are most often in the three degree range over the period of the storm. This is consistent with the warm nature of the storm.

In summary, the 01 January event is typified by generally uniform precipitation accompanied by a storm temperature lapse rate of 3 ^{o}F per 1000 feet. Significant melt occurred on January 2nd at all elevations below 8500 feet, and for the more western gages on January 3rd. The contribution to runoff above 8500 feet was probably minimal given the SWE observation at the Heavenly Valley gage, the potential of the snow pack to freeze rainfall and the potential for snow falling above this elevation.

Table 4.1: Daily precipitation and snow fall measurements, 01 January 1997

Date	Tahoe City Precipitation (in)	Dagget Pass snowfall (in)	Tahoe City snowfall(in)
	[1]6240 (ft)	7334 (ft)	6240 (ft)
30-Dec-96	1.72	0.00	0.00
31-Dec-96	1.22	0.00	0.00
1-Jan-97	2.43	0.00	0.00
2-Jan-97	4.65	0.17	0.00
3-Jan-97	1.58	0.33	0.42
4-Jan-97	0	0.00	0.00

[1]Elevation

Table 4.2: Snow water equivalent measurements, estimated melt rates 01 January 1997 event

Date	Echo Peak	Fallen Leaf Lake	Hagan's Meadow	Heavenly Valley	Marlette Lake	Rubicon	Squaw Valley	Tahoe City Cross	Ward Creek
	[1]7670	6236	7776	8582	7880	7689	8029	6797	6655
30-Dec-96	36.1	6.0	14.0	3.9	16.7	19.0	55.2	9.6	21.1
31-Dec-96	36.0	5.5	13.8	3.9	17	19.0	57.9	9.7	21.8
1-Jan-97	35.7	3.0	13.9	21.5	17.3	18.6	58.3	9.0	21.0
2-Jan-97	32.9	0.8	12.9	19.7	14.3	16.7	52.6	5.9	18.9
3-Jan-97	33.4	0.6	13.1	20.5	15.5	16.0	52.0	5.3	18.9
4-Jan-97	33.9	0.8	13.4	21.1	15.9	16.0	52.0	5.3	19.3
Max 1day	2.8	2.5	1.0	1.8	3.0	1.9	5.7	3.1	2.1
Max 2day	1.2	2.4	0.4	0.5	1.4	1.3	3.2	1.9	1.5
[2]Jan 2 peak	2.8	2.2	1.0	1.8	3.0	1.9	5.7	3.1	2.1

[1]Gage elevation, [2]Maximum average melt rate (in/day)

Table 4.3: Maximum and minimum daily temperatures, lapse rates, 01 January 1997 event

gage	Fallen Leaf	Heavenly		Fallen Leaf	Heavenly	
elevation	6236	8582		6236	8582	
	[1]Max T ^{o}F	Max T ^{o}F	[3]Laps Rate	[2]Min T ^{o}F	Min T ^{o}F	[3]Lapse Rate
27-Dec-96	38.3	32.0	2.7	31.5	27.9	1.5
28-Dec-96	36.1	28.0	3.5	30.6	21.7	3.8
29-Dec-96	44.8	31.8	5.5	32.0	22.5	4.1
30-Dec-96	----	----	----	----	----	----
31-Dec-96	43.7	35.1	3.7	37.9	30.6	3.1
1-Jan-97	46.8	39.2	3.2	38.7	31.1	3.2
2-Jan-97	48.4	41.0	3.1	44.4	37.9	2.8
3-Jan-97	46.2	38.5	3.3	32.0	26.8	2.2
4-Jan-97	42.4	40.0	1.0	17.2	7.9	4.0

[1]Maximum Daily Temperature, [2]Minimum Daily Temperature, [3]Laps rate per 1000 ft

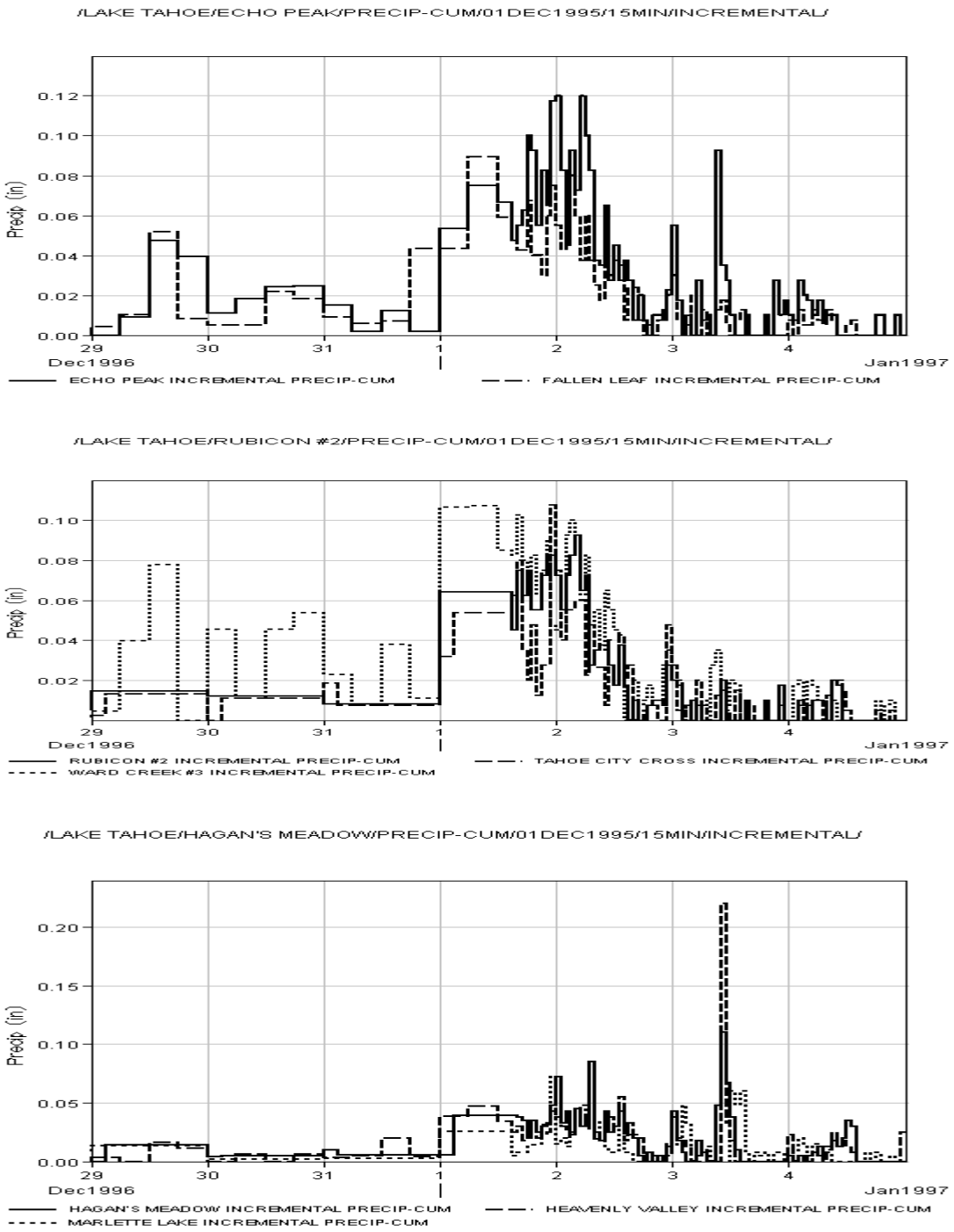


Figure 4.1: 01 January 1997 event precipitation

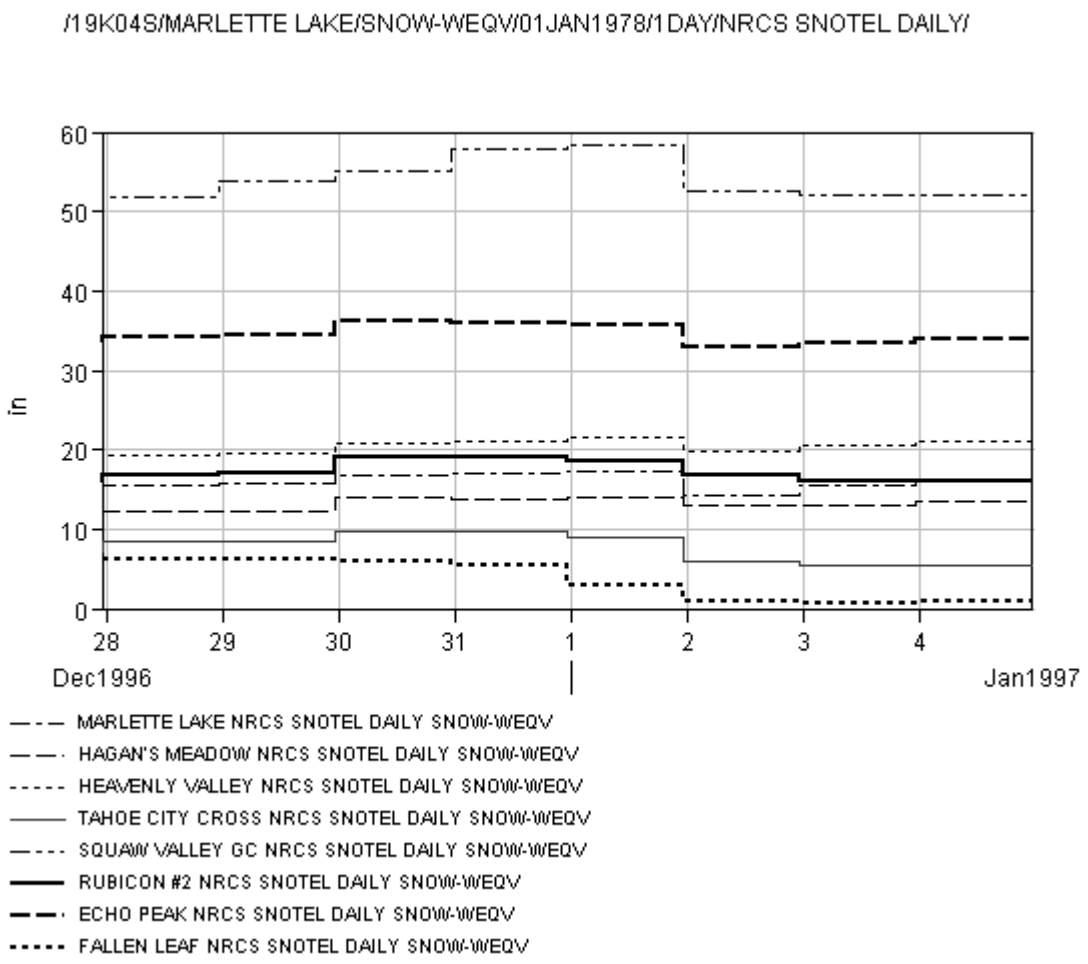


Figure 4.2: 01 January 1997 event snow pack storm water equivalent

4.2 Calibration results

Calibration was performed, in most circumstances, using a precipitation gage within the watershed. However, the Fallen Leaf Lake precipitation gage was used in combination with the Hagan's Meadow gage for Upper Truckee and Trout Creek watershed simulations partly because: the Fallen Leaf gage was thought to provide a better estimate of precipitation at lower elevations; and, partly because better simulation results were obtained. The Incline and Third Creek gages used the Tahoe City Cross Gage.

The temperature recording at all the gages were consistent, so the Fallen Leaf Lake Gage was used for all watersheds. A lapse rate of 3 ^{o}F/1000 feet (see previous section discussion on laps rate) was used to compute the change in temperature with elevation.

Short interval discharge measurements were not available for the General Creek Watershed. Consequently, the daily flow measurements together with the peak discharge for the event available from the USGS survey peak flow database (USGS, 2004) was used for calibration.

The calibration to the Upper Truckee gage was complicated by the different estimates for the peak discharge, the USGS peak flow file giving 5480 but the USGS short interval measurement reporting over 7,000 cfs. However, personnel at the USGS (2005) state that the peak flow file measurement is the supported value based on extrapolation of a rating curve. The short interval flow measurements were affected by debris blockage of the intake orifice.

The parameter estimates obtained from the calibration, the resulting melt rates and reduction in watershed elevation zone snow pack SWE are displayed in Table 4.4. The parameter estimates resulted in a reasonable reproduction of observed variation in SWE and melt rates (maximum melt rates being 1.0-2.0 inches per day).

The distribution of runoff generally reproduces the observed distribution of runoff throughout the watershed as shown in Table 4.5. This was achieved by assuming that the base flow throughout the simulation is equal to the initial flow value.

The reproduction of the observed peak discharge for each gage was very good, 24-hour maximum volumes seem reasonable; but preservation of the overall hydrograph shapes are mixed (see figures 4.3-4.8). The Upper Truckee River and Ward Creek simulated hydrographs seem reasonable. The Trout Creek reproduction under predicts the overall hydrograph volume at the beginning of the event, but these seems to be partly due to the timing caused by the precipitation hyetograph.

The reproduction of the Incline and Third Creek hydrographs is not particularly good. These hydrographs have somewhat unusual shapes, with a very flat response at the beginning of the events. The shape may be due to snowmelt response to the long period of above freezing temperature. The degree day method and constant loss rate method together with the simple temperature lapse rate used may not be capable of replicating this response.

The parameter estimates are given for the lowest three sub-basins used in the watershed models at each gage, because the primary interest is on estimating loss rates at lower elevations. In particular, the lowest elevation sub-basin (approximately 6200-6700 feet) is of importance in developing loss rate recommendations for a Lake Tahoe drainage design manual. The other sub-basin values are shown for comparison purposes.

The calibration resulted in SCS unit hydrograph lag values (hours) that are between one to two times the value of sub-basin drainage area (given in square miles). These are unexpectedly large values given: 1) the steepness of the watersheds; and 2) that lag is usually approximated as $0.6t_c$, and t_c in hours is usually on the order of the square root of drainage area (given in square miles). Perhaps, this is due to the effects of the snow pack on runoff.

Both initial and constant loss rates were estimated from the simulations. The initial loss rate was used to model the presumed capability of the snow pack at higher elevations to re-freeze rainfall earlier in an event. Zero initial loss assumed for the lowest sub-basin (1) presumed that the snow

pack was ripe almost immediately. This presumption worked well in reproducing the initial rise in the observed hydrograph.

The estimated constant loss rates ranged from 0.05-0.30 inches per hour. For the most part, the loss rates were higher for the eastern draining watersheds (Incline, Third, Glenbrook, and Trout creeks) when compared to the more western (Ward and Upper Truckee). However, the western draining General Creek does not follow this pattern, having relatively high constant losses (0.30 inches per hour). This was particularly unexpected because bedrock-soil seems to predominate more for this watershed in comparison to the other gages, except perhaps the Upper Truckee (see Jeton, 1999, Figure 2, pg.8). The loss rates for the Glenbrook gage may reflect the aspect and shape of the basin, the lower portion aligned east-west, but the upper portions align north-south; or, the usual difficulty in using point precipitation and temperature measurements to estimate runoff.

Table 4.4: 01 January 1997 event, Parameter estimates, melt rates and change in SWE

basin	USGS ID	[1]sub	[2]area	[3]melt C	[4]initial	[5]constant	[6]lag	[7]melt rate	[8]SWE	[9]max 1day
Upper Truckee	10336610	3	7.83	0.12	1.00	0.09	7.0	1.00	A	1.20
		2	6.32	0.15	0.50	0.09	5.0	1.40	3.00	2.00
		1	13.90	0.15	0.00	0.09	13.0	1.40	3.00	2.00
General Creek	10336645	3	2.10	0.12	1.00	0.25	2.0	1.00	0.60	1.10
		2	1.80	0.14	0.00	0.23	2.0	1.20	2.00	1.60
		1	2.02	0.15	0.00	0.23	2.0	1.40	3.00	2.00
Ward Creek	10336676	3	2.41	0.12	3.00	0.05	4.5	0.95	1.10	1.00
		2	3.05	0.14	2.50	0.05	6.0	1.30	2.80	1.60
		1	1.87	0.15	0.00	0.05	2.0	1.40	4.30	2.00
Incline Creek	10336700	3	1.53	0.10	0.00	0.28	6.0	0.80	0.05	0.80
		2	1.10	0.16	0.00	0.30	3.0	0.90	0.80	1.10
		1	0.82	0.17	0.00	0.27	1.0	1.10	2.00	1.60
Third Creek	10336698	3	0.24	0.10	1.50	0.15	0.5	0.80	A	1.00
		2	0.32	0.10	0.00	0.12	0.5	0.90	0.70	1.20
		1	0.30	0.14	0.00	0.10	0.5	1.30	2.50	1.90
Glenbrook Creek	10336730	3	1.15	0.07	3.50	0.10	3.0	0.60	A	0.70
		2	0.99	0.12	0.80	0.14	2.0	1.10	1.60	1.40
		1	1.11	0.12	0.00	0.14	2.0	1.10	2.30	1.60
Trout Creek	10336780	3	4.21	0.15	1.50	0.14	4.0	1.20	0.80	1.40
		2	4.20	0.11	0.00	0.30	6.0	1.00	1.20	1.30
		1	7.18	0.12	0.00	0.32	10.0	1.10	2.40	1.60

[1]sub-basin elevation zone, [2]area (sq-mi), [3]degree-day melt coefficient, [4]initial loss (in)), [5]constant loss (in/hr), [8]simulated reduction in snow pack SWE (in), [9]max simulated 1day melt (in)

Table 4.5: 01 January 1997, comparison of simulated and observed distributed response

Simulated							Observed					
USGS ID	[1]hec1	[2]area	[3]peak	[4]24hr max	[5]Peak frac	[6]24hr frac	Description	USGS ID	area	Area frac	[7]daily	[8]Daily frac
	5	16.46	1086	860	0.20	0.17	Upper Truckee River at S Upper Truckee Rd	10336580	14.09	0.26	350	0.15
	4	26.86	1966	1657	0.37	0.33	Upper Truckee River near Meyers	10336600	33.10	0.60	606	0.26
	3	34.69	2596	2200	0.48	0.44	Upper Truckee River at Highway 50	103366092	34.28	0.62	1240	0.53
10336610	1	54.91	5355	4977	1.00	1.00	Upper Truckee River at South Lake Tahoe	10336610	54.90	1.00	2350	1.00
	3	4.78	1214	1058	0.54	0.53	Ward Creek below Confluence near Tahoe City	10336674	4.96	0.51	700	0.50
	2	7.83	1914	1700	0.85	0.85	Ward Creek at Stanford Trail Crossing	10336675	8.97	0.92	1300	0.94
10336676	1	9.7	2257	2009	1.00	1.00	Ward Creek at Highway 89	10336676	9.70	1.00	1390	1.00
	56	15.62	163	111	0.31	0.24	Trout Creek at USFS RD 12N01	10336770	7.40	0.20	50	0.14
	3	25.32	449	356	0.86	0.76	Trout Creek at Pioneer Trail	10336775	23.70	0.65	251	0.72
10336780	1	36.7	523	467	1.00	1.00	Trout Creek near Tahoe Valley	10336780	36.70	1.00	350	1.00
	4	3.24	96	48	0.55	0.42	Incline Creek above Tyrol Village near Incline Village	103366993	2.85	0.43	27	0.34
	3	4.54	142	74	0.81	0.65	Incline Creek at Hwy 28	103366995	4.54	0.68	60	0.76
10336700	1	6.69	175	114	1.00	1.00	Incline Creek near Crystal Bay	10336700	6.69	1.00	79	1.00
	5		22	11	0.03	0.02			0.17	0.02		
	4		155	98	0.20	0.18			1.35	0.20		
	3		343	239	0.44	0.44			2.10	0.49		
	2		521	409	0.67	0.75			1.80	0.73		
10336645	1		781	545	1.00	1.00	General Creek near Meeks Bay		2.02	1.00		

[1]HEC-1 sub-basin, [2]Area (square miles), [3]Peak discharge (cfs), [4]24hr maximum average flow (cfs), [5]Fraction of watershed peak discharge, [6]Fraction of watershed maximum average flow, [7]Maximum daily flow at gage (cfs/day), [8]Fraction of maximum daily outflow

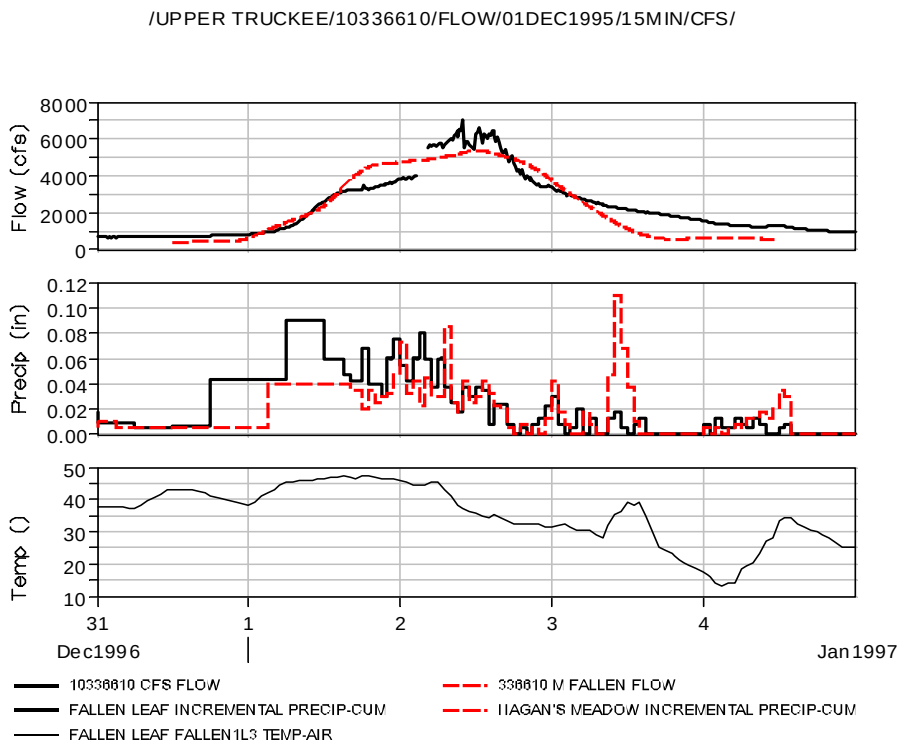


Figure 4.3: 01 January 1997 event calibration results Upper Truckee River

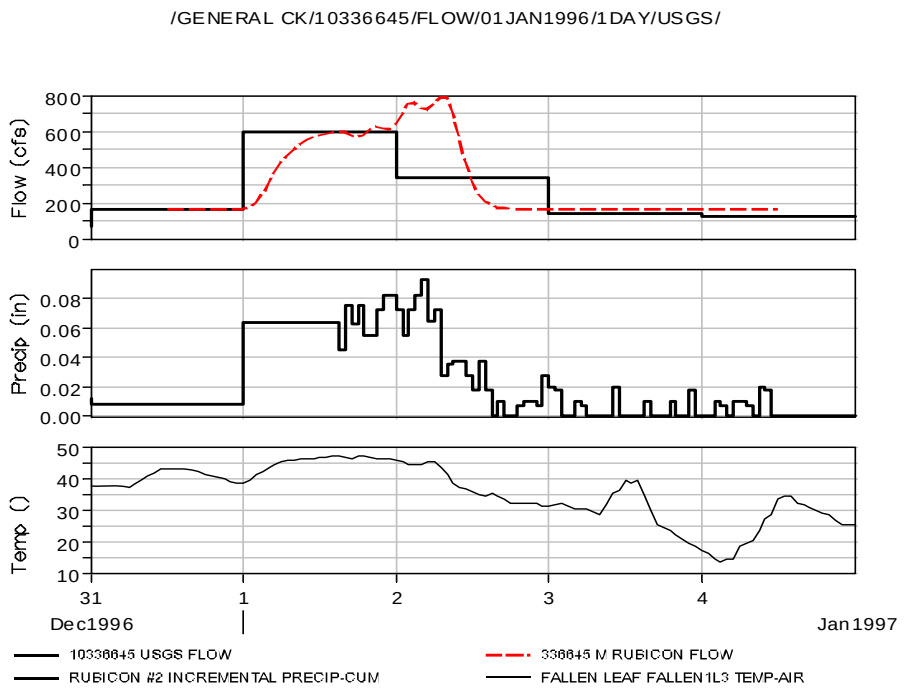


Figure 4.4: 01 January 1997 event calibration results General Creek (note USGS estimated peak is 797 cfs)

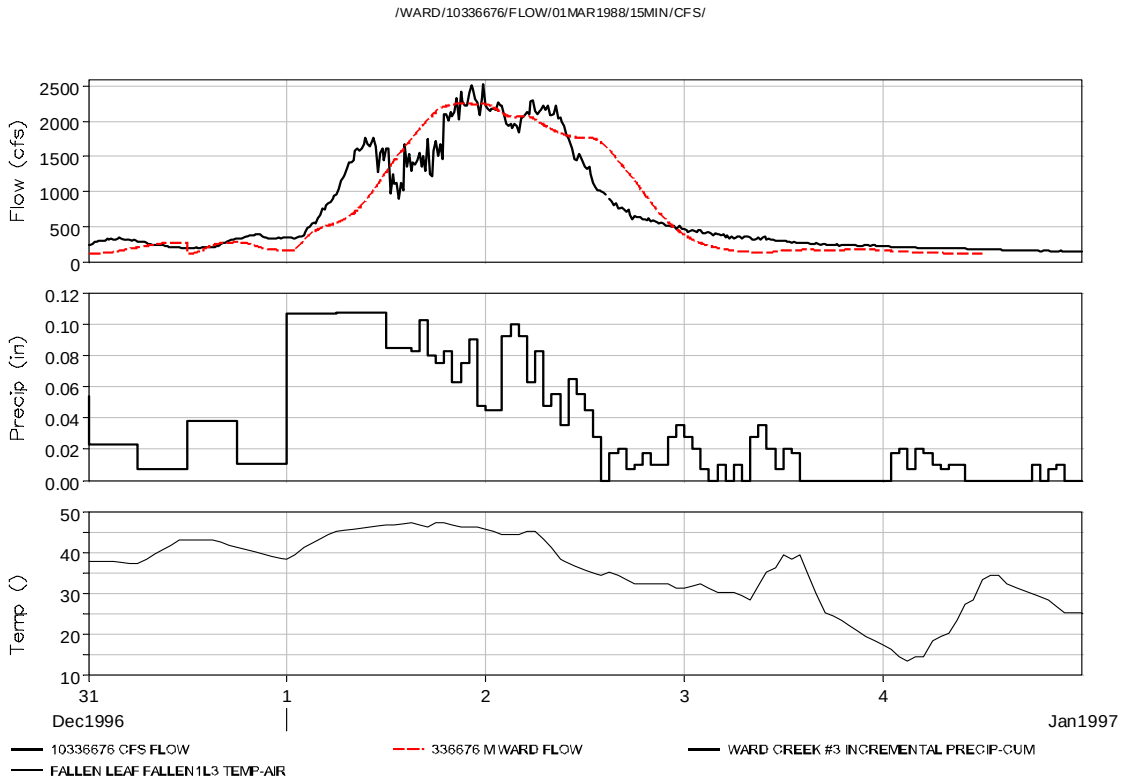


Figure 4.5: 01 January 1997 event calibration results Ward Creek

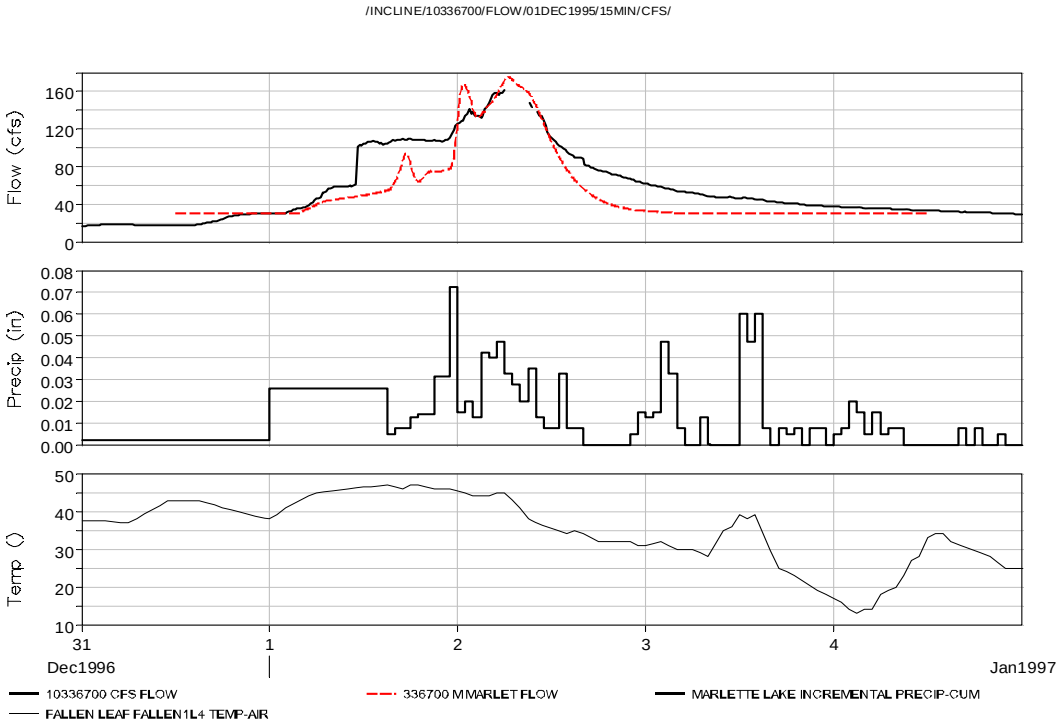


Figure 4.6: 01 January 1997 event calibration results Incline Creek

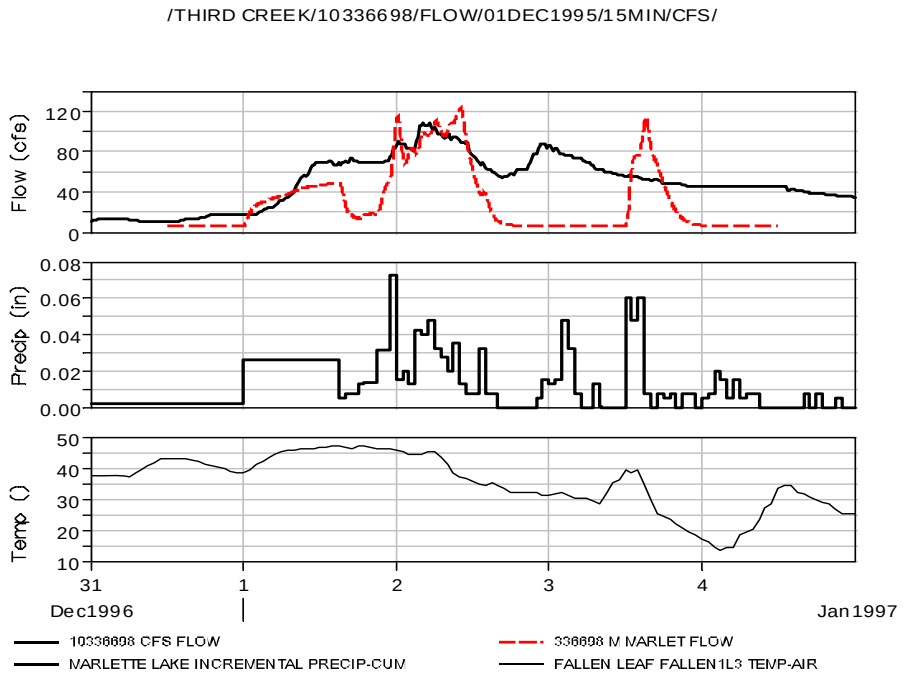


Figure 4.7: 01 January 1997 event calibration results Third Creek

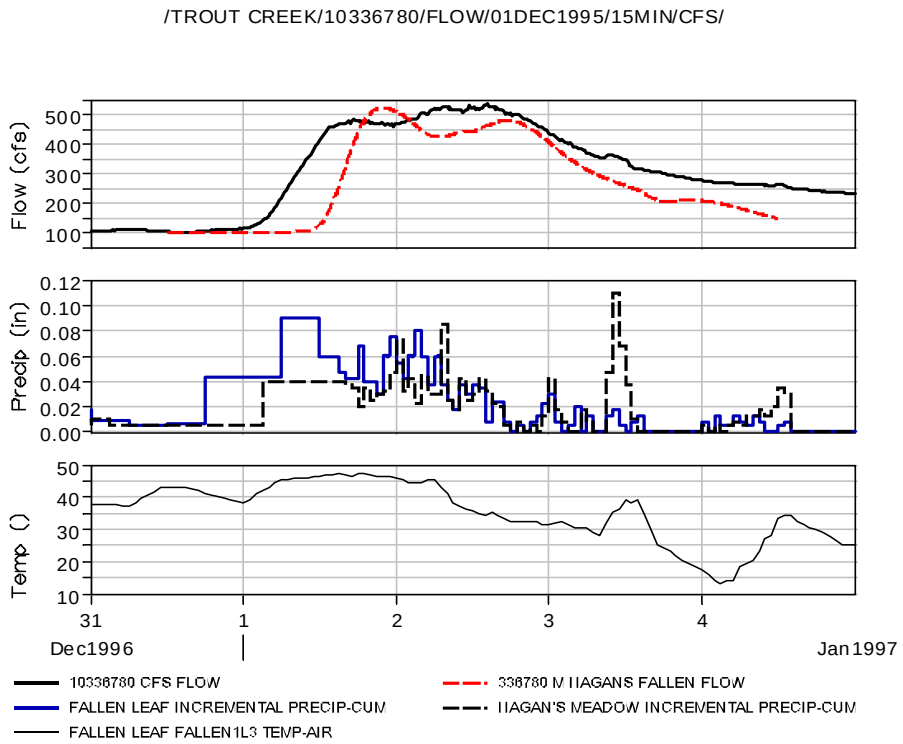


Figure 4.8: 01 January 1997 event calibration results Upper Truckee Basin

5 Event 24 March 1998

5.1 Event description

The 24 March 1998 event was chosen because: 1) runoff was due to both precipitation and snow melt; and, 2) short time interval (15 minute or less) temperature is available for the event. The peak discharges for the event at the gages where data is available are of about a 2-year magnitude (see section 7, and, SPK 2005, for flow frequency analysis of Lake Tahoe Basin gages). The low return interval of this event in comparison to the 01 January 1997 event is valuable because it examines the effect of precipitation magnitude on loss rates. This in turn is valuable when making recommendations for the Lake Tahoe Basin drainage design manual where a range in return interval events need to be considered.

Precipitation for this event had a higher fraction of snowfall than the 01 Jan 1997 (see Table 5.1); but, like the January event was reasonably uniform across the basin (see figure 5.1). The higher fraction of snowfall is indicative of the lower melt rates (see Table 5.2) of about 0.5-1.0 inches/day, higher lapse rates (about 4.0 ^{o}F/1000 ft when considering maximum temperatures in Table 5.3), and the general accumulation of snow pack over the event (see figure 5.2).

Given this data, the watershed model calibration efforts used a lapse rate of 4.0 ^{o}F/1000 ft and melt rates in the 0.5-1.0 inches per day for elevation less than 8500 feet. As in the case of the 01 January 1997 event, the contribution to runoff from greater elevations should be expected to be minimal.

Table 5.1: Daily precipitation and snow fall measurements, 24 March 1998

Date	Tahoe City Precipitation (in)	Dagget Pass snowfall (in)	Glenbrook snowfall (in)	Tahoe City snowfall(in)
	[1]6240 (ft)	7334 (ft)	6350(ft)	6240 (ft)
21-Mar-98	0	0.0	0.0	0.0
22-Mar-98	0.22	0.0	0.0	0.0
23-Mar-98	0.25	0.0	0.0	0.0
24-Mar-98	2.76	7.0	----	2.5
25-Mar-98	1.01	2.0	0.0	4.5
26-Mar-98	0.1	0.0	0.0	0.0
27-Mar-98	0.11	0.0	0.0	1.0

[1]Elevation

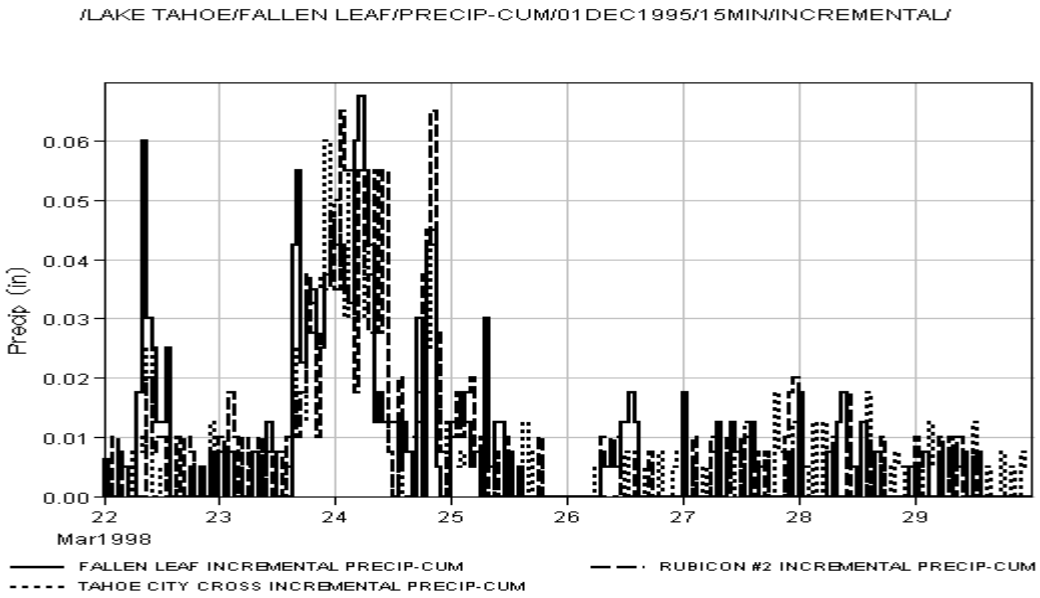
Table 5.2: Snow water equivalent measurements, 24 March 1998

Date	Echo Peak	Fallen Leaf Lake	Hagan's Meadow	Heavenly Valley	Marlette Lake	Rubicon #2	Squaw Valley	Tahoe City Cross	Ward Creek
	[1]7670	6236	7776	8582	7880	7689	8029	6797	6655
21-Mar-98	49.6	11.3	21.7	29.6	27.9	36.3	71.4	21.7	41.3
22-Mar-98	49.9	10.4	21.1	29.6	27.9	36.3	71.5	21.2	40.8
23-Mar-98	50.7	8.8	20.3	29.2	27.5	35.6	72.5	20.5	40.1
24-Mar-98	48.4	7.7	20.2	29.6	28.2	35.9	73.7	20.1	40.3
25-Mar-98	50.2	7.8	22.3	32.9	30.3	37.8	77.0	21.1	42.4
26-Mar-98	48.8	8.1	22.9	33.6	30.9	38.1	77.6	21.3	42.8
27-Mar-98	48.8	7.8	23.2	33.7	30.9	38.2	77.6	21.0	43.4
max 1day (in/day)	2.3	1.6	0.8	0.4	0.4	0.7	0.0	0.7	0.7
max 2day(in/day)	0.8	1.4	0.7	0.2	0.2	0.3	0.0	0.6	0.6
March 24(in/day)	2.3	1.1	0.1	0.0	0.0	0.0	0.0	0.4	0.0

Table 5.3: Maximum and minimum daily temperatures, lapse rates 24 March 1998

gage	Fallen Leaf	Heavenly		Fallen Leaf	Heavenly	
elevation	6236	8582		6236	8582	
	[1]Max T ^{o}F	Max T ^{o}F	[3]Laps Rate	[2]Min T ^{o}F	Min T ^{o}F	Laps Rate
21-Mar-98	58.82	49.64	3.9	26.96	25.34	0.7
22-Mar-98	58.1	46.04	5.1	26.6	24.98	0.7
23-Mar-98	53.78	42.08	5.0	39.2	32	3.1
24-Mar-98	53.42	44.96	3.6	33.98	29.84	1.8
25-Mar-98	44.6	34.34	4.4	30.92	26.24	2.0
26-Mar-98	46.4	36.68	4.1	29.3	24.62	2.0
27-Mar-98	49.46	43.7	2.5	23.72	18.32	2.3

[1]Maximum Daily Temperature, [2]Minimum Daily Temperature, [3]Laps rate per 1000 ft



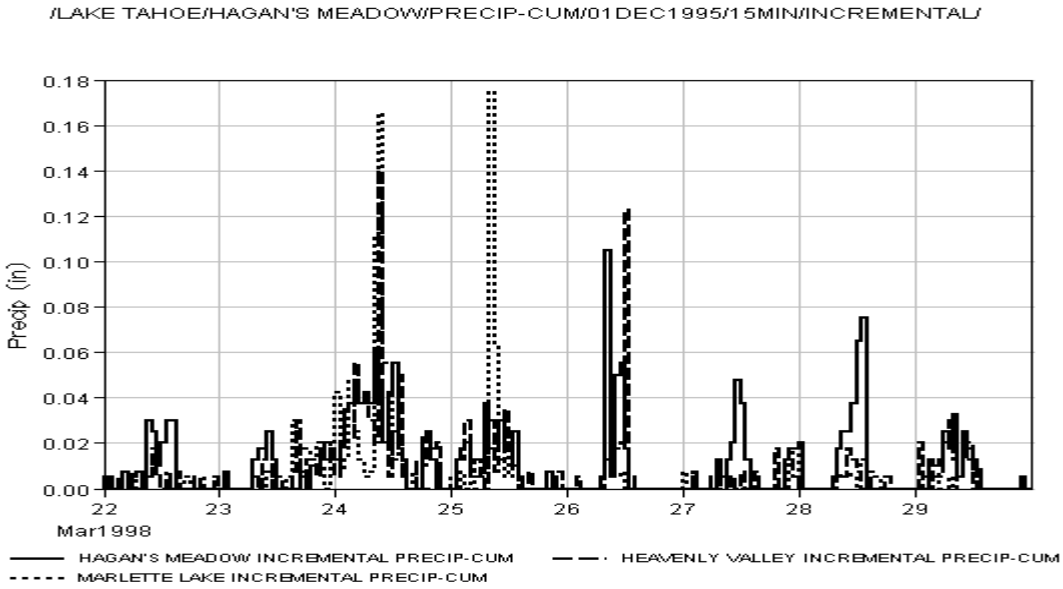
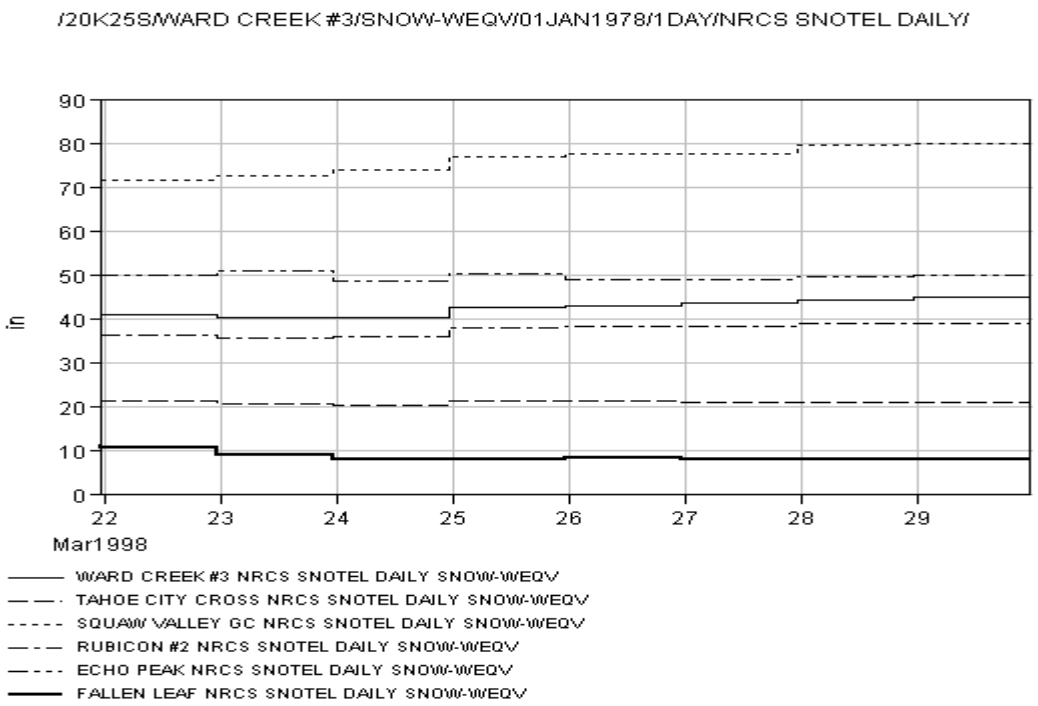


Figure 5.1: 24 March 1998 event precipitation



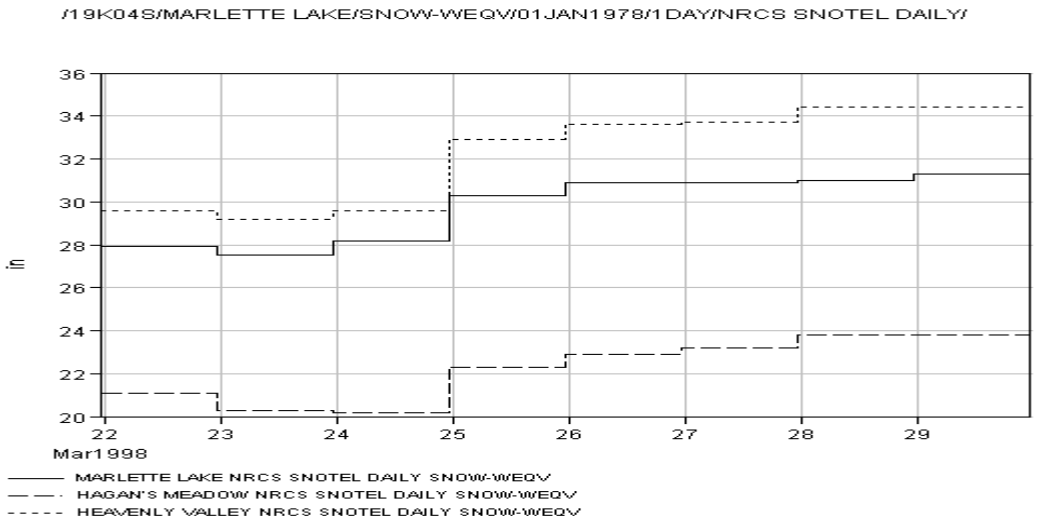


Figure 5.2: 24 March 1998 event snow pack storm water equivalent

5.2 Calibration results

The calibration approach for the 24 March 1998 event was similar to that for 01 Jan 1997 event. The main difference was that different temperature gages for each basin were used for each watershed and a lapse rate of 4 ^{o}F /1000 feet was used instead of 3 ^{o}F /1000 feet. Different temperature gages were used because the variation of temperature across the Lake Tahoe Basin seemed to be greater for this event.

The reproduction of observed hydrographs was not as successful for this event as for the January event. The peak and 24-hour maximum volume for the Upper Truckee River and Ward Creek (figures 5.3 and 5.4) are reasonably well preserved. The reproduction of the tail of the hydrograph perhaps suffers because no baseflow recession was used in the HEC-1 model. Another possibility is that there may be long-term snowmelt drainage through a ripe snow pack occurring that is not being captured well by the simple degree-day snowmelt algorithm employed.

Attempts to reproduce the Incline and Third Creek hydrographs were not successful primarily because these hydrographs are snowmelt dominated. As can be seen (figures 5.5 and 5.6) most of the response is due to temperatures above freezing rather than any response to precipitation. The reproduction of these hydrographs would require some careful adjustment of the time history of measured temperature. More effort was not expended to obtain a calibration because the loss rates obtained would not be relevant to the simulation of design events important for a drainage design manual.

The reproduction of the Glenbrook Creek (figure 5.7) was similar to that of the Upper Truckee River and Ward Creek in that the peak is well preserved but the overall hydrograph shape is not. The recession for this watershed seems uncharacteristic of baseflow (not exponentially decreasing) and could be snowmelt affected. The temperature is above freezing, at least at the watershed outlet, during the recession. However, a constant loss rate model could not both capture the peak and allow enough snow melt to reproduce this recession. The reproduction for the Trout Creek gage was much better (see figure 5.8), preserving peak and hydrograph shape.

The parameter estimates shown in Table 5.4 are very similar to those obtained for the January event (note as in the January event, the lowest three sub-basin results are shown as being most relevant to ascertaining parameters for drainage design criteria). SCS UH lag values (in hours) are in the range of one to two times the drainage area (in square miles). The initial loss rates are different in that even at the lowest zone an initial loss was used to reproduce the hydrographs. This perhaps reflects the colder conditions for this storm, the prevalence of a significant snow fraction for the high precipitation days, and the ability of the pack to absorb precipitation by refreezing rainfall.

The constant loss rates are somewhat smaller than for the January storm, ranging between 0.05-0.15 inches per hour. Loss rates for the January storm were found to be as large as 0.3 inches per hour. The loss rates for the western side Upper Truckee River and Ward Creek watersheds were less than that for the more eastern Glenbrook and Trout Creeks.

The simulated distribution of runoff throughout the watershed shown in Table 5.5 compares well with that of the observed values.

Table 5.4: 24 March 1998 event, Parameter estimates, melt rates and change in SWE

basin	USGS ID	[1]sub	[2]area	[3]melt C	[4]initial	[5]constant	[6]lag	[7]melt rate	[8]SWE	[9]max 1day
Upper Truckee	10336610	3	7.83	0.1	2	0.04	8	0.78	0.6	0.3
		2	6.32	0.1	1.5	0.06	7	0.78	0.6	0.4
		1	13.9	0.1	1	0.06	14	0.88	1.3	1.0
Ward Creek	10336676	3	2.41	0.1	0.5	0.05	5	0.57	A	0.6
		2	3.05	0.1	0.7	0.14	6	0.63	A	0.8
		1	1.87	0.1	0.6	0.06	5.4	0.69	0.5	0.5
Glenbrook	10336730	3	1.15	0.02	0	0.15	4	0.14	A	0.2
		2	0.99	0.02	0	0.15	4	0.15	0.3	0.2
		1	1.11	0.02	0	0.12	4	0.2	0.3	0.8
Trout Ck	10336780	3	4.21	0.04	1.5	0.07	8	0.55	A	0.5
		2	4.2	0.04	1	0.13	7	0.31	A	0.5
		1	7.18	0.04	1	0.14	11	0.35	0.4	0.6

[1]sub-basin elevation zone, [2]area (sq-mi), [3]degree-day melt coefficient, [4]initial loss (in)), [5]constant loss (in/hr), [8]simulated reduction in snow pack SWE (in) - A indicates net accumulation, [9]max simulated 1day melt (in)

Table 5.5: 24 March 1998, comparison of simulated and observed distributed response

Simulated							Observed					
USGS ID	[1]hec1	[2]area	[3]peak	[4]24hr max	[5]Peak frac	[6]24hr frac	Description	USGS ID	area	Area frac	[7]daily	[8]Daily frac
	5	16.46	160	93	0.11	0.07	Upper Truckee River at S Upper Truckee Rd	10336580	14.09	0.26	169	0.13
	3	34.69	462	240	0.33	0.17	Upper Truckee River at Highway 50	103366092	34.28	0.62	429	0.34
10336610	1	54.91	1413	1372	1.00	1.00	Upper Truckee River at South Lake Tahoe	10336610	54.9	1.00	1,260.00	1.00
	3	4.78	70	60	0.31	0.34	Ward Creek below Confluence near Tahoe City	10336674	8.97	0.92	160	0.94
10336676	1	9.7	224	174	1.00	1.00	Ward Creek at Highway 89	10336676	9.7	1.00	171	1.00
	56	15.62	39	31	0.18	0.19	Trout Creek at USFS RD 12N01	10336770	7.4	0.20	14	0.08
	3	25.32	152	111	0.69	0.68	Trout Creek at Pioneer Trail	10336775	23.7	0.65	112	0.61
10336780	1	36.7	215	180	1.00	1.10	Trout Creek near Tahoe Valley	10336780	36.7	1.00	183	1.00

[1]HEC-1 sub-basin, [2]Area (square miles), [3]Peak discharge (cfs), [4]24hr maximum average flow (cfs), [5]Fraction of watershed peak discharge, [6]Fraction of watershed maximum average flow, [7]Maximum daily flow at gage (cfs/day), [8]Fraction of maximum daily outflow

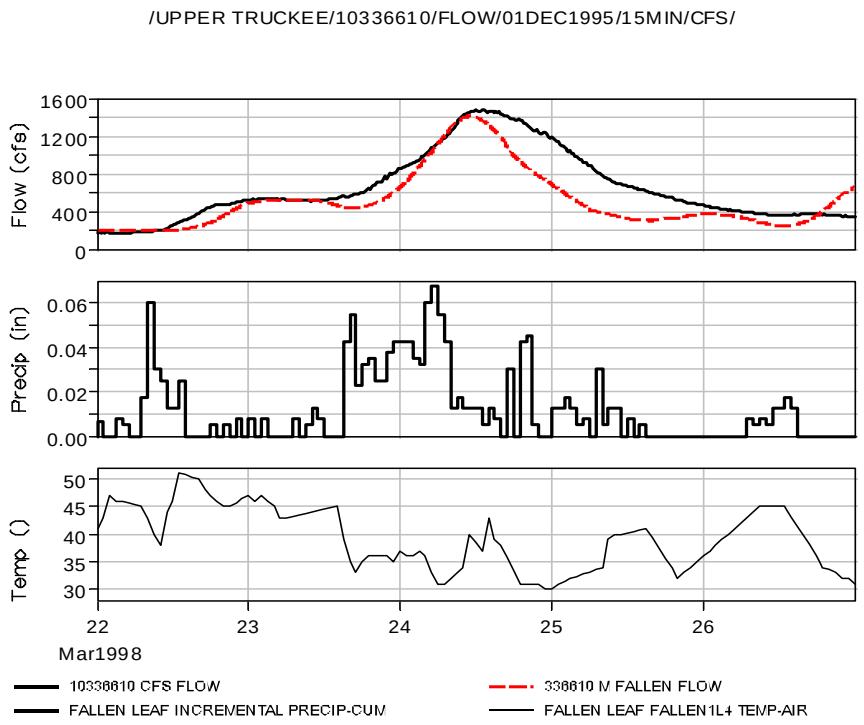


Figure 5.3: 24 March 1998 event calibration results Upper Truckee River

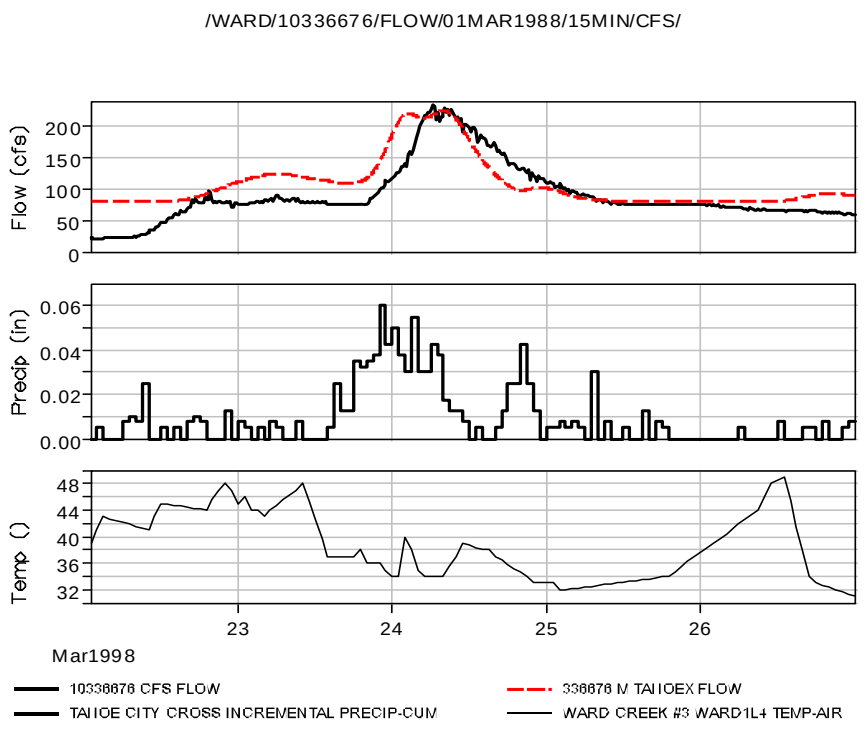


Figure 5.4: 24 March 1998 event calibration results Ward Creek

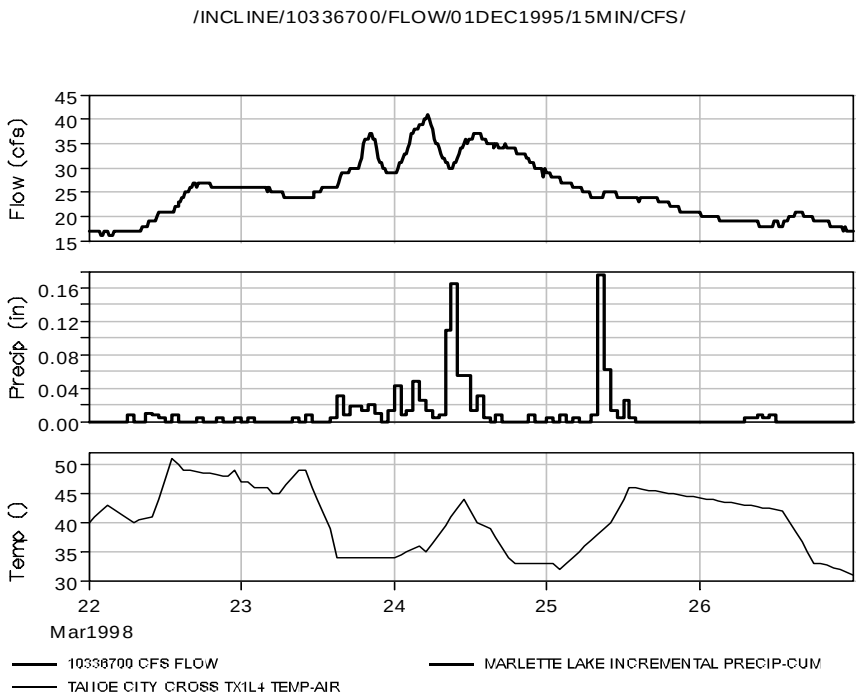


Figure 5.5: 24 March 1998 event observed hydrograph Incline Creek

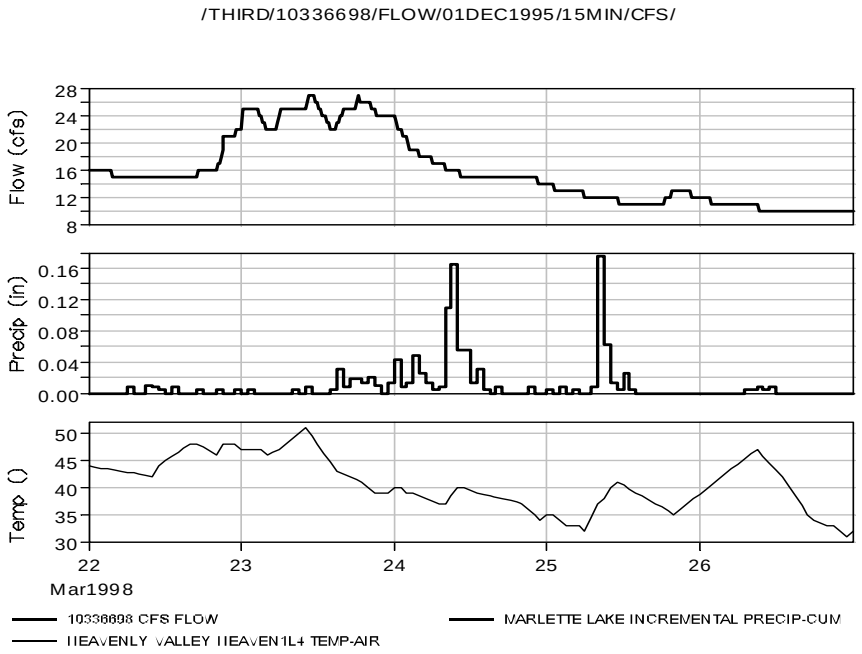


Figure 5.6: 24 March 1998 event observed hydrograph Third Creek

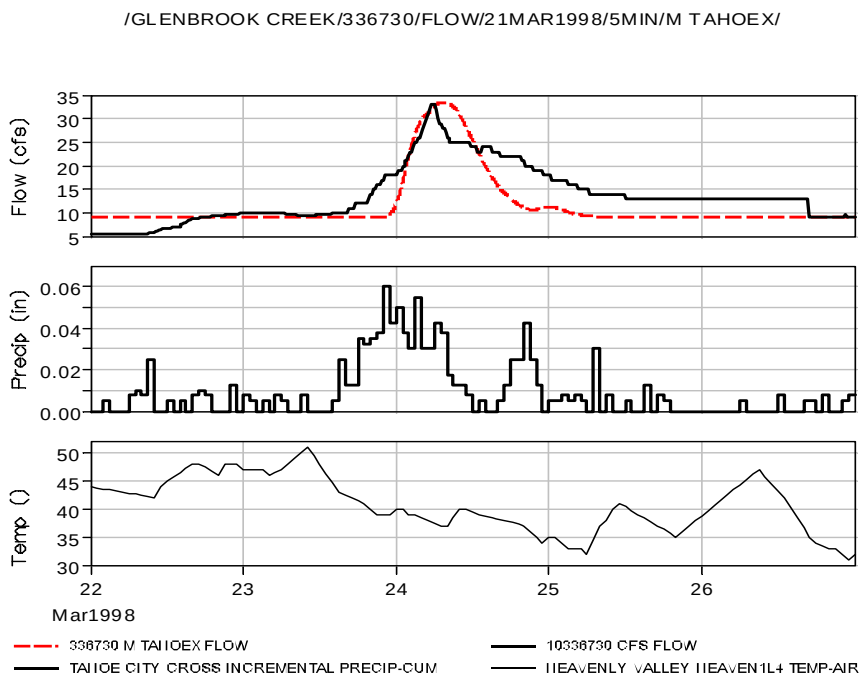


Figure 5.7: 24 March 1998 event calibration results Glenbrook Creek

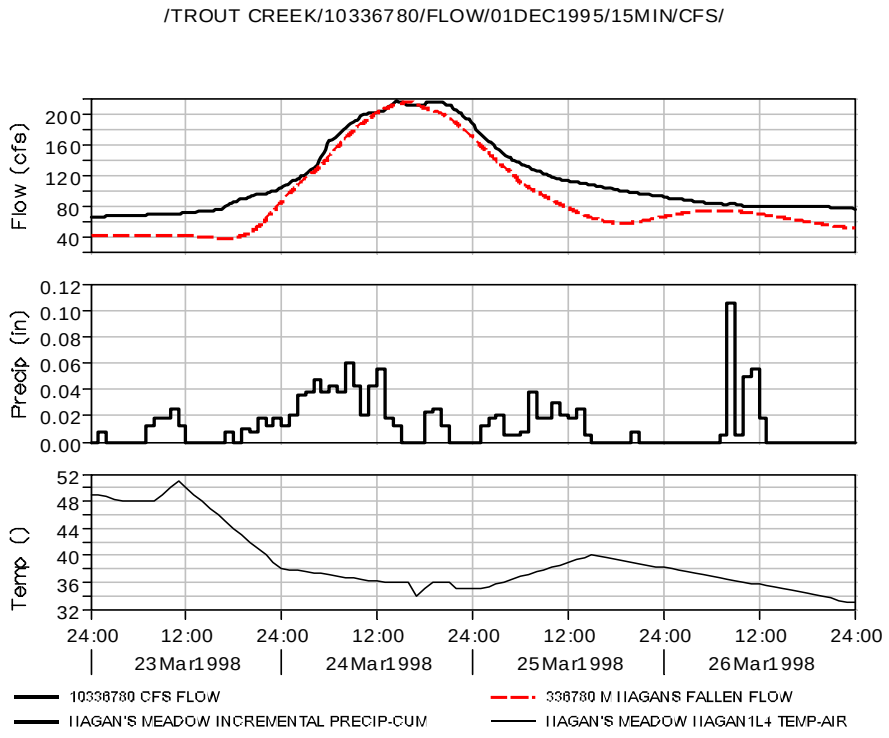


Figure 5.8: 24 March 1998 event calibration results Trout Creek

6 Loss rates estimated from watershed model calibration to flow quantiles

6.1 Introduction

The purpose of this section is to describe the computation of loss rates needed to reproduce estimated 100- and 2-year flow quantiles by simulating template events with previously developed watershed models. The resulting calibration provides the estimates of the 100-year and 2-year flows needed for calibrating a watershed model for the lowest elevation sub-basins when simulating hypothetical storm events.

Typically, flow quantiles are simulated using design storms that have triangular-shaped hyetographs that are supposed to represent some average characteristics of precipitation in a basin. In contrast, template events are the combination of precipitation patterns, temperature and initial watershed conditions based on actual events that are used as input to the watershed model simulation. The advantage to using a template event is that the input values used are based on an actual event; consequently, the coincidence of precipitation, snow pack, temperature, etc. is realistic. Perhaps, more reasonable estimates of the lowest sub-basin 100-year and 2-year discharges will be obtained by using these template events. The 01 January 1997 event and the 24 March 1998 events were used as templates for simulating respectively, the 100-year and 2-year events.

The watershed models developed in the previous sections were used to simulate template events, calibrate loss rates, and estimate lowest-elevation sub-basin flows as follows:

1) A dimensionless 48-hour storm was developed from the actual precipitation gage data.
2) The volume of the storm for each elevation zone was determined by proportioning the 24-hour maximum storm depth for each elevation zone to be equal to the 24-hour depth for a particular storm frequency. For example, if the area average 24-hour, 100-year depth for a watershed elevation zone is 2.00 inches, and the 24-hour dimensionless template storm volume is 0.50, then the total storm depth is proportioned to be (2.00/0.5) = 4.00 inches. As it turned out, the template storms were very nearly balanced, with the 24-hour dimensionless depth of 0.7 being approximately the value found for the ratio of 24-hour to 48-hour depths in NOAA14 (see Bonnin, 2003).
3) The watershed sub-basin or elevation zone precipitation depths for the 100-year and 2-year, 24-hour depths were computed using PRISM estimates and GIS technology developed for a previous effort to develop regional regression equations (see SPK, 2005). Table 6.1 provides the watershed average 24-hour depth obtained with this method.
4) Initial flow values for the simulation (i.e., the base flow) were computed as a fraction of the simulated peak flow. The fraction of peak flow used was based on an examination of the 01 January 1997 and 24 March 1998 events (see Table 6.2).
5) Loss rates were obtained as the calibration parameter used to match watershed model simulation predictions of the 100-year and 2-year flows with those obtained from a frequency analysis of gage annual peaks (see SPK, 2005).

The loss rates obtained from this approach are described in the next two sections.

Table 6.1: Watershed average 24-hour design precipitation

Watershed	USGS ID	100-year	2-year
Upper Truckee	10336610	7.70	3.70
General Creek	10336645	7.88	3.81
Ward Creek	10336676	10.00	4.83
Incline	10336700	8.45	3.56
Third	10336698	9.81	4.37
Glenbrook	10336730	6.01	2.63
Trout Ck	10336780	6.37	3.06

Table 6.2: Initial Flow as a function of peak discharge

			1-Jan-97			24-Mar-98		
Description	USGS ID	area	peak	initial flow	fraction	peak	initial flow	fraction
Upper Truckee River at Highway 50 above Meyers,	103366092	34.28				512	200	0.39
Upper Truckee Creek at South Lake Tahoe	10336610	54.9	5500	1000	0.18	1480	500	0.34
Ward Creek at Highway 89	10336676	9.7	2530	400	0.16	234	70	0.30
Glenbrook Ck at Glenbrook	10336730	4.11	140	20	0.14	33	10	0.30
Trout Creek near Tahoe Valleu	10336780	36.7				217	62	0.29

6.2 Storm Template calibration for the 100-year peak discharge

The dimensionless storm template used for the 100-year simulations shown in figure 6.1 is an average of the hyetographs patterns for the 01 January 1997 event. The average pattern was useful in this case partly because the precipitation was reasonably uniform across the basin and the peak precipitation intensity for the storm was still preserved in obtaining the average.

Table 6.3 summarizes the loss rates that were used to reproduce the 100-year peak flow estimates shown in Table 6.5. Table 6.4 provides the details of the application of regional regression equations used to obtain flow-frequency estimates for Incline and Third Creek, where a sufficient USGS peak gage record did not exist to perform a gage flow frequency analysis. The loss rates used not only resulted in a good reproduction of the 100-yr peaks obtained by frequency analysis; but also, did reproduce the distributed response throughout the watershed that would be expected from the analysis of the 01 January 1997 event (see Table 4.3).

The loss rates obtained to reproduce the 100yr peak flows are about 0.1-0.2 inches per hour greater than for the simulation of the 01 January 1997 event, except for Ward Creek where the values are equivalent. Interestingly, the loss rate needed to match the regional regression flow-frequency peak estimates for Incline and Third Creek were the largest; but, relatively large loss rates were needed in reproducing the 01 January 1997 as well (see Table 4.4).

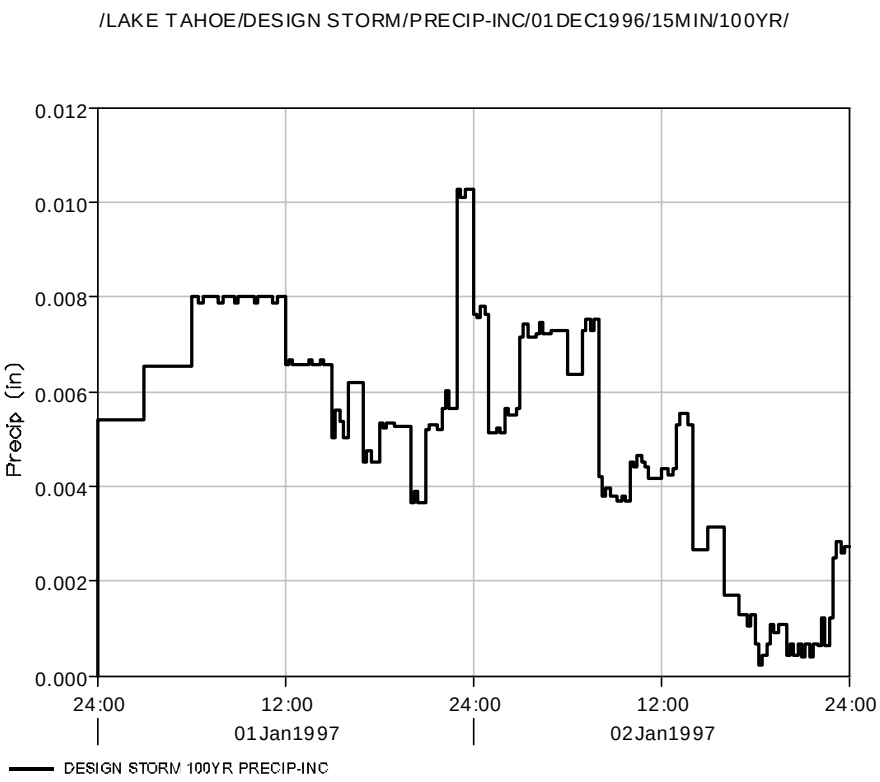


Figure 6.1: Dimensionless 100-year template event based on an average 01 January 1997 storm

Table 6.3: Simulation loss rates used to estimate 100-year peak quantiles

basin		sub-basin	area	initial	constant
Upper Truckee	10336610	3	7.83	1.00	0.27
		2	6.32	0.50	0.21
		1	13.9	0.00	0.21
General Creek	10336645	3	2.1	1.00	0.28
		2	1.8	0.00	0.26
		1	2.02	0.00	0.26
Ward Creek	10336676	3	2.41	3.00	0.05
		2	3.05	2.50	0.05
		1	1.87	0.00	0.05
Incline	10336700	3	1.53	0.00	0.38
		2	1.1	0.00	0.40
		1	0.82	0.00	0.37
Third	10336698	3	0.24	1.50	0.38
		2	0.32	0.00	0.40
		1	0.3	0.00	0.37
Trout Ck	10336780	3	4.21	1.50	0.22
		2	4.2	0.00	0.29
		1	7.18	0.00	0.30

Table 6.4: Regional regression estimates peak 100-year flow

(see SPK, 2005)

regression equation		b_0	b_1	b_2	b_3	
		24.8478	1.1256	-7.2637	3.0325	
watershed						
			area (sq mi)	mean elevation (ft)	MAP (inches)	[2]100-year (cfs)
Incline Creek above Tyrol Village	10336700		6.69	7752	36.7	186
Third Creek near Crystal Bay	10336780		6.02	8404	47.8	205

[1]MAP = watershed average mean annual precipitation

[2]$\log_{10}(Q_{100}) = b_0 + b_1 \log_{10}(\text{area}) + b_2\log_{10}(\text{elevation})\ b_3\log_{10}(\text{MAP})$

Table 6.5: Comparison of flow-frequency and template event simulated estimates of 100-year peak flow

description	USGS ID	area (sq mi)	[1]systematic POR	[2]systematic peak	[3]historic POR	[4]historic peak	[5]simulated peak
Upper Truckee River at South Lake Tahoe	10336610	54.9	25	6563	103	5468	5457
General Creek near Meeks Bay	10336645			1272		1070	1023
Ward Creek at Highway 89 near Tahoe Pines	10336676	9.7	30	3565	103	2742	2678
Trout Creek near Tahoe Valley	10336780	36.7	40	864	103	765	793
Incline Creek above Tyrol Village	10336700	6.69				[6]186	191
Third Creek near Crystal Bay	10336780	6.02				205	194

[1]systematic period of gage record used in frequency analysis (see SPK, 2005)
[2]peak flow from systematic period
[3]historic period of gage record used in frequency analysis (see SPK, 2005)
[4]peak flow from historic period
[5]HEC-1 simulate peak flow from template design event
[6]regional regression estimate (see Table 7.3)

6.3 Storm template calibration for the 2-year peak discharge

The loss rate calibration to the 2-year discharges differed somewhat from the 100-year in that: 1) the template precipitation hyetograph was based on the Fallen Leaf Lake gage; 2) estimates were not obtained for Incline or Third Creeks; and, 3) initial loss rates for the lowest elevation were reduced to zero. The Fallen Leaf Lake gage pattern (see figure 6.2) was used because obtaining an average precipitation pattern over all the gages would have reduced the storm peak intensity significantly. The pattern from the Fallen Leaf Lake gage was representative of the storm pattern seen at the other gages. No application to Incline or Third Creek gages was made because watershed models were not successfully developed for the 24 March 1998 for these gages.

Initial loss rates at the lowest elevation sub-basin were reduced to zero in the watershed model simulations. This reflects the observation that for the peak 48-hour precipitation period in the 24 March 1998 event, there was snow pack water equivalent loss. Consequently, the snow pack was not likely to absorb precipitation. Initial loss rates for higher elevation sub-basins were reduced by an inch to reflect this ripening of the snow pack condition.

The loss rates obtained from calibration and the calibration results to the 2-year frequency estimates of peak discharge are shown in Tables 6.6 and 6.7. The loss rates obtained are at most 0.1 inches per hour greater than obtained for the calibration. As is the case for the 01 January 1997 event, the Ward Creek Loss Rates were about the same.

6.4 Assessment of calibration

The calibrated loss rates obtained from the simulation of the template events are at generally 0.10-0.20 inches per hour greater than obtained from the values obtained in calibration to the observed events. The exception is Ward Creek where the values do not change.

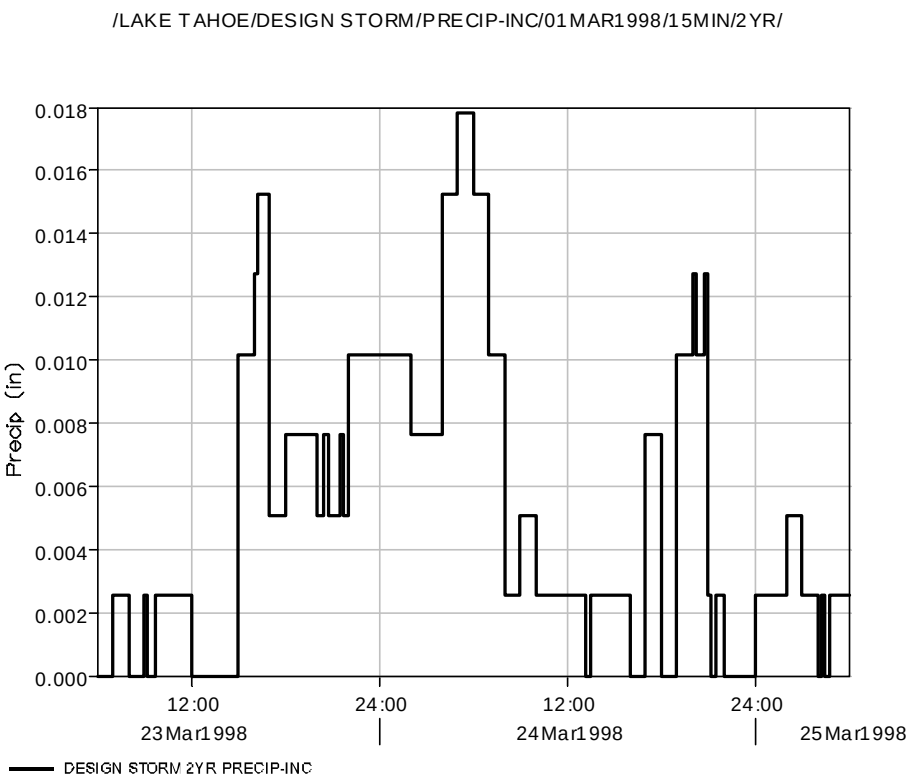


Figure 6.2: Dimensionless 2-year template event based on Fallen Leaf Lake 24 March 1998 storm

Table 6.6: Simulation loss rates used to estimate 2-year peak quantiles

basin		subbasin	area	2yr initial	2yr constant
Upper Truckee	10336610	3	7.83	0.25	0.02
		2	6.32	0.50	0.14
		1	13.90	0.00	0.14
Ward Creek	10336676	3	2.41	0.00	0.04
		2	3.05	0.00	0.06
		1	1.87	0.00	0.06
Glenbrook	10336730	3	1.15	0.00	0.23
		2	0.99	0.00	0.23
		1	1.11	0.00	0.20
Trout Creek	10336780	3	4.21	0.50	0.17
		2	4.20	0.00	0.14
		1	7.18	0.00	0.15

Table 6.7: Comparison of flow-frequency and template event simulated estimates of 2-year peak flow

description	USGS ID	area (sq mi)	[1]systematic POR	[2]systematic peak	[3]historic POR	[4]historic peak	[5]simulated peak
Upper Truckee River at South Lake Tahoe	10336610	54.9	25	743.2	103	721.65	714
Ward Creek at Highway 89 near Tahoe Pines	10336676	9.7	30	290.2	103	280.04	261
Glenbrook Creek at Glenbrook	10336730	4.11	18	9.1	103	8.46	8
Trout Creek near Tahoe Valley	10336780	36.7	40	144.8	103	139.05	146

[1]systematic period of gage record used in frequency analysis (see SPK, 2005)
[2]peak flow from systematic period
[3]historic period of gage record used in frequency analysis (see SPK, 2005)
[4]peak flow from historic period
[5]HEC-1 simulate peak flow from template design event

7 Design flows from model simulations of hypothetical storm rainfall

7.1 Introduction

The purpose of this section is to develop a modeling approach to using hypothetical storm rainfall for estimating design flows. These events are intended for use in the elevations between about 6200 -7000 feet, where most of the drainage design efforts will occur. Watershed model simulation of hypothetical storm rainfall is a standard approach to estimating drainage design flows (e.g., see NRCS, 1986). These hypothetical storms are created based on knowledge of historical storm patterns and precipitation depth-duration-frequency (ddf) curves for a watershed (see figures 7.1 and 7.2).

The application of hypothetical storms is complicated by the need to select storm shape, identifying the phase of precipitation, antecedent conditions (snow pack and soil moisture), and runoff loss rates in simulating a design runoff hydrograph. The goal is to simplify the problem by assuming that the hypothetical storm is all rainfall, and that a constant loss rate can be used to effectively account for all the factors mentioned which affect the amount of precipitation that will cause runoff. The key to accomplishing this is to use the calibration results of section 6 to select the appropriate precipitation ddf curves and calibrate the constant loss rates to replicate the 100year and 2-year peak discharges estimated in section 6.

Simulation of hypothetical rainfall having a particular return interval is intended to produce a design runoff hydrograph having the same return interval. For example, simulating a 100-year hypothetical rainfall results in a 100-year runoff hydrograph. What the 100-year runoff hydrograph represents is not entirely clear, but the expectation is that the 100-year peak is obtained from the simulation. Whether or not the associated hydrograph volumes (e.g., 24 hour maximum volume) is also computed depends on a number of factors, including storm duration and shape and the calibration of the watershed model. In general, simulating a hydrograph that preserves all the flow volume-duration-frequency characteristics is very difficult.

Designing a hypothetical storm is complicated by the selection of, storm shape, antecedent soil moisture conditions and loss rates as is shown in Figure 7.2. In the Lake Tahoe Basin, this is further complicated by the effects of precipitation phase (snow versus rain) and initial snow pack conditions. This problem is avoided, or dispensed with, if a template event is chosen, such as the 01 January 1997 event to represent the 100-year event. All the coincident conditions affecting runoff for this event are assumed for major design events such as the 100-year. However, the hypothetical event approach is popular, readily useable in available watershed modeling software, and is accepted in drainage design practice.

The complications associated with applying the hypothetical storm approach were dispensed with by making the following assumptions:

- storm precipitation phase will be rainfall;
- snowmelt affects will be ignored;
- a constant loss rate will be used.

The key to obtaining reasonable predictions using these assumptions is to combine appropriate precipitation depth-duration-frequency statistics and loss rates that result in reasonable design hydrographs. To do this, loss rates need to be calibrated to the lowest (6200-6700 feet) elevation sub-basin runoff estimates obtained for the 100-year and 2-year discharges obtained in section 6.

The effective loss rate estimated in the calibration effort will account for the contribution of snowmelt to the runoff hydrographs. The contribution by snowmelt can be accounted for in this way because the melt rates modeled in the calibration studies in section 6 ranged between about 0.5-2.00 inches per day. Presuming an 8 hour melt period, this is about 0.05-0.25 inches per hour. Consequently, loss rates recommended for application with the hypothetical storm events may differ from the calibrated values in section 6 by this amount.

In section 7.2, the possible depth-duration frequency relationships that could be reasonable used in developing the design storms is described. Sections 7.3 and 7.4 describe the calibration effort for the 100- and 2-year peak discharge. Finally, section 7.5 provides summary recommendations.

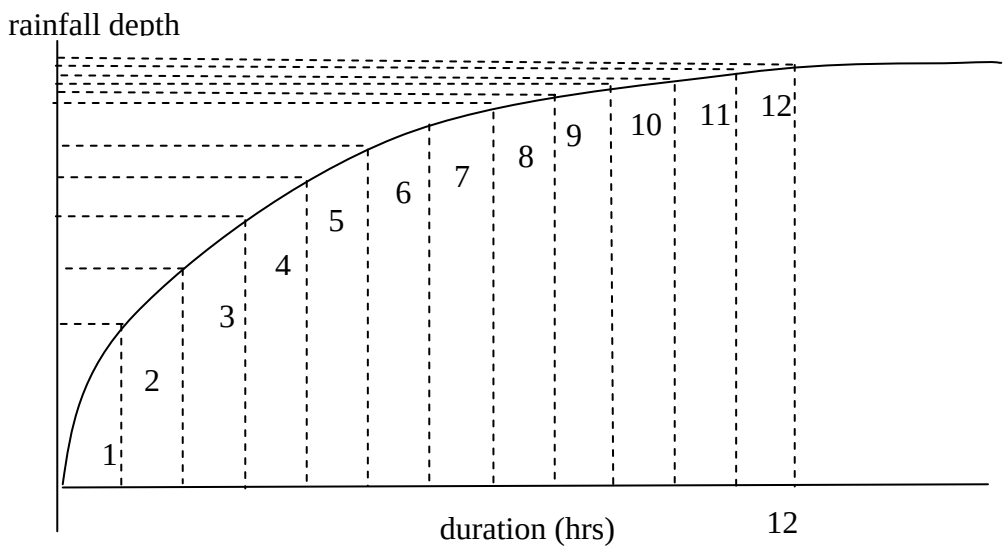


Figure 7.1: Precipitation depth-duration-frequency durations for creating hypothetical storm rainfall

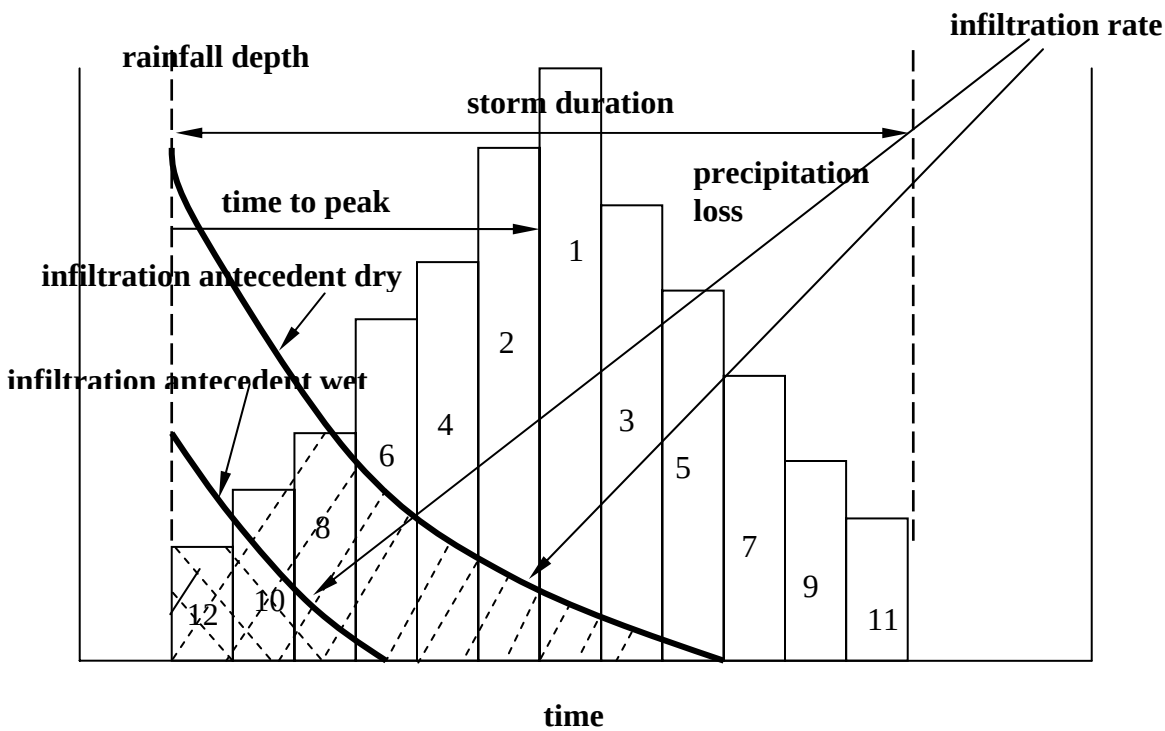


Figure: 7.2 Hypothetical storm event pattern, antecedent conditions, and runoff infiltration

7.2 Precipitation depth-duration-frequency relationships

7.2.1 Depth-duration estimates

As pictured in figures 7.1 and 7.2, precipitation depth-duration-frequency (ddf) relationships are used to formulate a hypothetical storm. The ddf relationships do not completely define the storm because there is a relationship between the peak intensity within a storm, storm duration and, possibly, storm volume. The NRCS (1986) has investigated the relationship between precipitation intensity and storm shape in developing hypothetical 24-hour storms as shown in figure 7.1). The storm types that are potentially typical of the Lake Tahoe Basin are the type 1A and Type II storms, the type 1 storm being more typical of south western California. The dimensionless precipitation depth-duration relationships implied by these storms are provided in Table 7.1.

NOAA14 (NOAA, 2004) provides the most recent estimates of precipitation DDF curves for the Lake Tahoe Basin. These ddf curves do not represent exactly the same ddf relationship as derived from the NRCS hypothetical storms. The NOAA14 ddf curve is an amalgam of the maximum annual intensities found from all storms for a specific duration (e.g., 5-min,15-min 1-hour, 24-hour, etc.). These maximum intensities will not always be found within an actual precipitation event. The NRCS storms capture on the average the relationship between duration and intensity for a typical 24-hour storm period.

The sub-basin average NOAA14 depth-duration relationship obtained for the lowest elevation sub-basins used in the calibration studies in section 6 are also given in Table 7.1. As it turns out, the ratio of various depths for different durations to the total 24-hour depth is not a strong function of return interval in the Lake Tahoe Basin. Consequently, the 2-year and 100-yr dimensionless depth-duration curves are not that different. The relationship does vary some from west to east; but the relationship shown is useful for comparison purposes.

Note that the depth-duration relationship shown is a sub-basin average of the 1km grid estimates obtained from NOAA14. This sub-basin average is not the same as might be obtained from a depth-area reduction factor. However, depth-area reduction factors for NOAA 14 have not yet been published for the Lake Tahoe Basin. Consequently, the sub-basin average values have been employed as being representative of sub-basin average design precipitation.

Another depth-duration relationship was developed based on some representative winter storms that have occurred in the Lake Tahoe Basin (see Table 7.1). Two of the depth-duration relationships were developed from the storm templates described in section 6, and a third from a major storm event occurring in December. Note that the depth-duration relationship does not vary greatly between the storms. An average storm relationship is also shown.

A comparison of the relationships (see Table 7.1 and Figure 7.4) shows that the winter storm depth-duration relationships are significantly less intense than the other ddf storm relationships. Not surprisingly, the depth-duration relationship is closest to the NRCS type 1A storm, typical of north-western California.

The difference between the various ddf relationships for drainage design is important, particularly for durations less than 60 minutes. Unfortunately there is not a great deal of information to base the relationship between the 60 minute and shorter durations as is noted in the NOAA14 study (see NOAA, 2004, pg. 47):

> ***Development of n-minute grids.*** *Durations shorter than 60-minute (i.e., n-minute precipitation frequency estimates) were calculated using linear scaling factors applied to final grids of spatially interpolated 60-minute precipitation frequency estimates. Because there were so few n-minute stations in the project area, global ratios of n-minute to 60-minute estimates were averaged over the entire study area (Section 4.1.1). Using these ratios (listed again in Table 4.8.2), the final 60-minute grids were multiplied by the appropriate ratio to compute the appropriate n-minute grid. These ratios were used for all frequencies as well as both the n-minute upper- and lower- confidence limit grids.*
>
> Table 4.8.2. NOAA Atlas 14 Volume 1 n-minute ratios: 5-, 10-, 15- and 30-minute to 60-minute.

Duration	5-minute	10-minute	15-minute	30-minute
Ratio	0.318	0.484	0.600	0.808

Choosing the appropriate relationship perhaps is best done by seeing which results in a hypothetical storm that results in the best comparisons with estimated design flow (i.e., the best correspondence estimated 100-yr and 2-yr discharges).

Figure B-2 Approximate geographic boundaries for NRCS (SCS) rainfall distributions

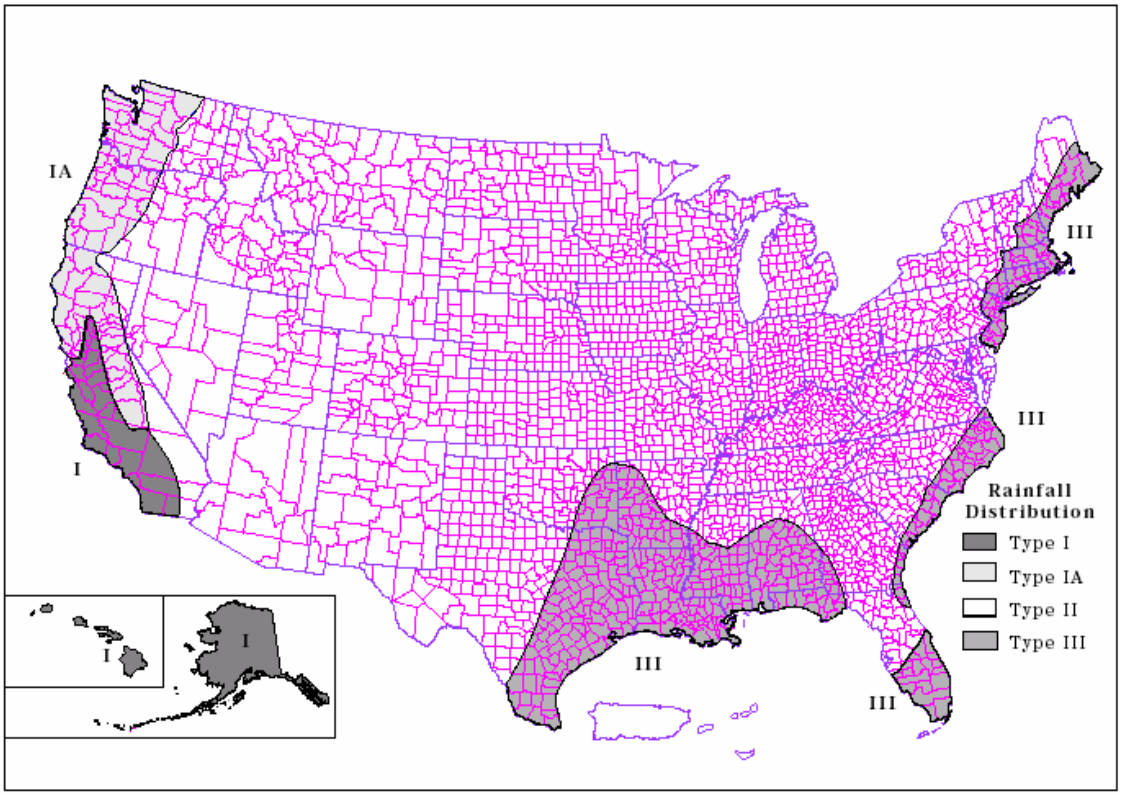


Figure 7.3: Regions for NRCS 24 hour design rainfall (from TR55, NRCS, 1986)

Table 7.1 Dimensionless 24 hour precipitation depth-duration curves

	[1]type 1	type 1A	type II	[2]01jan97	[3]24mar98	[4]12dec98	[5]average	[6]NOAA14
24hr	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
12hr	0.76	0.69	0.84	0.55	0.66	0.61	0.61	0.78
6hr	0.58	0.47	0.71	0.30	0.39	0.34	0.34	0.57
3hr	0.44	0.31	0.60	0.15	0.25	0.17	0.19	0.35
2hr	0.37	0.25	0.54	0.11	0.17	0.11	0.13	0.22
1hr	0.28	0.17	0.45	0.06	0.09	0.06	0.07	0.16
15min	0.15	0.06	0.28	0.02	0.02	0.01	0.02	0.13
5min	0.06	0.02	0.12				[7]0.01	0.10

[1]From 24-hour NRCS design storm patterns (NRCS, 1986), [2]Obtained from gage average storm pattern for 48-hours, [3]Obtained from Fallen Leaf Lake gage, [4]Obtained from Ward Creek gage, [5]Average of observed storm values, [6]From NOAA14 lowest elevation zone 100-year sub-basin average estimates, [7]computed using ratio derived from NRCS type 1A 5/15 minute.

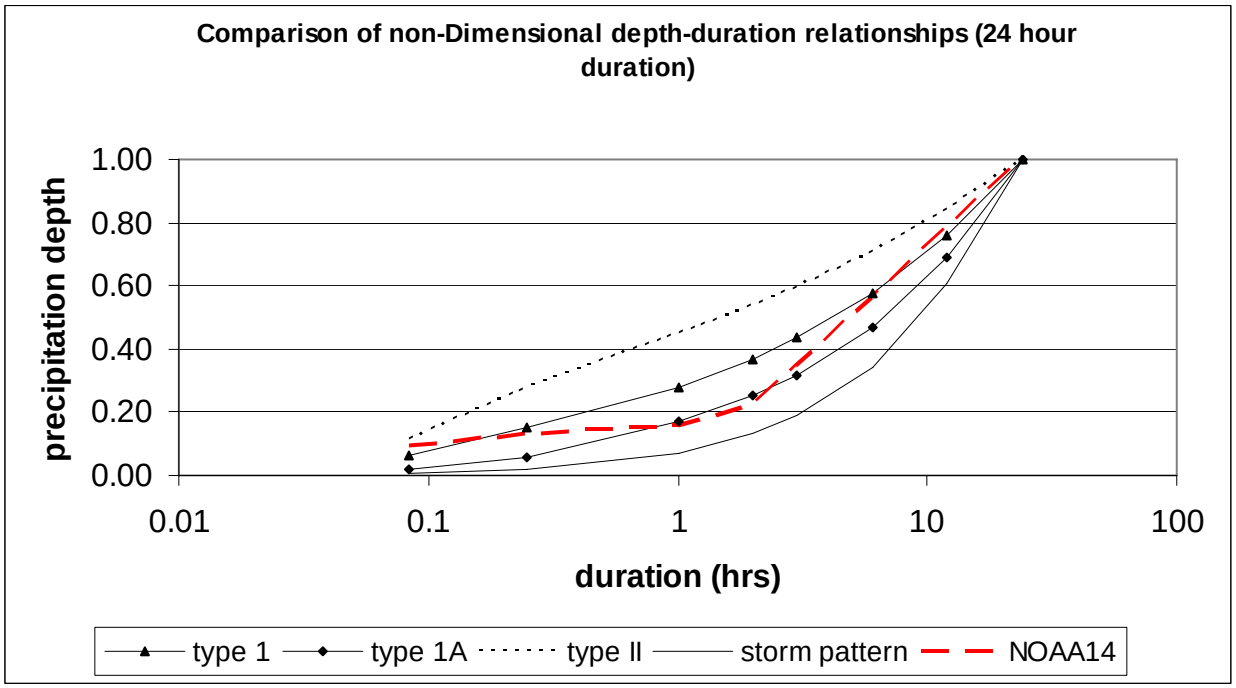


Figure 7.4: Dimensionless precipitation depth-duration curves
(see Table 7.1)

7.2.2 Influence of precipitation phase

The NOAA14 ddf curves are of precipitation not rainfall. Snow certainly has to affect the statistics of these curves. Table 7.2 shows the results of a period of record study of the fraction of total rainfall obtained from an analysis of daily precipitation and snowfall measurements. As can be seen, the fraction is about 60%-70% in the high precipitation winter months of December – March.

This fraction is likely to vary with size of the event. For example, the 01 January 1997 storm was a very warm event, where the 24hour maximum precipitation was rainfall at lake level. However, the 24 March 1997 event most likely had snow during the 24 hour maximum precipitation period.

The fact that snowfall occurred during an event does not mean this volume of water will not contribute to runoff. Still, the effect of the snow fraction will generally make the amount of rainfall assumed to occur during the storm conservative. This would be true unless some snowfall/snowmelt algorithm is applied when simulating the design storm.

In the approach proposed herein, the hypothetical storm event obtained from the ddf curves is assumed to be all rainfall. The calibrated **effective** loss rates will need to account for the conservatism in the assumption that the phase of precipitation is rain when in fact the storm was derived from precipitation ddf curves. Basically, the loss rates are used as a surrogate runoff coefficient.

Table 7.2: Analysis of monthly rain fraction of precipitation, Tahoe City daily gage

[1]month	relative frequency	rain fraction mean	rain fraction [2]sdev
jan	0.13	0.62	0.35
feb	0.12	0.60	0.35
mar	0.11	0.62	0.35
apr	0.08	0.62	0.36
may	0.08	0.89	0.24
jun	0.05	0.98	0.10
jul	0.02	1.00	0.00
aug	0.02	1.00	0.00
sep	0.04	0.97	0.12
oct	0.08	0.92	0.20
nov	0.13	0.78	0.30
dec	0.13	0.68	0.34

[1]Assumption that 12.0” snow equivalent to 1.0” water, Period of Record 1939-1998
[2]Standard deviation

7.3 Hypothetical storm calibration to 100-year design template discharges

The lowest elevation sub-basins were used to evaluate different hypothetical storm patterns in simulations of the 100-year discharge. In these simulations, loss rates were calibrated to reproduce the 100-year discharges obtained for these sub-basins in the simulations of the template events described in section 6.

The hypothetical storms were created by specifying in HEC-1 the depth-duration relationships described in the previous section together with 100-year, 24-hour basin average NOAA14 precipitation depth. HEC-1 creates the standard triangular storm distribution with the peak intensity in the middle of the storm (see figure 7.2). Depth-duration relationships for NRCS type 1A, NOAA14, and average winter storm events were chosen to create the hypothetical storms (see Table 7.1).

Tables 7.3 and 7.4 describe the simulated discharges and the resulting loss rates for the calibration simulations. Initially, loss rates obtained in the design storm templates were used in the simulation, no calibration. The storm events obtained from the storm average depth-duration curves produced discharge comparing most favorably with the discharges obtained from the storm template simulations. The NRCS type1A produced discharges that were next closest to the template discharge, which was to be expected given the better correspondence to the average storm depth-duration curves than those for NOAA14.

Loss rates were then adjusted for the average and type 1A storm simulations to obtain better correspondence with the design storm template discharges. Adjustments with NOAA14 storm was not performed because it performed most poorly. As can be seen from Table 7.3, the calibration using the storm average depth-duration curves performed better in preserving both the peak discharge and 6hour maximum volumes.

Table 7.3: Comparison of HEC-1 100 yr flows obtained from calibration of template and hypothetical design storms (lowest elevation sub-basins)

	storm	(1)		(2)		(3)		(4)		(5)		(6)	
stream gage	[1]area	1hr	6hr	1hr	6hr	1hr	6hr	1hr	6hr	1hr	6hr	1hr	6hr
Upper Truckee	13.9	1864	1838	1944	1887	1244	1215	1871	1832	1556	1513	1881	1831
General	2.02	230	217	655	446	237	184			600	353	318	167
Ward	1.87	563	548	962	762	560	500			972	689	671	389
Incline	0.82	72	49	352	159	60	24			321	103	198	52
Third	0.30	29	13	198	55	29	8			166	35	115	18
Trout	7.18	201	193	605	574	96	92	209	199	371	352	226	215

(1) HEC-1 model calibrated runoff from simulation of template event for lowest elevation sub-basin (see section 6)
(2) NOAA14 dimensionless DDF curve (see Table 7.1)
(3) Storm average DDF curve (see Table 7.1)
(4) Storm average DDF curve (see Table 7.1), adjusted loss rates
(5) NRCS type 1A DDF curve (see Table 7.1)
(6) NRCS type 1A DDF curve (see Table 7.1), adjusted loss rates
[1]drainage area (sq mi)

Table 7.4: Comparison of loss rates used to simulate 100-year Storm Template Precipitation and Hypothetical Rainfall

(see Table 7.3)

stream gage	(1)	(2)	(3)
Upper Truckee	0.21	0.14	0.17
General	0.26		0.55
Ward	0.05		0.3
Incline	0.37		0.65
Third	0.37		0.65
Trout	0.31	0.25	0.45

(1) HEC-1 model calibrated loss rates for lowest elevation sub-basin (see section 6), see columns (2), (3) and (5) Table 7.2
(2) Storm average depth-duration curve (see Table 7.1), adjusted loss rates
(3) NRCS type 1A depth-duration curve (see Table 7.1), adjusted loss rates

7.4 Hypothetical storm calibration to 2- year design template discharges

The model simulations from the previous section made it apparent that only the storm average depth-duration relationship would provide a satisfactory replication of design peak discharge and a measure of runoff volume. Consequently, this depth-duration relationship was selected as the best to be used for creating a 24 hour hypothetical storm. The simulation approach is the same as that describes for the 100year storm described in the previous section. Table 7.5 and 7.6 describe the simulation results. A minor amount of adjustment to the loss rates was needed for the reproduction of the 2-year peak discharge and 6 hour maximum volumes.

7.5 Recommendations

The calibration studies completed both in this section and section 6 provide convincing evidence that a winter storm depth-duration frequency curve should be used for a 24-hour design storm for open areas. The shape of the resulting hypothetical storm hyetographs (centering of the peak) is probably not that critical given that a constant loss rate method is being employed. The standard HEC-1 symmetrical storm pattern is practically useful.

The loss rates recommended in Table 7.5 are slightly on the conservative side, being rounded to the lowest 0.1 inch per hour (except for Ward Creek). These loss rates vary with watershed, but mostly reflect west versus east location within the Lake Tahoe Basin. Ward Creek is an outlier, but this really reflects the generally high runoff potential for this basin that occurs because of the watersheds orientation (being on the western side of Lake Tahoe and aligned directly east-west) and low rim elevation.

Table 7.5: Comparison of HEC-1 100-yr flows obtained from calibration of template and hypothetical design storms (lowest elevation sub-basin)

	storm	(1)		(2)		(3)		(4)	
stream gage	[1]area	1hr	6hr	1hr	6hr	1hr	6hr	1hr	6hr
Upper Truckee	13.9	426	416	701	683	300	294	432	422
Ward	1.87	134	127	293	267	191	183	131	124
Glenbrook	1.11	8	5	54	40	2	2	8	6
Trout	7.18	52	50	249	239	32	31	51	32

(1) HEC-1 model calibrated runoff from simulation of template event for lowest elevation sub-basin (see section 6)
(2) NOAA14 dimensionless DDF curve (see Table 7.1)
(3) Storm average depth-duration curve (see Table 7.1)
(4) Storm average depth-duration curve (see Table 7.1), adjusted loss rates
[1]drainage area (sq mi)

Table 7.6: Comparison of loss rates used to simulate 100-year Storm Template Precipitation and Hypothetical Rainfall

(see Table 7.5)

stream gage	(1)	(2)
Upper Truckee	0.14	0.12
Ward	0.06	0.11
Glenbrook	0.195	0.135
Trout	0.15	0.135

(1) HEC-1 model calibrated loss rates for lowest elevation sub-basin (see section 6), see columns (2), (3) and (5) Table 7.4
(2) Storm average depth-duration curve (see Table 7.1), adjusted loss rates

Table 7.7 Recommended loss rates to be used with storm average depth-duration precipitation curve

(see Table 7.1)

stream gage	(1)	(2)	(3)	(4)	(5)	(6)
Upper Truckee	0.21	0.14	0.2	0.14	0.12	0.1
General	0.26		0.2	----	-----	0.1
Ward	0.05		0.05	0.06	0.11	0.1
Incline	0.37		0.3	----	-----	0.1
Third	0.37		0.3	----	----	0.1
Glenbrook	----	-----	0.3	0.195	0.135	0.1
Trout	0.31	0.25	0.3	0.15	0.135	0.1

(1) 100-year loss rates obtained from storm template simulations (see section 6)
(2) 100-year adjusted loss rates used with storm average depth duration curves
(3) 100-year recommended loss rates
(4) 2-year loss rates obtained from storm template simulations (see section 6)
(5) 2-year adjusted loss rates used with storm average depth duration curves
(6) 2-year recommended loss rates

8 Application to estimating urban design flows

8.1 Modeling recommendations

The application of the calibration studies in the previous sections has been to relatively large open areas. However, the majority of the drainage design problem will involve smaller urban areas. Even though urban runoff is involved, including runoff from impervious areas, consideration still needs to be given to the coincidence of factors (storm depth, pattern and antecedent conditions) that result in flow quantiles (e.g., the 100-year peak or maximum 24-hour volume). In the previous sections, a combination of hypothetical storm precipitation and **effective loss rates** were determined that reasonably produced flow quantiles for primarily natural open watersheds. Application of these storms and loss rates to urban watersheds requires an extrapolation of results to significantly smaller open areas.

The applications of these results to impervious urban areas is limited perhaps by the type of event that may be important to design of small drainage structures (culverts and catch basins). The hypothetical storm recommended for open areas in the previous section assumes that large area winter storms are most important to computing design runoff for the open area lower elevation sub-basins in Lake Tahoe. This is based on the observation that 01 January 1997 event produced the largest discharges in the basin in more than 100-years of record. However, short-duration, thunderstorm events might be more important to estimating design runoff for impervious areas. Consequently, recommendations for computing the runoff from both open and impervious surfaces needs to consider both kinds of storms, a regional winter and local thunderstorm.

The recommendations for a modeling approach relies, to the extent possible, on the results of the calibration studies performed in the previous section. The basic presumption of that study is that regional winter storm and coincident antecedent conditions (i.e., antecedent snow pack) will produce rainfall and snowmelt resulting in the annual maximum peak and runoff volume from open areas. This type of event should be used to compute maximum runoff from open areas in urban watersheds as well.

The depth-duration storm characteristics of the winter storms may not be appropriate for the impervious areas. Consequently, either the NOAA14, or,NRCS type 1A or 2 depth-duration relationships might be applied.

The following procedure is recommended to simulate design flow for urban basins given the differing runoff characteristics of the open and impervious surfaces

1) Determine the 24-hour watershed precipitation depth from NOAA14.
2) Compute the peak annual flow and corresponding runoff volumes for the open areas using the storm average depth-duration and effective loss rates described in section 7 (see Table 7.1 and 7.7). The peak discharges computed in this way reflect the coincidence of conditions (precipitation, soil moisture and snow pack) causing runoff.
3) Select a depth-duration relationship that is, perhaps, more indicative of the local thunderstorm (high intensity) rainfall that is more important to impervious area runoff. The NRCS type 1A, 24-hour storm is probably a good choice in that it agrees more closely with NOAA14 depth-duration characteristics than type 2 (see Table 7.1).
4) Determine a snowmelt rate that is indicative of the return interval of the event. Calibration studies performed in section 4 and 5 indicate melt rates from 1-2 inches per day for the 100-year event and about 0.5 inches per day for the 2-year event. Add this rate, perhaps over an 8 hour period, to the hypothetical storm
5) Simulate the runoff from the impervious surface using zero constant loss rates. A nominal initial loss might be applied (0.1” being typical for impervious surfaces). The assumption is that the impervious area is connected to the drainage system. Unconnected impervious areas, such as rooftops draining to flower beds or backyards, probably should be considered open area.
6) Sum the runoff hydrographs from the open and impervious areas.

If the modeling approach uses a distributed kinematic wave sub-basin, such as in HEC-1, where impervious and overland flow planes assume the same storm pattern, then a single storm depth-duration relationship is needed. An additional step in the modeling procedure would be included

where loss rates for the open overland flow plane are determined by calibration runoff computed from the storm event selected in step 3 for the impervious area to the runoff results from step 2. These loss rates could then be used for the open overland flow plane when using the HEC-1 two overland flow plane kinematic wave distributed model.

8.2 Residual risk and economic considerations

The estimation of flow quantiles, particularly infrequent occurrences such as the 100-year flow, are highly uncertain and involve significant residual risk, even for gaged basins. Residual risk here refers to the chance that the flow quantile is significantly different than the estimate. Estimating these flow values for ungaged, urban basins, involves even a greater degree of residual risk.

Under these circumstances, the consequences of exceeding design capacity need to be balanced by the incremental cost of a degree of safety in design. This is a typical problem faced by engineers when choosing safety factors. Probably, the biggest impact on the cost of the urban drainage systems will be the selection of the depth-duration relationship used to create the hypothetical storms for simulation. The difference between the runoff between an NRCS type 1A and type 2 storm will be very significant and will likely have an important impact on the cost of the design. Decisions regarding which depth-duration relationship to adopt should carefully consider the tradeoff between the consequences of exceeding design capacity and the cost of the design