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To: Professor Jessica Newlin
Date: November 25, 2014
Subject: Rainfall-Runoff Analysis to determine design discharge of larger watersheds

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There are various methods to estimate the design discharge of watersheds. Some can be found in the Pennsylvania Department of Transportation (PennDOT) Drainage Manual. These include *rational method*, *regression methods*, and *HEC-HMS*. The appropriateness of each depends on the size and conditions of the watershed. As prescribed by design assignment three, the 2-year, 10-year, 50-year, and 100-year return period design storm peak discharges at a given point of interest were evaluated using two methods: SCS rainfall-runoff method using HEC-HMS 3.5, and PennDOT (2010) regression equations.

This memorandum summarizes and compares the 2-year, 10-year, 50-year, and 100-year design storm peak discharges at a point of interest; downstream of the Montour Preserve Dam, Montour County, PennDOT zone three; as shown in Figure 1.

Figure 1. Point of Interest indicated by the red dot.

The point of interest shows the location of a proposed roadway crossing over the Chillisquaque creek. According to the PennDOT Drainage Manual (2010), the rational method is only recommended for estimating peak flows of drainage areas up to 0.3125 mi^2. The rational method is also deemed unsuitable if there are multiple drainage channels with individual hydrologic properties and/or if storage is an important factor. Therefore, the rational method was ruled out considering the watershed has an area of 16.8 mi^2 and is comprised of three sub-basins with varying hydrologic properties. On the other hand, the regression method is applicable because the equations can predict the magnitudes of flood flows for certain recurrence intervals in most un-gaged Pennsylvania streams with drainage areas less than 2 000 mi^2 (Roland and Stuckey, 2008). Therefore, finding the design peak discharge was accomplished using the HEC-HMS 3.5 software as a predictive tool by means of the SCS rainfall-runoff method, as well as the regression method as outlined by Roland and Stuckey (2008). Below is the summary of the discharges:

Table 1. Comparison of the data from HEC-HMS 3.5 and Regression method

Return period (years)	Discharge in the point of interest, POI (cfs)		
	HEC- HMS 3.5	Regression Method	% Difference
2	955	738	-22.72
10	2097	1699	-18.98
50	4263	2841	-33.36
100	6100	3417	-43.98

For the rainfall-runoff method (HEC-HMS 3.5) the watershed was subdivided into three smaller sub-basins. These are named east branch (EBChilli), lower-mid branch, and upper-mid branch. The upper branch is the largest sub-basin and contains the effluent east of the reservoir; the lower-mid branch stretches from the point of interest to the reservoir outlet; and the upper-mid branch includes the reservoir and upstream influents. The analysis encompassed measuring the area of each sub-basin, estimating times of concentration, rainfall depths, and storage routing across the reservoir to the point of interest. The procedures for the SCS rainfall-runoff analysis are explained in more detail in the Appendix. The values obtained from ArcMap 10.2 were used as the inputs for HEC-HMS 3.5. The detailed description of the methods used in the HEC-HMS 3.5 is in the Appendix.

For the regression method by Roland and Stuckey (2008), equations were generated using peak-flow data from 322 stream flow-gaging stations within the state and some surrounding areas. The regression equation used is:

$$LogQ_T = A + bLogDA + cLogEl + dLog(1 + 0.01U) + fLog(1 + 0.1Sto) \qquad (1)$$

where *A* is the intercept (determined by GLS), *DA* is drainage area (mi^2), *El* is the mean elevation (ft), *C* is the percentage of basic underlain by carbonate bedrock, *U* is the percentage of urban area in the basin, *Sto* is the percentage of storage in the basin, and *a, b, c, d, e,* and *f* are coefficients related their corresponding basin characteristics in the regression equation. The point of interest is located in Region 1, which disregards the impacts of mean elevation, percent carbonate rock, and percent urban area on the stream flow. These GLS coefficients are found in Table 3 of the USGS report and can be found in the Appendix. Calculations for the design discharges of the return periods of interest can be found in the Appendix.

Conclusion:

A quick glance at the data reveals the HEC-HMS 3.5 results in larger peak discharge values than those of the Regression Method. It can only be concluded that using the higher values for design discharge results in safer conditions. HEC-HMS 3.5 is known for being a very applicable hydrologic simulation that works for watersheds of almost any size and complexity (PennDOT, 2010). Furthermore, the regression equations are empirical and based from gage data which might be smaller than actual peak discharges. For instance, PennDOT (2010) provides tables of watersheds where the peak discharge values were under-predicted, one of which is the EB Chillisquake Creek, which had from 50 to 63 percent lower predicted values than observed. This is corroborated by the discharge values obtained using the HEC-HMS 3.5 method which were up to 44 percent higher than predicted by the regression method in the Chillisquake watershed which includes the EB Chillisquake Creek. These are the reasons why the HEC-HMS 3.5 peak discharge values are suitable for design.

References:

PennDOT. (2010). Retrieved from ftp://ftp.dot.state.pa.us/public/bureaus/design/PUB584/PDMChapter07.pdf

Roland and Stuckey. (2008). Retrieved from http://pubs.usgs.gov/sir/2008/5102/pdf/sir2008-5102.pdf

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Appendix:

1. Regression Method: Sample Calculations

Coefficients from PA USGS Publication Table 3 (Roland and Stuckey, 2008):			
T-year Peak Flow	***Intercept, a***	***Drainage Area, b***	***% Storage, f***
Q2	1.84257	0.86396	-0.4918
Q10	2.24305	0.83197	-0.47595
Q50	2.47845	0.81981	-0.43501
Q100	2.56172	0.81626	-0.41724

Constants:	
Drainage Area, DA (mi^2)	16.8
Reservoir Area, RA (mi^2)	0.28
Storage = RA/DA (%)	1.69

Sample Calculations for the log(Qx) and Qx values:

logQx	a + blog(DA) + flog(1+0.01(sto))	
logQ2 =	1.84257 + 0.86396*log(16.8) + (-0.4918)*log(1+0.1(1.69)) =	2.8678
logQ10 =	2.24305 + 0.83197*log(16.8) + (-0.47595)*log(1+0.1(1.69)) =	3.2302
logQ50 =	2.47845 + 0.81981*log(16.8) + (-0.43501)*log(1+0.1(1.69)) =	3.4535
logQ100 =	2.56172 + 0.81626*log(16.8) + (-0.41724)*log(1+0.1(1.69)) =	3.5336

Qx (ft^3/s)		
Q2 =	10^2.8678 =	737.61
Q10 =	10^3.2302 =	1698.97
Q50 =	10^3.4535 =	2840.95
Q100 =	10^3.5536 =	3416.56

2. HEC HMS 3.5 Proceedings:

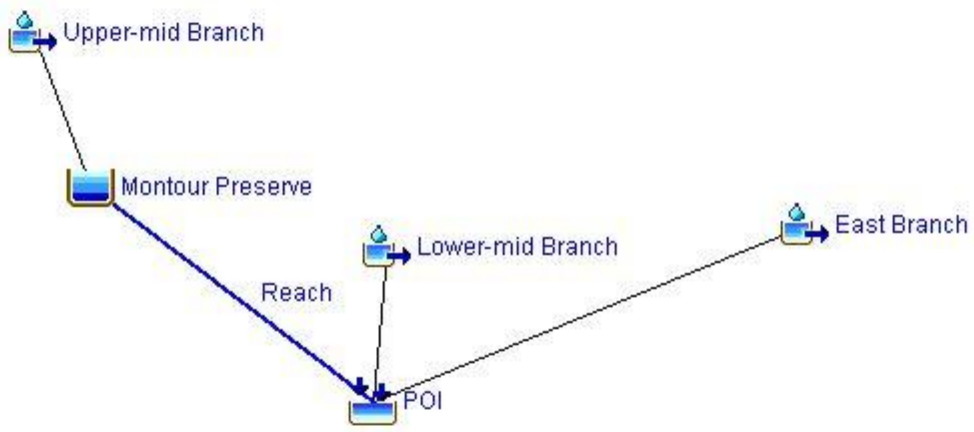


Figure 4: HEC-HMS 3.5 model of the watershed.

Watershed sub-sub-basin properties used in HEC-HMS 3.5, which were obtained from ArcMAP analysis:

Table 9: Watershed Sub-basin properties

	Sub-basins		
	upper-mid*	**lower-mid**	**east**
Area (mi^2)	5.73	1.39	9.77
CN	73	73	73
Time of Concentration, T_c (min)	196.7	49.0	243.3
Lag Time (min) [60% of T_c]	118	29.4	146

*Note: For the upper-mid sub-basin T_c was computed up to the beginning of the reservoir

2.1. Meteorological Models:

The Meteorological model included the 2-year, 10-year, 50-year, and 100-year SCS storms that needed the depth of precipitation as the inputs. These values were taken from Chapter 7, Appendix A - Field Manual for Pennsylvania Design Rainfall Intensity (*ftp://ftp.dot.state.pa.us/public/bureaus/design/PUB584/PDMChapter07A.pdf*).
The duration of the storm was taken to be 24 hours as required by the Manual and the Control was specified as 36 hours frame from 21st November 2014 14:25 to 23rd November 2014 14:25. These models were applied to all the sub-basins. The Input values were as follows:

Table 10: The precipitation depths for the SCS storms of different return periods in inches

2 year	**10 year**	**50 year**	**100 year**
2.92	4.20	5.9	6.83

2.2. Montour Preserve Reservoir:

The initial elevation of water in the reservoir was at 598 ft, and it was specified that the Outflow was controlled by a 24 in. diameter pipe when water levels hit the elevation of 597.15 ft, and by a broad crested spillway when it hit 600 ft. The outflow discharge was computed using Equations 2 and 3:

Pipe Orifice: $$Q_{out} = CA\sqrt{2gH} \quad (2)$$

Where C = 0.55, A is the cross sectional area of the pipe, g is the gravitational constant, and H is the head or elevation of water above the invert.

Spillway: $$Q_{out} = CLH^{1.5} \quad (3)$$

Where C = 2.63, L is the length of the weir (750 ft), and H is the head or elevation of water above the spillway elevation.

The Elevation-Storage data were given, so the Elevation-Storage-Discharge for the reservoir were therefore, calculated as follows:

Table 11: The Elevation-Storage-Discharge data for the Reservoir

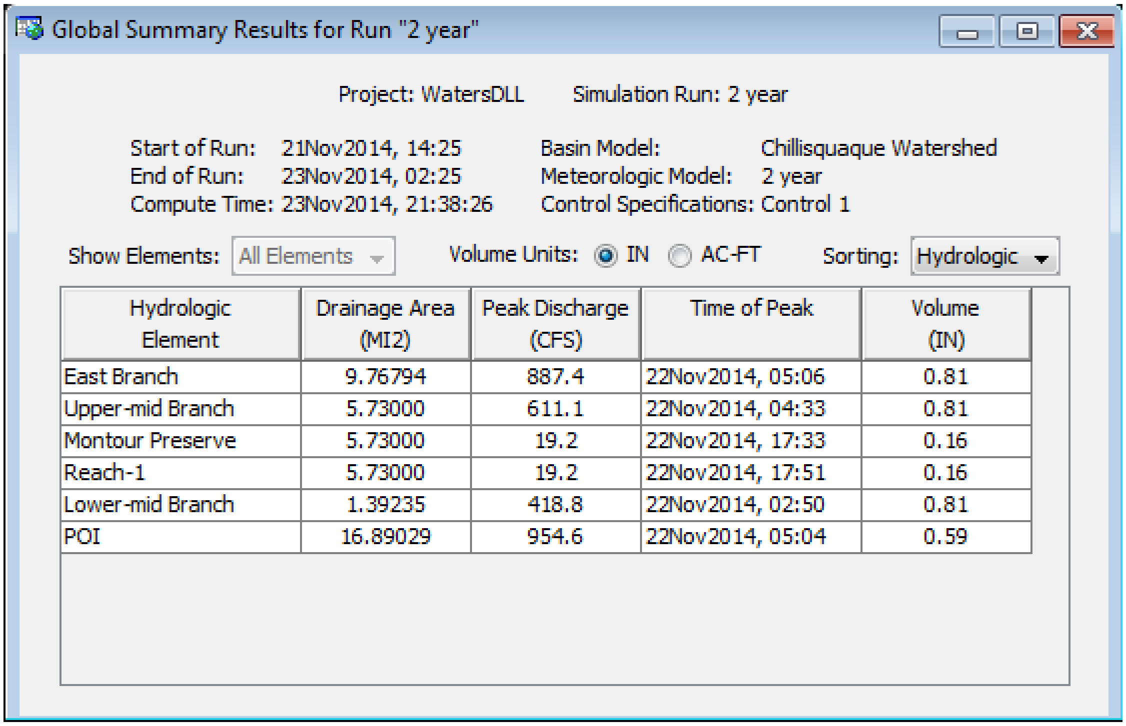
Elevation (ft.)	Storage (ac-ft.)	Discharge, Q_{out} (cfs)
597.15	2858.3	0
598	3000	12.8
600	3350	23.4
601	3500	1999.7
603	4000	10283
605.5	4450	25482.7

These data were input in the HEC-HMS 3.5 as two paired data tables: Elevation-Storage and Storage-Discharge. The Lag time for the outflow to reach the point of interest (POI) was specified as 0.30 hours. It was assumed that there was no channel loss in the Reach.

The simulation run outputs based on these input values given by HEC-HMS 3.5 are given below.

2.3. Simulation Runs:

2 year design storm



Global Summary Results for Run "2 year"

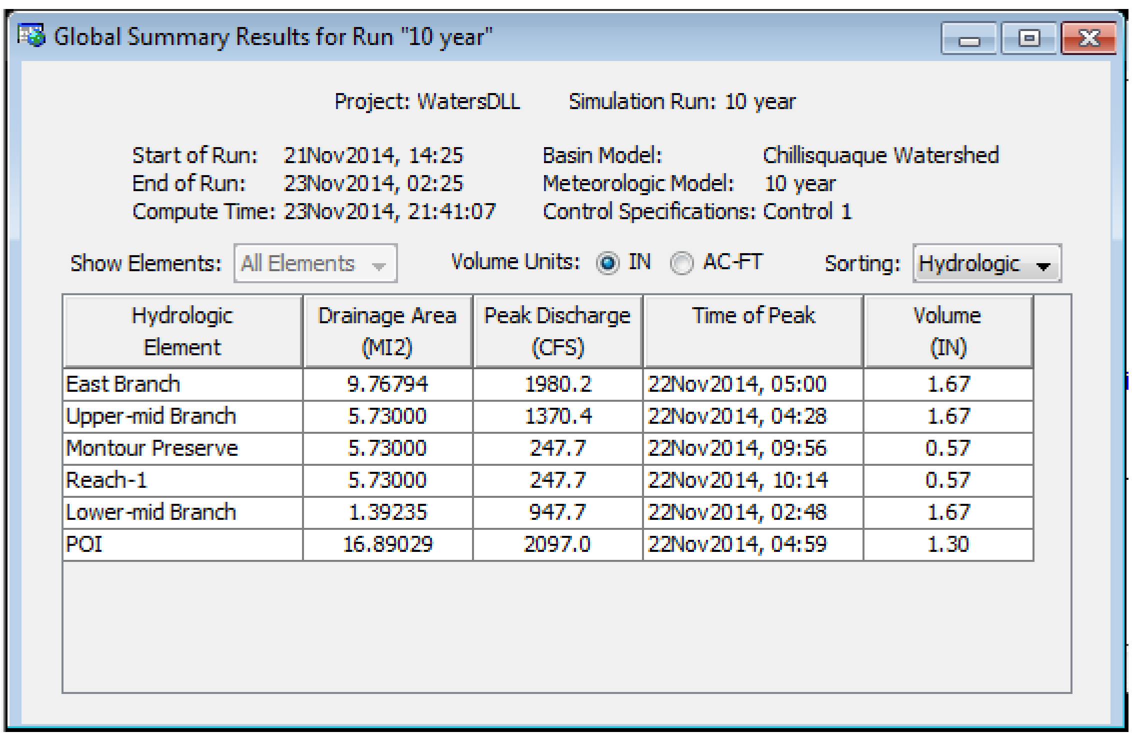
Project: WatersDLL Simulation Run: 2 year

Start of Run: 21Nov2014, 14:25 Basin Model: Chillisquaque Watershed
End of Run: 23Nov2014, 02:25 Meteorologic Model: 2 year
Compute Time: 23Nov2014, 21:38:26 Control Specifications: Control 1

Show Elements: All Elements Volume Units: IN AC-FT Sorting: Hydrologic

Hydrologic Element	Drainage Area (MI2)	Peak Discharge (CFS)	Time of Peak	Volume (IN)
East Branch	9.76794	887.4	22Nov2014, 05:06	0.81
Upper-mid Branch	5.73000	611.1	22Nov2014, 04:33	0.81
Montour Preserve	5.73000	19.2	22Nov2014, 17:33	0.16
Reach-1	5.73000	19.2	22Nov2014, 17:51	0.16
Lower-mid Branch	1.39235	418.8	22Nov2014, 02:50	0.81
POI	16.89029	954.6	22Nov2014, 05:04	0.59

10 year design storm



Global Summary Results for Run "10 year"

Project: WatersDLL Simulation Run: 10 year

Start of Run: 21Nov2014, 14:25 Basin Model: Chillisquaque Watershed
End of Run: 23Nov2014, 02:25 Meteorologic Model: 10 year
Compute Time: 23Nov2014, 21:41:07 Control Specifications: Control 1

Show Elements: All Elements Volume Units: IN AC-FT Sorting: Hydrologic

Hydrologic Element	Drainage Area (MI2)	Peak Discharge (CFS)	Time of Peak	Volume (IN)
East Branch	9.76794	1980.2	22Nov2014, 05:00	1.67
Upper-mid Branch	5.73000	1370.4	22Nov2014, 04:28	1.67
Montour Preserve	5.73000	247.7	22Nov2014, 09:56	0.57
Reach-1	5.73000	247.7	22Nov2014, 10:14	0.57
Lower-mid Branch	1.39235	947.7	22Nov2014, 02:48	1.67
POI	16.89029	2097.0	22Nov2014, 04:59	1.30

50 year design storm

Global Summary Results for Run "50 year"

Project: WatersDLL   Simulation Run: 50 year

Start of Run: 21Nov2014, 14:25   Basin Model: Chillisquaque Watershed
End of Run: 23Nov2014, 02:25   Meteorologic Model: 50 year
Compute Time: 23Nov2014, 21:43:12   Control Specifications: Control 1

Show Elements: All Elements   Volume Units: IN AC-FT   Sorting: Hydrologic

Hydrologic Element	Drainage Area (MI2)	Peak Discharge (CFS)	Time of Peak	Volume (IN)
East Branch	9.76794	3685.7	22Nov2014, 04:57	3.01
Upper-mid Branch	5.73000	2552.6	22Nov2014, 04:25	3.01
Montour Preserve	5.73000	1242.7	22Nov2014, 06:18	1.90
Reach-1	5.73000	1242.7	22Nov2014, 06:36	1.90
Lower-mid Branch	1.39235	1758.5	22Nov2014, 02:47	3.01
POI	16.89029	4263.2	22Nov2014, 05:47	2.63

100 year design storm

Global Summary Results for Run "100 year"

Project: WatersDLL   Simulation Run: 100 year

Start of Run: 21Nov2014, 14:25   Basin Model: Chillisquaque Watershed
End of Run: 23Nov2014, 02:25   Meteorologic Model: 100 year
Compute Time: 23Nov2014, 21:44:25   Control Specifications: Control 1

Show Elements: All Elements   Volume Units: IN AC-FT   Sorting: Hydrologic

Hydrologic Element	Drainage Area (MI2)	Peak Discharge (CFS)	Time of Peak	Volume (IN)
East Branch	9.76794	4684.8	22Nov2014, 04:56	3.79
Upper-mid Branch	5.73000	3244.3	22Nov2014, 04:24	3.79
Montour Preserve	5.73000	1897.7	22Nov2014, 05:52	2.68
Reach-1	5.73000	1897.7	22Nov2014, 06:10	2.68
Lower-mid Branch	1.39235	2230.4	22Nov2014, 02:47	3.79
POI	16.89029	6100.0	22Nov2014, 05:34	3.41

3. ArcMap 10.2 Proceedings:

3.1. The surface area was solved for by the software in square miles of each sub-basin:

Table 2. Area of each sub-basin and total area measured in square miles

east branch	upper-mid branch	lower-mid branch	total
9.77	5.73	1.39	16.8

3.2. The curve number (CN) of each sub-basin was also gaged. The CN of the upper-mid branch was computed beforehand to be 73 (Fall 2014 Week 9 GIS lab, 10/30/14):

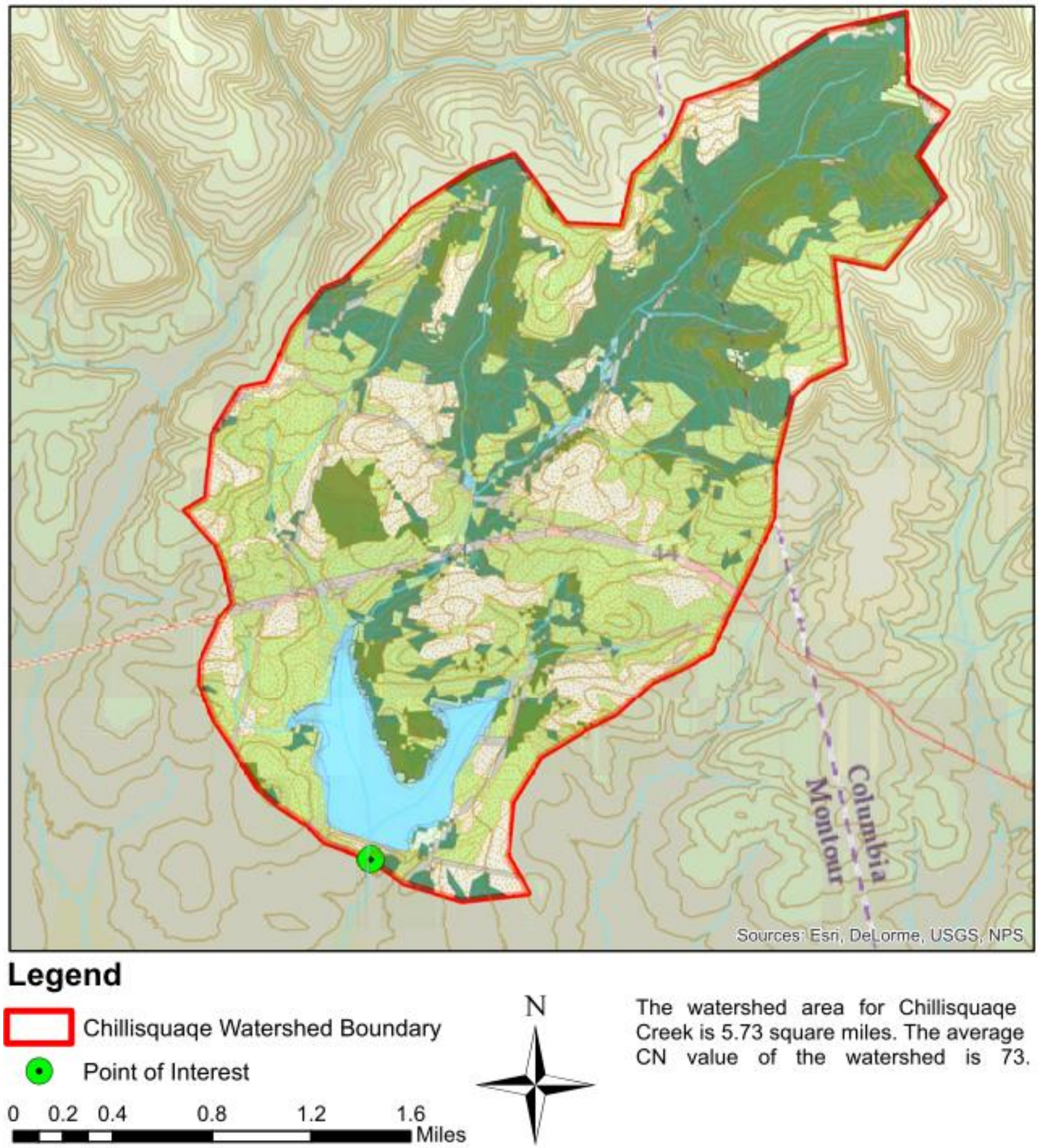


Figure 2. Map of the upper-mid branch sub-basin, area and CN

The CN is a weighted average by area of the CN corresponding to each possible cover type-soil group combination. The soil cover and the soil group data were clipped together. All soil cover-soil group combinations were summarized using the area as the summary statistic. A CN was assigned to each individual cover type-soil group combination assuming equivalence among the following terms:

shrubs = wood-grass
herbaceous = meadows
developed, low = 2-acre residential
developed, medium = ½-acre residential
developed, high = ⅛-acre residential

Open space was assumed to be fair condition. Moreover, no soil type was assumed to represent fully permeable soil (CN = 0) and no cover type was assumed to represent water (CN = 100). Lastly, if two soil types were present (e.g. B/D), the lower one (B) was chosen if there was development of any sort. Otherwise, D was chosen. If the curve number was to be calculated again, Wikipedia provides a comprehensive list of the curve numbers that were otherwise assumed in this project: (*http://en.wikipedia.org/wiki/Runoff_curve_number*) as well as Chapter 7A of PennDOT Drainage Manual (*ftp://ftp.dot.state.pa.us/public/bureaus/design/PUB584/PDMChapter07A.pdf*).

Table 3. Cover type - Soil Group Combinations, CN, and Area of lower-mid branch sub-basin

OID	LU_Soil	Count_LU_Soil	Sum_Area_sqmi	CN	CN_Area
0	Cultivated Crops_B	5	0.0133	75	0.9975
1	Cultivated Crops_B/D	4	0.0227	75	1.7025
2	Cultivated Crops_C	65	0.2492	82	20.4344
3	Cultivated Crops_D	2	0.0048	86	0.4128
4	Deciduous Forest_B	8	0.0202	55	1.111
5	Deciduous Forest_B/D	7	0.0285	77	2.1945
6	Deciduous Forest_C	49	0.1937	70	13.559
7	Deciduous Forest_D	3	0.0127	77	0.9779
8	Developed, High Intensity_B	1	0.0026	85	0.221
9	Developed, High Intensity_C	1	0.0001	90	0.009
10	Developed, Low Intensity_B	6	0.0044	92	0.4048
11	Developed, Low Intensity_C	2	0.001	77	0.077
12	Developed, Open Space_B	8	0.011	69	0.759
13	Developed, Open Space_B/D	2	0.0026	69	0.1794
14	Developed, Open Space_C	80	0.0658	79	5.1982
15	Developed, Open Space_D	1	0.0004	84	0.0336
16	Hay/Pasture_A	1	0.0113	39	0.4407
17	Hay/Pasture_B	9	0.0765	61	4.6665
18	Hay/Pasture_B/D	8	0.1155	61	7.0455
19	Hay/Pasture_C	76	0.5093	74	37.6882
20	Hay/Pasture_D	2	0.011	80	0.88
21	Mixed Forest_B	10	0.0053	55	0.2915
22	Mixed Forest_B/D	4	0.0026	77	0.2002
23	Mixed Forest_C	26	0.0237	70	1.659
24	Mixed Forest_D	2	0.0004	77	0.0308
25	Shrub/Scrub_C	4	0.0016	72	0.1152
26	Woody Wetlands_D	1	0.0023	100	0.23

Summing the products of the area and CN of each soil cover-soil group combination gives 101.519 mi^2. Dividing by the total area of the sub-basin (1.392 mi^2) gives an average CN of 72.91 for the lower-mid branch. Similarly, for the lower-mid branch, the sum of the products of area and CN is 717.496 mi^2, and dividing by an area of 9.768 mi^2 gives an average CN of 73.45 for the east branch sub-basin.

Table 4. Cover type - Soil Group Combinations, CN, and Area of east branch sub-basin

OID	LU_Soil	Cnt_LU_Soi	Sum_Areq_s	CN	CN_Area
0	Cultivated Crops_	1	0	0	0
1	Cultivated Crops_	1	0.0013	0	0
2	Cultivated Crops_A	3	0.0158	65	1.027
3	Cultivated Crops_B	46	0.2368	75	17.76
4	Cultivated Crops_B/D	21	0.1042	75	7.815
5	Cultivated Crops_C	342	1.4849	82	121.762
6	Cultivated Crops_D	35	0.1401	86	12.0486
7	Deciduous Forest_	1	0	0	0
8	Deciduous Forest_	2	0.0006	0	0
9	Deciduous Forest_A	1	0.0001	30	0.003
10	Deciduous Forest_B	63	0.3132	55	17.226
11	Deciduous Forest_B/D	17	0.0561	77	4.3197
12	Deciduous Forest_C	414	2.6861	70	188.027
13	Deciduous Forest_D	48	0.1488	77	11.4576
14	Developed, Low Intensity_	2	0.0003	0	0
15	Developed, Low Intensity_B	4	0.0027	65	0.1755
16	Developed, Low Intensity_B/D	2	0.0004	65	0.026
17	Developed, Low Intensity_C	61	0.0326	77	2.5102
18	Developed, Low Intensity_D	2	0.0005	82	0.041
19	Developed, Medium Intensity_C	6	0.0033	80	0.264
20	Developed, Open Space_	1	0	0	0
21	Developed, Open Space_	2	0	0	0
22	Developed, Open Space_A	3	0.0013	49	0.0637
23	Developed, Open Space_B	88	0.0451	69	3.1119
24	Developed, Open Space_B/D	24	0.0151	69	1.0419
25	Developed, Open Space_C	479	0.2928	79	23.1312
26	Developed, Open Space_D	59	0.0376	84	3.1584
27	Evergreen Forest_B	23	0.0118	55	0.649
28	Evergreen Forest_B/D	1	0.0014	77	0.1078
29	Evergreen Forest_C	56	0.0892	70	6.244
30	Hay/Pasture_	2	0	0	0
31	Hay/Pasture_	4	0.0038	0	0
32	Hay/Pasture_A	1	0.0057	39	0.2223
33	Hay/Pasture_B	64	0.227	61	13.847
34	Hay/Pasture_B/D	22	0.1323	80	10.584
35	Hay/Pasture_C	598	2.6946	74	199.4
36	Hay/Pasture_D	53	0.2884	80	23.072
37	Herbaceuous_	1	0.0006	0	0
38	Herbaceuous_C	5	0.0099	71	0.7029
39	Mixed Forest_B	42	0.0689	55	3.7895
40	Mixed Forest_B/D	11	0.007	77	0.539
41	Mixed Forest_C	287	0.4857	70	33.999
42	Mixed Forest_D	19	0.0285	77	2.1945
43	Open Water_	1	0.0033	10	0.33
44	Open Water_D	1	0.0006	10	0.06
45	Shrub/Scrub_B	7	0.0018	58	0.1044
46	Shrub/Scrub_B/D	2	0.0008	79	0.0632
47	Shrub/Scrub_C	52	0.0553	72	3.9816
48	Shrub/Scrub_D	3	0.0121	79	0.9559
49	Woody Wetlands_	3	0.0028	0	0
50	Woody Wetlands_B	1	0	10	0
51	Woody Wetlands_B/D	4	0.0103	10	1.03
52	Woody Wetlands_C	7	0.0017	10	0.17
53	Woody Wetlands_D	5	0.0048	10	0.48

The following figure shows the map of the lower-mid sub-basin and the east branch sub-basin, as well as information relating the areas and curve numbers.

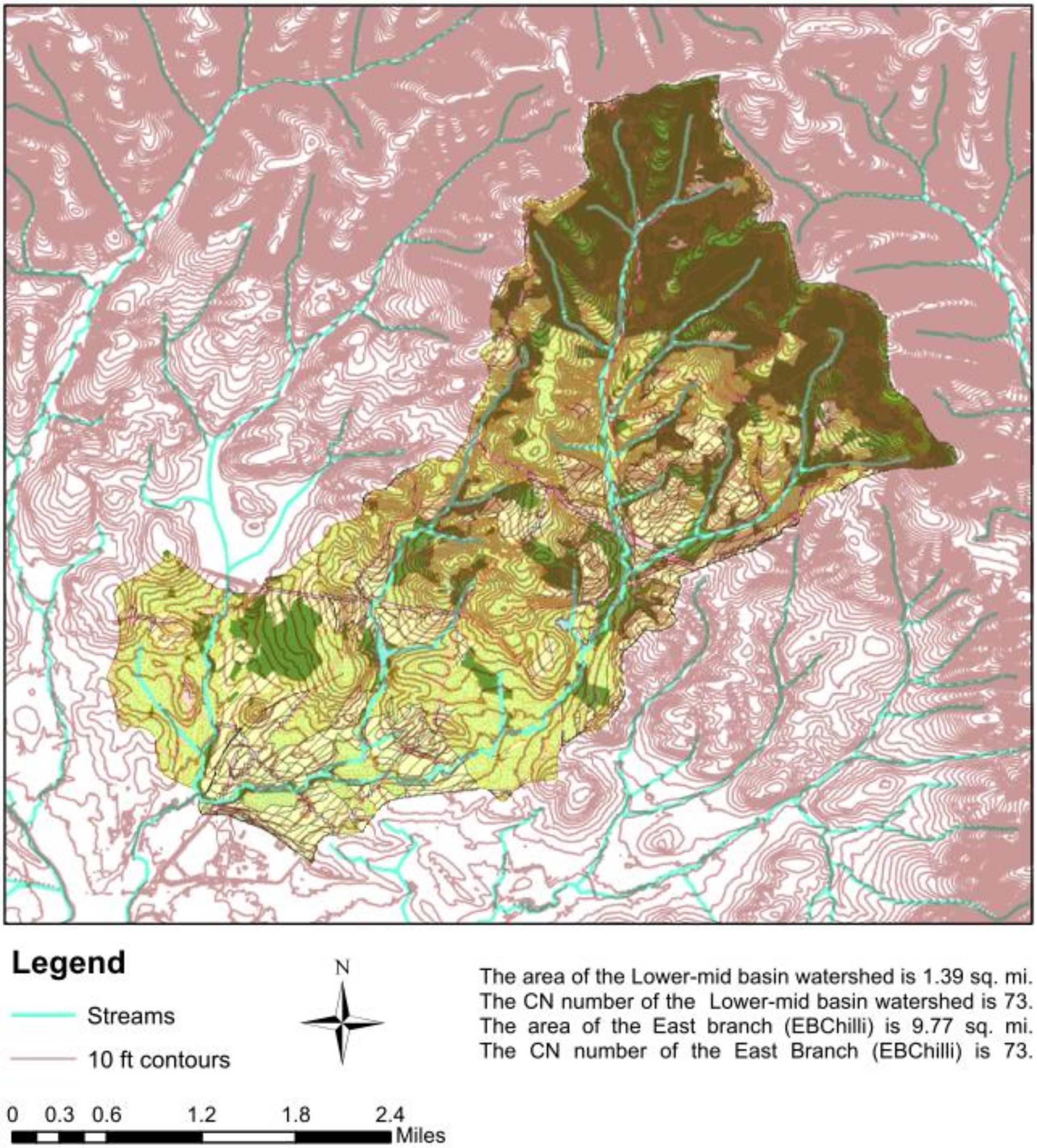


Figure 3. Map of the lower-mid sub-basin and the east branch sub-basin, areas and curve numbers

3.3. The time of concentration for each sub-basin was obtained by means of the SCS (NRCS) Procedure. This involved assessing the slope as a function of length along the path of longest travel; allocating into three subcategories: sheet flow, shallow concentrated flow and open channel flow; and totaling the travel time along each. Table 5 shows the measurements done along the first 1683 feet of flow in the east branch sub-basin, which include sheet flow along the first 100 feet and shallow concentrated flow.

Table 5. Travel time for overland sheet flow and shallow concentrated flow of the East Branch, assuming woods with medium underbrush, n = 0.6

Height (ft)*	*ΔL (ft)*	*Length L (ft)*	*Slope S_0 (ft/ft)*	*ΔT_{t1} / ΔT_{t2} (hr)*
1240	100	100	0.028	0.422
	260	360	0.028	0.027
1230	66	426	0.152	0.003
1220	46	472	0.217	0.002
1210	24	496	0.417	0.001
1200	24	520	0.417	0.001
1190	21	541	0.476	0.001
1180	24	565	0.417	0.001
1170	22	587	0.455	0.001
1160	24	611	0.417	0.001
1150	26	637	0.385	0.001
1140	26	663	0.385	0.001
1130	27	690	0.370	0.001
1120	21	711	0.476	0.001
1110	51	762	0.196	0.002
1100	30	792	0.333	0.001
1090	42	834	0.238	0.001
1080	34	868	0.294	0.001
1070	37	905	0.270	0.001
1060	41	946	0.244	0.001
1050	44	990	0.227	0.002
1040	39	1029	0.256	0.001
1030	43	1072	0.233	0.002
1020	55	1127	0.182	0.002
1010	61	1188	0.164	0.003
1000	51	1239	0.196	0.002
990	54	1293	0.185	0.002
980	52	1345	0.192	0.002
970	72	1417	0.139	0.003
960	52	1469	0.192	0.002
950	64	1533	0.156	0.003
940	86	1619	0.116	0.004
930	64	1683	0.156	0.003
**Assume Starting Height = 1230 ft*			**T_{t1}+T_{t2} (hr) =**	**0.499**

The equation used for sheet flow time T_{t1} is $T_{t1} = [0.007(nL)^{0.8}]/(P_2^{0.5}s^{0.4})$; where T_{t1} is the time in hours, n is Manning's roughness for sheet flow (assumed n = 6), P_2 is the 2-year, 24-hour precipitation depth in inches and s is the land slope, i.e. S_0.

For the shallow concentrated flow (after 100 feet), the time T_{t2} is given by $T_{t2} = L/V$, where T_{t2} is the time in seconds and $V = 16.1345s^{0.5}$ in feet per second.

Table 6 shows the travel distance L and the slope for the remainder of the path to the point of interest of the east branch. Adding the total time from tables 5 and 6 gives a total travel time of 4.05 hours for the east sub-basin.

Table 6. Travel time for open channel flow of the East Branch

H (ft)	*L* (ft)	*Δ L* (ft)	S_0 (ft/ft)	*V* (ft/s)	ΔT_{t3} (hr)			
920	530	530	0.01887	4.505	0.033	**East Branch Chillisquake Creek**		
910	1219	689	0.01451	3.951	0.048	**(upper portion)**		
900	1857	638	0.01567	4.106	0.043	Bottom Width b	19	ft
890	2580	723	0.01383	3.857	0.052	Depth y	1.1	ft
860	3035	455	0.06593	8.422	0.015	Area A	20.9	ft^2
820	4614	1579	0.02533	5.220	0.084	Wetted Perimeter P	21.2	ft
790	5478	864	0.03472	6.112	0.039	Hydraulic Radius Rh	0.99	ft
760	6392	914	0.03282	5.942	0.043	Manning's n	0.045	
750	7648	1256	0.00796	2.927	0.119			
740	8047	399	0.02506	5.192	0.021			
730	8241	194	0.05155	7.446	0.007			
720	8388	147	0.06803	8.554	0.005			
710	8752	364	0.02747	5.436	0.019			
680	10478	1726	0.01738	4.324	0.111			
670	11316	838	0.01193	3.583	0.065			
660	11789	473	0.02114	4.769	0.028			
650	12427	638	0.01567	4.106	0.043			
640	14817	2390	0.00418	2.122	0.313			
630	17280	2463	0.00406	2.090	0.327			
620	18847	1567	0.00638	3.679	0.118	**East Branch Chillisquake Creek**		
610	20066	1219	0.00820	4.171	0.081	**(lower portion)**		
600	21580	1514	0.00661	3.743	0.112	Bottom Width b	37	ft
590	23812	2232	0.00448	3.083	0.201	Depth y	1.8	ft
580	25343	1531	0.00653	3.722	0.114	Area A	66.6	ft^2
570	28012	2669	0.00375	2.819	0.263	Wetted Perimeter P	40.6	ft
560	30544	2532	0.00395	2.894	0.243	Hydraulic Radius Rh	1.64	ft
550	33629	3085	0.00324	2.622	0.327	Manning's n	0.045	
540	36435	2806	0.00356	2.749	0.284			
530	39933	3498	0.00286	2.462	0.395			
			T_{t3} (hr) =		**3.55**			

H is height, L is distance traveled, S_0 is the slope of the channel, V is velocity & Tt3 is travel time for open channel flow

The velocity of the flow in Table 6 was estimated using Manning's equation, given by $V = (1.49/n)(R_h)^{2/3}(S_e)^{1/2}$, where n is Manning's coefficient, R_h is the hydraulic radius in feet, and S_e is the slope of the EGL (assume equal to S_0). The time T_{t3} in seconds was obtained from $T_{t3} = L/V$.

Similarly, the travel time for the lower-mid basin was obtained using Manning's equation because the entire path from the reservoir to the point of interest was channel flow. The time is 0.816 hours as shown in Table 7.

Table 7. Travel time for open channel flow of the Lower-Mid Branch

***H* (ft)**	***L* (ft)**	***Δ L* (ft)**	***S_0* (ft/ft)**	***V* (ft/s)**	***$ΔT_{t3}$* (hr)**	**Middle Branch Chillisquake Creek (below reservoir)**		
560	980	980	0.01020	4.117	0.066	Bottom Width b	30.5	ft
550	3356	2376	0.00421	2.644	0.250	Depth y	1.5	ft
540	5651	2295	0.00436	2.690	0.237	Area A	45.75	ft^2
530	8115	2464	0.00406	2.596	0.264	Wetted Perimeter P	33.5	ft
			T_{t3} (hr) =		**0.816**	Hydraulic Radius Rh	1.37	ft
						Manning's n	0.045	

H is height, L is distance traveled, S_0 is the slope of the channel, V is velocity & Tt3 is travel time for open channel flow

Lastly, for the upper-mid basin, all three travel time equations were used to obtain the total travel time of 3.30 hours. This is shown in Table 8.

Table 8. Time of Concentration of the Upper-Mid Branch

***H* (ft)**	***L* (ft)**	***Δ L* (ft)**	***S_0* (ft/ft)**	***V* (ft/s)**	***$ΔT_{t1}$ / $ΔT_{t2}$* (hr)**			
830	100	100	0.01300	-	0.574	<-Overland Sheet Flow		
	771	661	0.01300	1.84	0.100	P_2 = 0.14 in/hr ; 24 hr		
820	1681	910	0.01099	1.691	0.149			
810	2739	1058	0.00945	1.569	0.187	Assume wood with medium underbrush		
800	3900	1161	0.00861	1.497	0.215			
790	5215	1315	0.00760	1.407	0.260	n = 0.6		
780	6735	1520	0.00658	1.309	0.323			
			T_{t1}+T_{t2} (hr) =		**1.808**			
***H* (ft)**	***L* (ft)**	***Δ L* (ft)**	***S_0* (ft/ft)**	***V* (ft/s)**	***$ΔT_{t3}$* (hr)**	**Middle Branch Chillisquake Creek (above reservoir)**		
770	1645	1645	0.03040	7.106	0.064	Bottom Width b	30.5	ft
720	3838	2193	0.02280	6.154	0.099	Depth y	1.5	ft
670	11203	7365	0.00679	3.358	0.609	Area A	45.75	ft^2
620	13665	2462	0.00406	2.598	0.263	Wetted Perimeter P	33.5	ft
610	17211	3546	0.00282	2.164	0.455	Hydraulic Radius Rh	1.37	ft
			T_{t3} (hr) =		**1.49**	Manning's n	0.045	
		T_{t1}+T_{t2}+T_{t3} (hr)=			**3.30**			

H is height, L is distance traveled, S_0 is the slope of the channel, V is velocity & Tt3 is travel time for open channel flow