Variability in Time of Concentration with Finite Increment Computations

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Abstract

The Soil Conservation Service's (SCS) time of concentration calculation methodology is one of the most universally used methods when computing the time of concentration for a hydrologic basin. The approach is to break up the path of a drop of water into three distinct flow types: (1) sheet flow for up to the first 300 feet of flow length, (2) shallow concentrated flow from the point at which sheet flow ends, and (3) stream flow from the point the flow enters a well-defined channel. By using the raster calculation functions available within ArcView 9.1 along with the Spatial Analyst Extension, the effects of finite increment calculations on the results of the SCS equations are examined. This paper presents the potentially large variability in time of concentration calculations introduced by performing the calculations as the cumulative of finite increment calculations.

Background

Currently in the area of water resources, and more specifically stormwater engineering, the methods being used date back to well before the age of computers. While these methods are still based in good engineering science, the assumptions and limitations that accompany them are sometimes overlooked when using them in engineering analyses. Out of necessity, the science of performing stormwater studies was based on simplifications of real world processes in order to actually perform the calculations. For example, when these methods were first proposed, computers were not available to perform fully dynamic flow routing even though the equations were first put forth decades earlier. These simplifications, when applied as the engineers and researchers had intended, did a great deal to further stormwater engineering.

The capabilities to perform most any type of advanced calculation have greatly expanded in today's modern, computer-driven world. This is not to say that the widely accepted stormwater analysis methods are out of date, however, greater care must be exercised when choosing methods, the data to be used in the chosen method(s), and the way in which this data is computed/analyzed. This paper focuses on the latter – the way the data to be used in stormwater runoff analyses is synthesized for use. More specifically, this paper focuses on the applicability of the current methodology of computing the time of concentration and lag time parameters for a drainage basin to be analyzed for stormwater runoff.

Synthetic unit hydrograph methods imply that the maximum runoff rate for a drainage basin is indirectly proportional to the rate at which precipitation excess moves from the most hydraulically remote point through the basin to the outlet, also known as the time of concentration. Therefore, it is very important to compute the most accurate time of concentration for the basin as possible. This paper presents a look into the inherent variability in these calculations and, perhaps more importantly, a recommendation that these time of concentration values should not simply be "accepted" without further investigation of their appropriateness.

Study Area

The study area is roughly an 18 square mile watershed that covers the vast majority of a rapidly developing city. The main stem runs directly through the historic downtown area and had a history of significant flooding prior to 1997. In 1997, a significant flood control project was completed, involving the construction of levees at the upstream and downstream ends of a conduit system designed to completely contain the creek. The study hereinafter referred to as the ‘Original Study’ was performed by AMEC Earth and Environmental, Inc., in order to more accurately depict the flood hazards of this dynamic system.

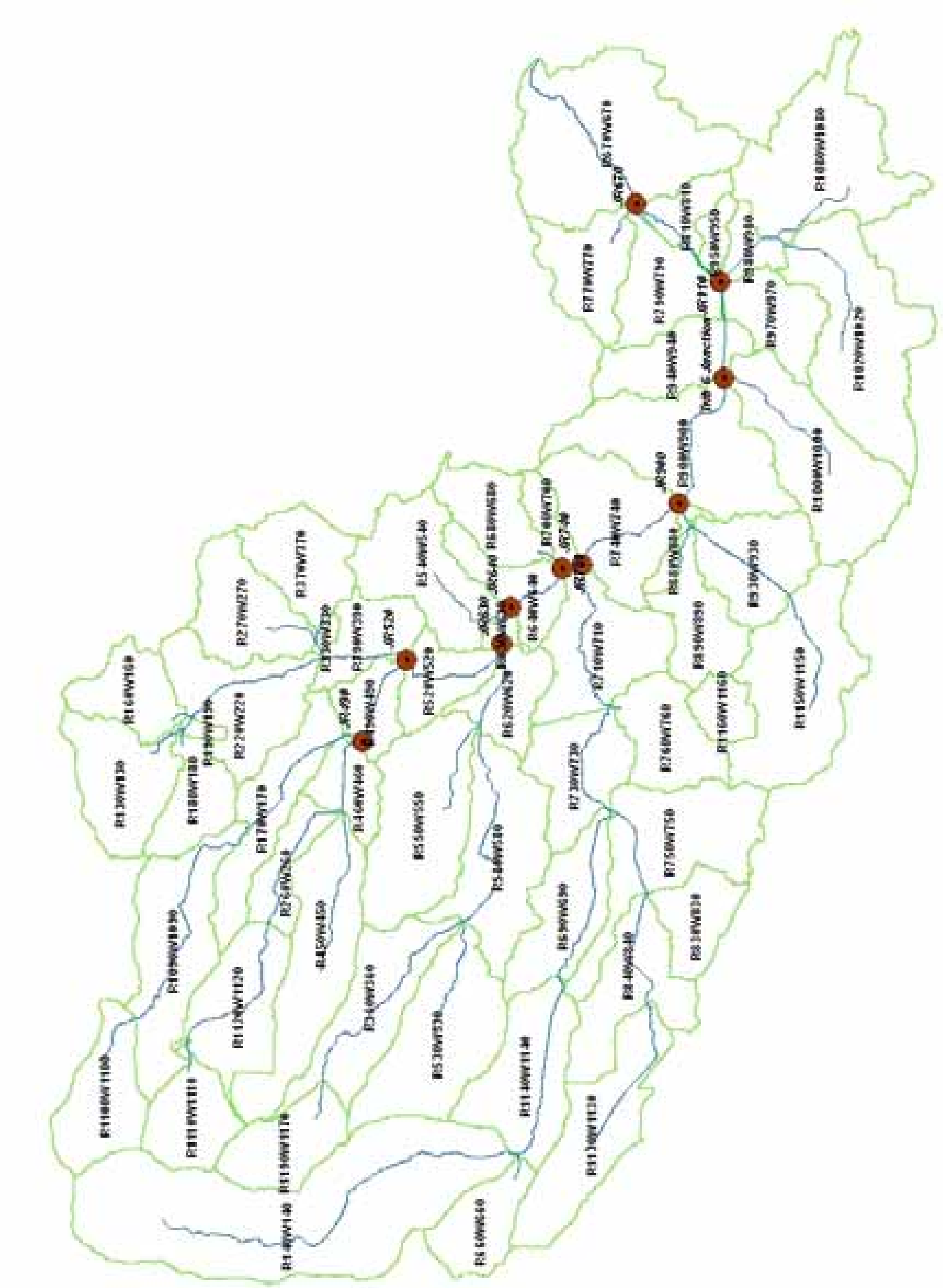

Figure 1. Basin layout of study area with reported junction locations.

Analysis Methodology

The analysis methodology used for this study was to divide the time of concentration flowpath into finite increments based on the grid cell size of the digital elevation model (DEM), 3 feet by 3 feet cells for this study. In order to ensure consistency in comparing this time of concentration methodology with the original hydrologic study described in the preceding section, the flowpaths used were the same as in the original study, the only difference being in the way that the time of concentration was computed for each drainage basin.

Typically a flowpath is broken into three distinct segments – one for each flow regime that is assumed to occur along its length. There can be more than three segments, however, if the characteristics of the basin's land surface vary substantially within one or more flow regimes. For instance, the open channel flow segment of a flowpath can be open channel for part of the channel flow and a culvert for the remaining part of the flowpath requiring that this flow regime be broken into two sub-segments within the open channel computations. This method ignores the local elevation variability and produces a length-weighted time of concentration.

The methodology employed for this study was to compute the time of concentration from cell to cell along the flowpath. This allowed for the most realistic values of landuse and computed slope which are required for the calculation of time of concentration. As described in TR-55 (SCS, 1986) the three flow regimes and their equations for travel time are given as follows:

Sheet Flow:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5} s^{0.4}}$$

where:

T_t = travel time (hr)

n = Manning's roughness coefficient

L = Flow length

P_2 = 2 year, 24 hour rainfall (in)

s = slope of hydraulic grade line (land slope, ft/ft)

Shallow Concentrated Flow:

In order to compute velocities for shallow concentrated flow, the equation given in the FHWA HEC 22 manual was used. This equation computes travel time based on the length of flow, the slope of the flow path, and an intercept coefficient that relates to the surface characteristics of the flow path. This equation is given as:

$$T_t = \frac{L}{60k\sqrt{S}}$$

where:

L = length of flow segment (ft)

k = intercept coefficient (ranges from 0.076 for forest with heavy ground litter, hay meadow to 0.619 for Paved area, small upland gullies)
S = slope of ground (%)

Open Channel Flow:

$$V = \frac{1.49 r^{\frac{2}{3}} s^{\frac{1}{2}}}{n}$$

where:
V = Average velocity (ft/sec)
r = hydraulic radius (ft)
s = slope of hydraulic grade line (land slope, ft/ft)
n = Manning’s roughness coefficient for open channel flow

These equations were used on a cell to cell basis for both the sheet flow and shallow concentrated flow regimes in order to compute a cumulative, finite increment time of concentration. The open channel travel times were not changed from the original model. The results of these calculations are shown in **Table 1** below along with time of concentrations computed in the original study. For cases in which the elevation did not change from a cell to its downstream neighbor, the average slope for the entire watershed was used to prevent having a slope of 0.0 ft/ft.

Table 1. Time of concentration for each basin within the study area

Basin	Original Study Tc	Adjusted Tc	Percent Difference
R1000W1000	130	137	5
R1020W1020	130	148	14
R1080W1080	113	135	19
R1090W1090	57	93	65
R1100W1100	38	67	74
R1110W1110	30	65	117
R1120W1120	33	70	110
R1130W1130	35	50	43
R1140W1140	55	58	6
R1150W1150	60	72	19
R1160W1160	30	42	39
R1190W1170	77	102	33
R130W130	40	53	33
R140W140	73	90	23
R160W160	100	115	15
R170W170	73	85	16
R180W180	38	48	26
R190W190	20	27	33
R220W220	67	78	18
R260W260	30	40	33
R270W270	42	80	92
R360W360	38	70	83
R370W370	73	128	75
R390W390	43	53	23

R450W450	87	117	35
R460W460	38	68	78
R490W490	48	58	21
R520W520	62	75	22
R530W530	107	138	30
R540W540	75	87	16
R550W550	118	125	6
R580W580	47	55	18
R620W620	42	48	16
R630W630	13	15	13
R640W640	32	37	16
R660W660	65	98	51
R670W670	83	97	16
R680W680	60	68	14
R690W690	38	45	17
R700W700	58	63	9
R710W710	38	42	9
R730W730	32	50	58
R740W740	40	63	58
R750W750	75	92	22
R760W760	23	23	0
R760AW760A	40	55	38
R770W770	32	35	11
R790W790	28	40	41
R810W810	50	53	7
R830W830	30	43	44
R840W840	57	67	18
R880W880	43	58	35
R890W890	37	52	41
R900W900	30	65	117
R930W930	20	62	208
R940W940	37	60	64
R950W950	23	27	14
R970W970	65	70	8
R980W980	27	30	13
Median	42	63	23
Standard Deviation	27.8	31.2	36.5
Mean	53	69	37

The next step in this study was to determine the effects of these timing changes on the computed flow at the outlet of each basin and the watershed as a whole. This is important as these numbers are the goal of virtually every stormwater study. As can be seen in **Table 2**, the time of concentration change has an obvious effect on the runoff characteristics of a basin. Fortunately, the effects on this study tend to reduce the peak flows so that, in general, the peak flows will not be underestimated, however, the timing effects are changed substantially as well which could impact design storage volumes.

Table 2. Comparison of peak flows and times to peak.

Basin		**Original Run**	**Adjusted Run**	**Comparison**

	Drainage Area	Peak Flow	Time to Peak	Peak Flow	Time to Peak	Peak Flow Reduction	Time to Peak Delay
	(mi^2)	(cfs)	(HH:MM)	(cfs)	(HH:MM)	(cfs)	(HH:MM)
R1000W1000	0.496	390.99	13:26	378.31	13:30	12.68	0:04
R1020W1020	0.595	432.66	13:27	396.17	13:39	36.49	0:12
R1080W1080	0.543	443.53	13:16	396.03	13:30	47.5	0:14
R1090W1090	0.452	566.36	12:38	427.18	13:03	139.18	0:25
R1100W1100	0.278	265.11	12:28	198.91	12:48	66.2	0:20
R1110W1110	0.215	229.81	12:22	156.02	12:46	73.79	0:24
R1120W1120	0.323	443.08	12:23	303.13	12:48	139.95	0:25
R1130W1130	0.408	793.85	12:23	667.39	12:33	126.46	0:10
R1140W1140	0.372	556.76	12:36	539.72	12:39	17.04	0:03
R1150W1150	0.538	768.89	12:40	697.34	12:47	71.55	0:07
R1160W1160	0.097	209.87	12:20	180.11	12:27	29.76	0:07
R1190W1170	0.234	195.13	12:53	165.03	13:10	30.1	0:17
R130W130	0.314	562.66	12:27	487.28	12:35	75.38	0:08
R140W140	1.238	985.93	12:51	875.07	13:03	110.86	0:12
R160W160	0.196	204.95	13:06	188.02	13:16	16.93	0:10
R170W170	0.301	344.27	12:49	316.23	12:57	28.04	0:08
R180W180	0.185	338.28	12:25	302	12:32	36.28	0:07
R190W190	0.019	44.4	12:13	39.37	12:18	5.03	0:05
R220W220	0.361	435.5	12:45	397.62	12:52	37.88	0:07
R260W260	0.146	262.35	12:20	229.56	12:27	32.79	0:07
R270W270	0.288	496.1	12:28	350.7	12:53	145.4	0:25
R360W360	0.363	610.39	12:26	446.76	12:47	163.63	0:21
R370W370	0.249	361.29	12:48	258.74	13:23	102.55	0:35
R390W390	0.181	312	12:29	280.89	12:35	31.11	0:06
R450W450	0.483	513.93	12:58	428.91	13:17	85.02	0:19
R460W460	0.136	185.72	12:26	137.62	12:47	48.1	0:21
R490W490	0.139	174.33	12:33	157.98	12:40	16.35	0:07
R520W520	0.165	150.11	12:43	134.54	12:52	15.57	0:09
R530W530	0.475	446.14	13:11	377.7	13:31	68.44	0:20
R540W540	0.358	496.66	12:49	457.13	12:56	39.53	0:07
R550W550	0.494	434.73	13:18	419.73	13:23	15	0:05
R580W580	0.441	595.17	12:32	546.74	12:37	48.43	0:05
R620W620	0.168	213.84	12:29	198.5	12:33	15.34	0:04
R630W630	0.032	66.31	12:09	63.37	12:10	2.94	0:01
R640W640	0.169	296.35	12:22	277	12:25	19.35	0:03
R660W660	0.197	223.18	12:44	175.69	13:06	47.49	0:22
R670W670	0.750	554.8	12:58	507.83	13:07	46.97	0:09
R680W680	0.210	248.52	12:41	231.38	12:46	17.14	0:05
R690W690	0.297	521.63	12:26	482.55	12:30	39.08	0:04
R700W700	0.074	88.91	12:40	85.04	12:43	3.87	0:03
R710W710	0.356	571.31	12:26	548.74	12:28	22.57	0:02
R730W730	0.278	427.55	12:22	342.64	12:34	84.91	0:12
R740W740	0.376	517.95	12:28	408.64	12:43	109.31	0:15
R750W750	0.467	647.88	12:49	577.12	13:00	70.76	0:11

R760W760	0.093	235.26	12:15	235.26	12:15	0	0:00
R760W760A	0.153	304.23	12:26	259.45	12:36	44.78	0:10
R770W770	0.240	430.99	12:21	411.62	12:24	19.37	0:03
R790W790	0.236	403.08	12:19	343.72	12:27	59.36	0:08
R810W810	0.110	119.83	12:35	115.87	12:37	3.96	0:02
R830W830	0.177	355.39	12:20	299.11	12:29	56.28	0:09
R840W840	0.319	498.08	12:37	456.24	12:44	41.84	0:07
R880W880	0.046	67.85	12:29	58.22	12:39	9.63	0:10
R890W890	0.214	367.49	12:25	310.18	12:35	57.31	0:10
R900W900	0.475	914.48	12:20	622.91	12:43	291.57	0:23
R930W930	0.292	638.85	12:14	376.56	12:41	262.29	0:27
R940W940	0.242	493.77	12:24	385.85	12:39	107.92	0:15
R950W950	0.054	64.4	12:17	60.8	12:19	3.6	0:02
R970W970	0.202	203.88	12:45	195.65	12:48	8.23	0:03
R980W980	0.078	114.5	12:19	108.69	12:21	5.81	0:02

As one last step, the effects at each junction or confluence were inspected to assess the impact time of concentration changes have as stream hydrographs are combined. As can be seen from **Table 3**, the impacts

Table 3. Peak flow and times for original and adjusted model.

Junction (along main stem)		**Original Run**		**Adusted Run**			
	Drainage Area	**Peak Flow**	**Time to Peak**	**Peak Flow**	**Time to Peak**	**Peak Flow Reduction**	**Time to Peak Delay**
	(mi^2)	**(cfs)**	**(HH:MM)**	**(cfs)**	**(HH:MM)**	**(cfs)**	**(HH:MM)**
JR490	2.334	2507.91	12:47	1988.17	13:10	519.74	0:23
JR520	4.266	5091.98	12:48	3993.01	13:06	1098.97	0:18
JR630	6.606	7060.28	12:52	5740.66	13:11	1319.62	0:19
JR640	6.996	7536.84	12:53	6156.11	13:12	1380.73	0:19
JR700	7.375	7820.2	12:56	6387.95	13:14	1432.25	0:18
JR740	11.901	12607.42	12:56	10649.83	13:09	1957.59	0:13
JR900	13.367	13930.06	12:58	12015.74	13:10	1914.32	0:12
Trib 6 Junction	14.338	14552.95	13:09	12789.34	13:20	1763.61	0:11
JR810	16.052	15601.78	13:21	13785.69	13:32	1816.09	0:11
JR670	16.638	15613.04	13:30	13859.99	13:41	1753.05	0:11

Table 4. Percent differences in peak flow.

Junction (along main stem)	**Percent Difference in Peak Flow**
JR490	20.7
JR520	21.6
JR630	18.7
JR640	18.3

JR700	18.3
JR740	15.5
JR900	13.7
Trib 6 Junction	12.1
JR810	11.6
JR670	11.2

Conclusions

The conclusion of this study is that caution should be exercised when representing the runoff characteristics of a basin with one time of concentration value. It should be apparent from this paper that the computed time of concentration can vary by as much as 2 times the traditionally computed value and it would be wise to investigate the effects this can have on predicted flow as well as time to peak. As an extra precaution, the actual time of concentration used should be inspected and verified against any data available that shows a basin's true runoff characteristic for that storm.

For instance, any streamflow gages found in the watershed being studied should be used to verify whether or not the hydrologic model can reproduce the measured flow within certain tolerances. If no streamflow gages are available, high water marks can be used to determine the accuracy of the flow predictions or USGS values of flow per unit area can be used as a rule of thumb. The point being the values produced by the hydrologic model should not simply be "accepted" without some type of verification. In some cases, the basin may be so hydrologically unique that a synthetic hydrograph approach may not even be applicable due to things such as urbanization or significant storage areas.

In conclusion, this paper investigated only one commonly employed method to compute one commonly used parameter in hydrologic models. There are many other inputs that go into developing a hydrologic model to support a stormwater study and every one of these inputs should be examined and understood before accepting any model as final. As one additional step, one may even want to perform a sensitivity analysis to better understand the impacts each parameter has on the model predictions.

Acknowledgements

References

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