COMPLIANCE

storm water awareness week

WATERSHED SURFACE AND CHANNEL RUNOFF COEFFICIENT ASSESSMENT WITH UNIFIED RUNOFF TIME IMPLICATIONS

AN EVALUATION OF ESTIMATING THE TIME OF CONCENTRATION TO DETERMINE PEAK RUNOFF FLOWS FOR SMALL WATERSHED BASINS

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Factors Affecting Stormwater Runoff:

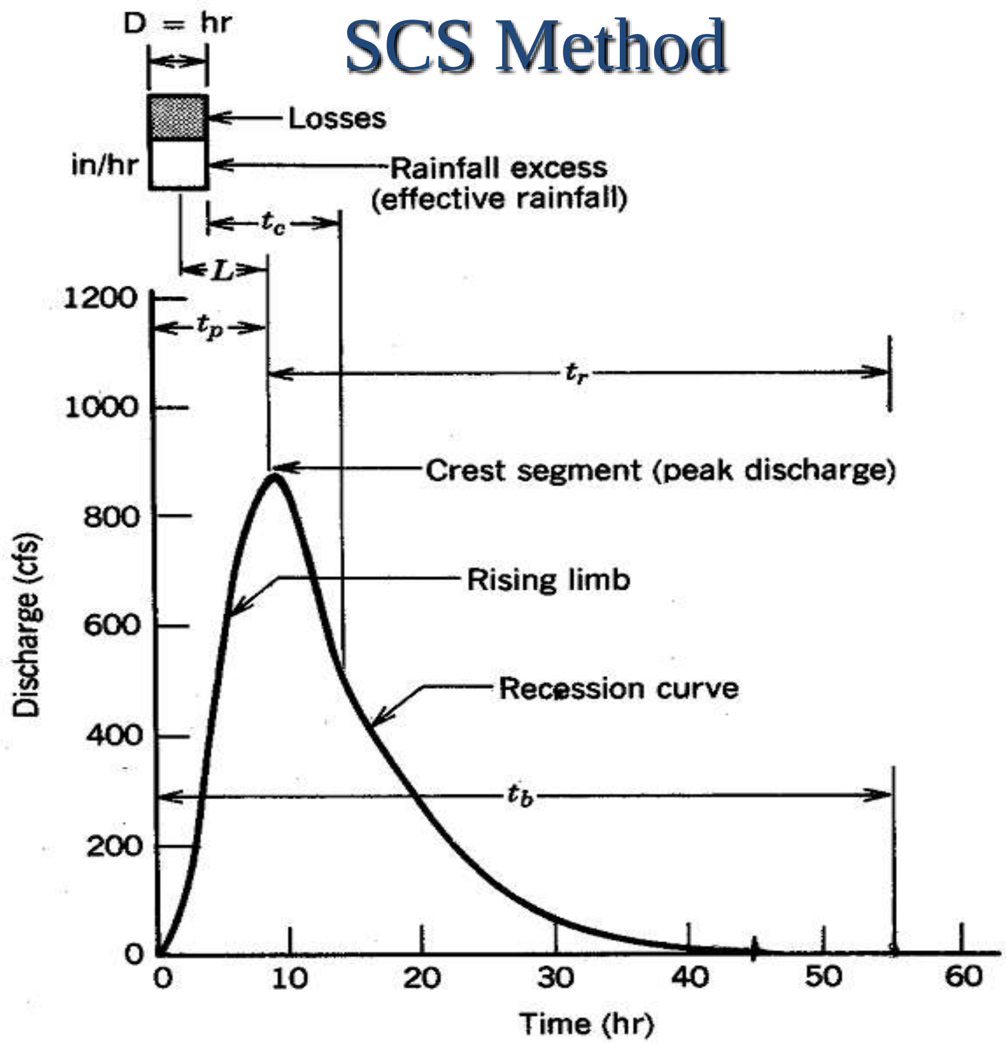
- **Surface Conditions / Soil Type**
- **Watershed Size / Length of Runoff**
- **Basin Slope / Rainfall Depth**

This Presentation Offers Insight to T_c Calculations & T_c Analogies in Small Watersheds for the Following:

- Four Types of Surface Runoff Coefficients are Evaluated & Compared to Impervious Surface.
- NRCS's Segmental Equations are Calculated & Graphically Displayed by Watershed Attributes.
- Four Different T_c Empirical Equations are Compared to NRCS's Segmental Calculations.

Time of Concentration's Definition

SCS Method



Taken from Wanielista, M., R. Kersten, and R. Eaglin, *Hydrology: Water Quantity and Quality Control*, p. 184

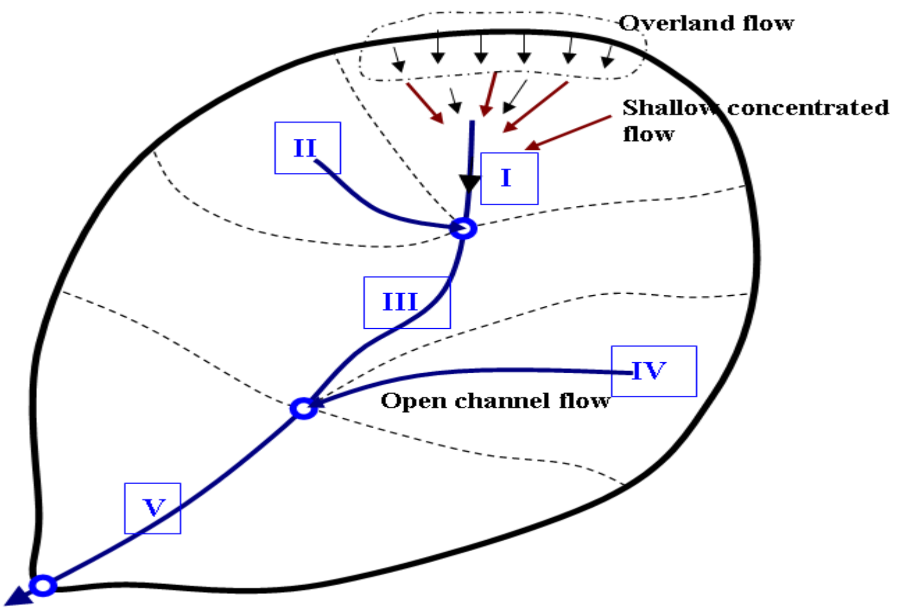
Time of Concentration t_c:

Time required for water to travel from the most hydraulically remote point in the basin to the basin outlet.

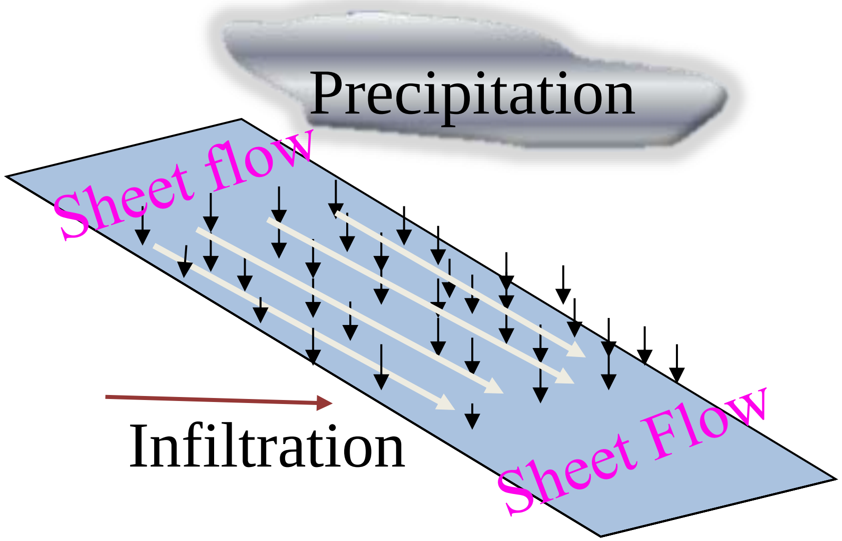
This time is determined by drainage characteristics such as surface density, slope, channel roughness, and soil infiltration. Many empirical equations have been developed through watershed research.

Velocity Equations Used in NRCS Segmental Method

- Sheet Flow – Overland Flow
- Shallow Flow (Rills and Gullies)
- Open Channel/Pipe Flow (Conveyance)



Sheet Flow



A basin unit flow expressed by an implicit channelized flow (Used in surface & channel flow)

TR-55 Sheet Flow—The sheet flow time computed for each area of sheet flow that requires the following input data:

Hydraulic Length—Defined **flow length** for the sheet flow.

Manning's n—Manning's roughness value of the sheet flow.

Slope— The defined slope of the sheet flow/catchment.

Manning's Kinematic Wave Eq.

$$T_c = \frac{0.42\,(nL)^{0.8}}{P_2^{0.5}\,S^{0.4}}$$

Where: L= Sheet Flow Length (0 < L < 100 ft)
S = Slope (ft/ft)
P = Depth 2-yr. 24-hr. Precipitation (in.)
Tc = Estimated Runoff Time (min.)

Table 15–1 Manning's roughness coefficients for sheet flow (flow depth generally ≤ 0.1 ft)

Surface description	n [1]
Smooth surface (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Grass:	
Short-grass prairie	0.15
Dense grasses [2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods: [3]	
Light underbrush	0.40
Dense underbrush	0.80

1 The Manning's n values are a composite of information compiled by Engman (1986).

2 Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

3 When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

Sheet Flow Limitations

National Engineering Handbook

Kibler and Aron (1982) and others indicated the maximum sheet flow length is less than 100 feet. To support the sheet flow limit of 100 feet, Merkel (2001) reviewed a number of technical papers on sheet flow. McCuen and Spiess (1995) indicated larger sheet flow length variables lead to less accurate designs, and proposed a limitation with equation (15–8) shown below be considered:

Eq. 15-8 $$l = \frac{100\sqrt{S}}{n}$$

where:

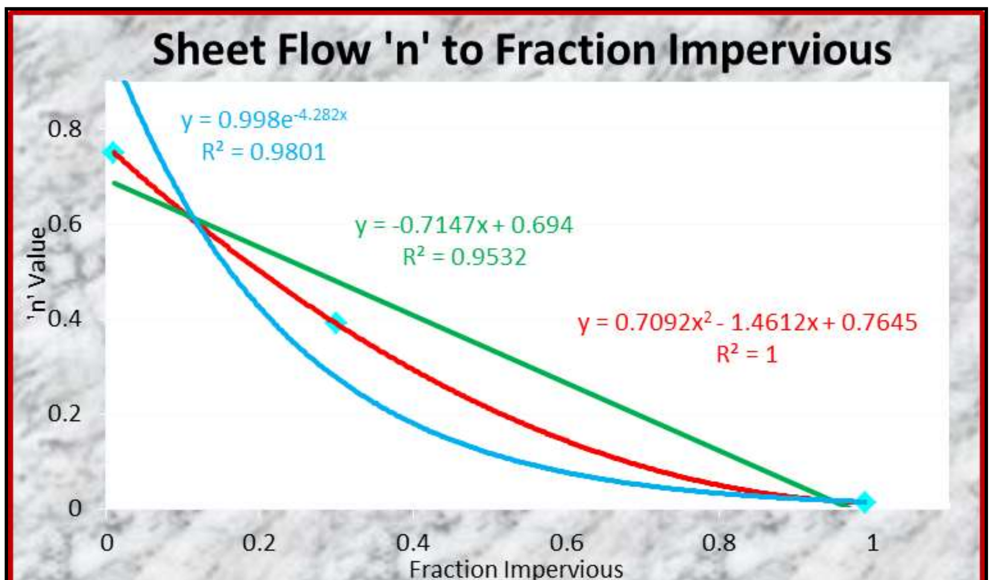
n = Manning's roughness coefficient

l = limiting length of flow (ft)

S = slope (ft/ft)

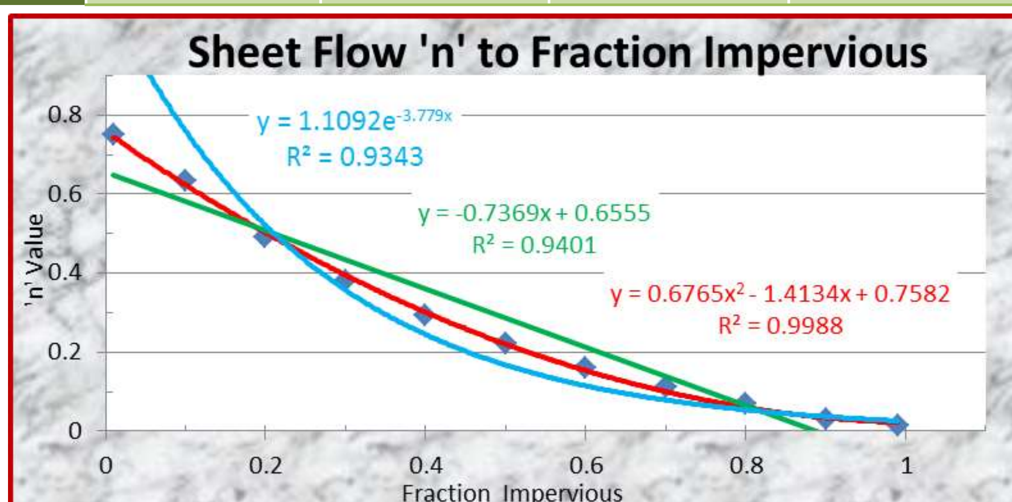
What are ‘n’ Sheet Flow Relationships to Other Surface Runoff Values?

Percent Impervious	Manning’s Low ‘n’ Sheet Flow Values	Manning’s High ‘n’ Sheet Flow Values	Manning’s Average ‘n’ Sheet Flow Values
1%	0.700	0.800	0.750
	0.450	0.550	0.500
30%	0.300	0.480	0.390
	0.160	0.420	0.290
	0.100	0.200	0.150
	0.022	0.033	0.028
99%	0.011	0.015	0.013



Sheet Flow 'n' Coefficient Interpolated to Percent Impervious Surface

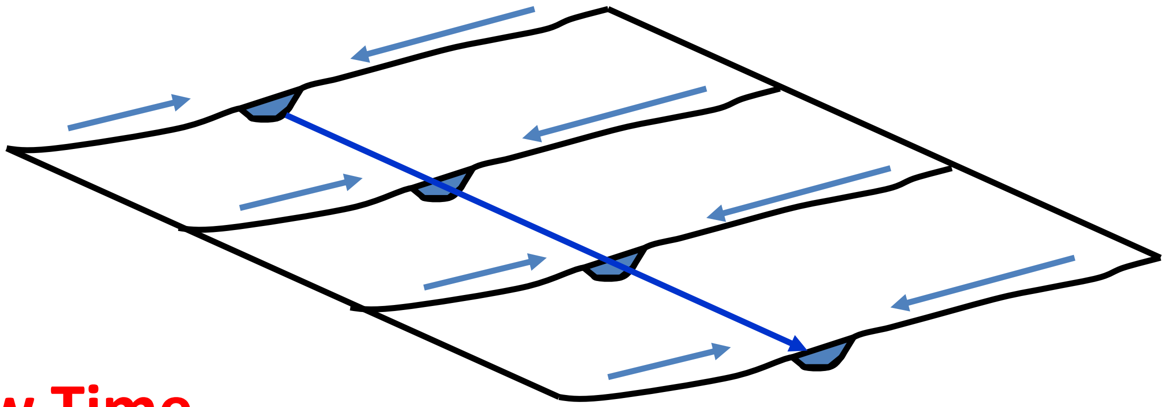
Percent Impervious	Exponential 'n' Values	Linear 'n' Values	Polynomial 'n' Values	Average 'n' Sheet Flow Values
1%	0.750	0.750	0.750	0.750
10%	0.650	0.623	0.625	0.633
20%	0.424	0.551	0.501	0.492
30%	0.276	0.480	0.390	0.382
40%	0.180	0.408	0.293	0.294
50%	0.117	0.337	0.211	0.222
60%	0.076	0.265	0.143	0.162
70%	0.050	0.194	0.089	0.111
80%	0.032	0.122	0.049	0.068
90%	0.021	0.051	0.024	0.032
99%	0.013	0.013	0.013	0.013



Shallow Concentrated Flow

$$t = \frac{L}{V}$$

Channelized Flow Time



Chapter 15

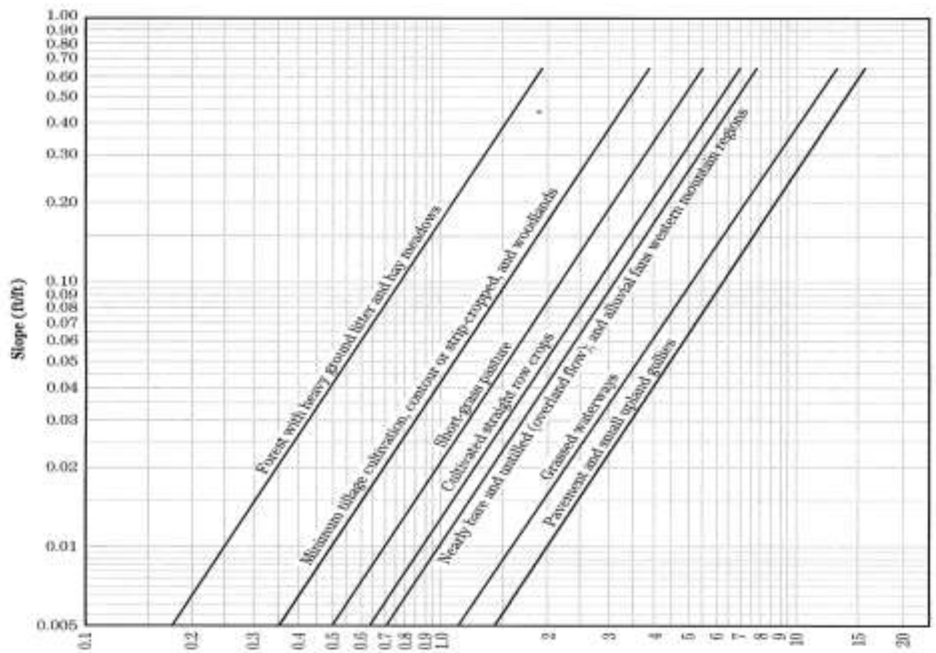
Part 630

of National

Engineering

Handbook

Figure 15–4 Velocity versus slope for shallow concentrated flow



NRCS definition of shallow flow is 1 inch to 6 inches deep

Shallow Flow Equations from NEH, May 2010

Table 15–3 Equations and assumptions developed from figure 15–4

Flow type	Depth (ft)	Manning's *n*	Velocity equation (ft/s)
Pavement and small upland gullies	0.2	0.025	$V = 20.328(s)^{0.5}$
Grassed waterways	0.4	0.050	$V = 16.135(s)^{0.5}$
Nearly bare and untilled (overland flow); and alluvial fans in western mountain regions	0.2	0.051	$V = 9.965(s)^{0.5}$
Cultivated straight row crops	0.2	0.058	$V = 8.762(s)^{0.5}$
Short-grass pasture	0.2	0.073	$V = 6.962(s)^{0.5}$
Minimum tillage cultivation, contour or strip-cropped, and woodlands	0.2	0.101	$V = 5.032(s)^{0.5}$
Forest with heavy ground litter and hay meadows	0.2	0.202	$V = 2.516(s)^{0.5}$

Shallow Flow Velocity Equations for 0.25 ft. of Depth and Manning's "n"

Mannings "n" Value	Depth of Flow (ft.)	Velocity Equations (ft./s)
0.200	0.25	$V = 2.949(s)^{0.5}$
0.160	0.25	$V = 3.686(s)^{0.5}$
0.130	0.25	$V = 4.536(s)^{0.5}$
0.110	0.25	$V = 5.361(s)^{0.5}$
0.086	0.25	$V = 6.857(s)^{0.5}$
0.067	0.25	$V = 8.802(s)^{0.5}$
0.052	0.25	$V = 11.341(s)^{0.5}$
0.039	0.25	$V = 15.121(s)^{0.5}$
0.029	0.25	$V = 20.335(s)^{0.5}$
0.022	0.25	$V = 26.805(s)^{0.5}$
0.013	0.25	$V = 45.363(s)^{0.5}$

Open Channel Flow Equation

Manning's Equation

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

Conveyance Flow for Uniform Geometry

Hydraulic Radius Can Equal Flow Depth in Manning's Eq. for Small-Wide Channels

$$T_{c\ \text{conveyance flow}} = \text{Length / Velocity}$$

NRCS's considers 6 in. or deeper to be channel flow

An initial **8** in. depth is used to initiate channel flows & increased to **16** in. depth for an average depth of **1** ft.

Manning's 'n' Channel Coefficients

Table 3-1 Manning's 'n' Values

Type of Channel and Description	Minimum	Normal	Maximum
A. *Natural Streams*			
1. **Main Channels**			
a. Clean, straight, full, no rifts or deep pools	0.025	0.030	0.033
b. Same as above, but more stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Same as above, but some weeds and stones	0.035	0.045	0.050
e. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as "d" but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy. deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.070	0.100	0.150
2. **Flood Plains**			
a. Pasture no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
2. Same as above, but heavy sprouts	0.050	0.060	0.080
3. Heavy stand of timber, few down trees, little undergrowth, flow below branches	0.080	0.100	0.120
4. Same as above, but with flow into branches	0.100	0.120	0.160
5. Dense willows, summer, straight	0.110	0.150	0.200
3. **Mountain Streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged**			
a. Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070

From USACE, January 2010, *HEC-RAS River Analysis System, Hydraulic Reference Manual*, Version 4.1.

Velocity Equations with an 8 to 16 Inch Flow Depth for a Channel "n" Value

Mannings "n" Value	Initial Depth of Flow (ft.)	Velocity Equations (ft./s)	Ending Depth of Flow (ft.)	Velocity Equations (ft./s)
0.140	0.67	$V = 8.127(s)^{0.5}$	1.35	$V = 13.157(s)^{0.5}$
0.120	0.67	$V = 9.482(s)^{0.5}$	1.35	$V = 15.349(s)^{0.5}$
0.100	0.67	$V = 11.378(s)^{0.5}$	1.35	$V = 18.419(s)^{0.5}$
0.085	0.67	$V = 13.386(s)^{0.5}$	1.35	$V = 21.670(s)^{0.5}$
0.074	0.67	$V = 15.376(s)^{0.5}$	1.35	$V = 24.891(s)^{0.5}$
0.057	0.67	$V = 19.962(s)^{0.5}$	1.35	$V = 32.314(s)^{0.5}$
0.042	0.67	$V = 27.091(s)^{0.5}$	1.35	$V = 43.855(s)^{0.5}$
0.034	0.67	$V = 33.465(s)^{0.5}$	1.35	$V = 54.174(s)^{0.5}$
0.027	0.67	$V = 42.141(s)^{0.5}$	1.35	$V = 68.219(s)^{0.5}$
0.021	0.67	$V = 54.181(s)^{0.5}$	1.35	$V = 87.711(s)^{0.5}$
0.012	0.67	$V = 94.817(s)^{0.5}$	1.35	$V = 153.494(s)^{0.5}$

Total Hydraulic Time Calculations (TR55, Velocity, or SCS Method)

Sheet Flow $T_t = 0.007(nL)^{0.8}/(P_2^{0.5}S^{0.4})$

Shallow Concentrated Flow $T_t = L/3600V$

Open Channel Flow (Manning's Equation) $T_t = (L*n)/(1.49R^{0.67}S^{0.5})$

Where Hydraulic Radius = conveyance flow depth then:
Manning's equation becomes $T_t = L/3600V$

Total Watershed Time of Concentration

$$t_c = \Sigma T_t$$

L= ft., T_t = hr., S= % slope, R= ft., P= in.(2yr.24hr.) , V= ft./sec.

Visualizing Tc with Manning's 'n', McCuren & Spiess Limits, & NRCS Velocity Equations

- Sheet flow lengths are 90-110 ft. for 2 & 10% slopes respectively at a full impervious surface then reduced by 10% for each 10% drop in impervious area towards a no impervious woods with 30-40 ft. flow lengths for a 2 & 10% slope respectively.

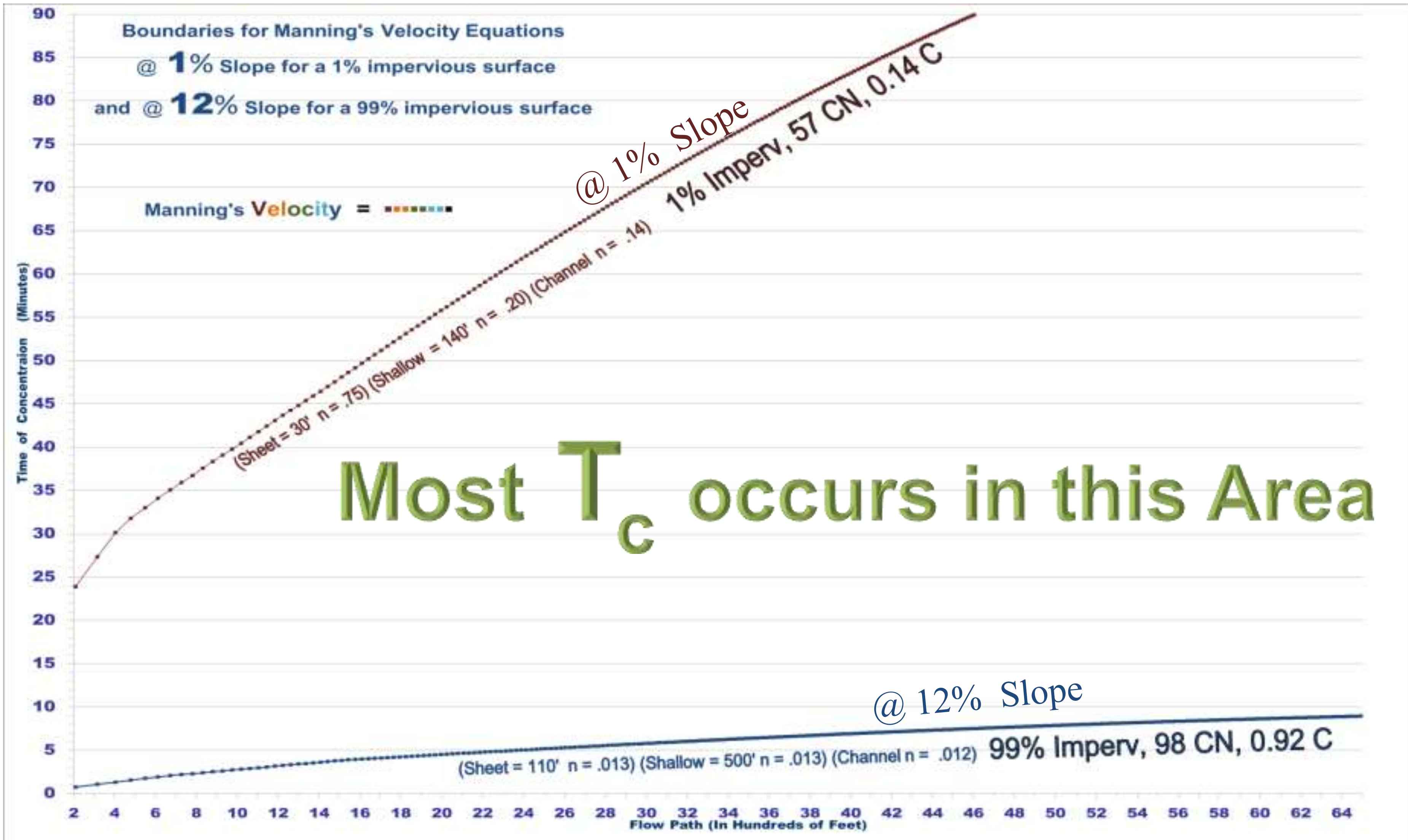
- Shallow concentrated flow lengths are 400-500 ft. for 2 & 10% slopes respectively at a full impervious surface then reduced by 10% for each 10% drop in impervious area towards a no impervious woods with 140-175 ft. flow lengths for a 2 & 10% slope.

Visualizing T_C with Manning's 'n', McCuren & Spiess Limits, & the Velocity Equations

- The remaining flow path length is considered channel flow with a comparable Manning's 'n' coefficient to the sheet flow and shallow flow.
- The equations consider flow, path geometry, slope, and surface conditions homogenous.
- NEH has noted by Folmar & Miller (2008) that it was discovered the velocity method can underestimate time of concentration for larger watersheds.

The Following Plot is T_C Velocity Eq. Boundary:

Tc Pervious & Impervious Boundaries for 1% & 12% Basin slopes Respectively



Implicit assumptions from the graph

- The very high impervious surfaces basins are defined by the lower graph line and high pervious surfaces basins are defined by upper graph line.
- Most hydrographs are defined by the area between the upper & lower graph lines. Typical designs use Tc's between the two lines to create hydrographs.
- The following interpolations for relationships of % impervious, CN, C, & "n" values will help establish these commonly used Tc values in a watershed.

NRCS's 'CN' Values for Soil Groups

Land Use Description on Input Screen	Curve Numbers from TR-55 (Urban Hydrology)					
	Cover Description		Curve Number for Hydrologic Soil Group			
	Cover Type and Hydrologic Condition	% Impervious Areas	A	B	C	D
Agricultural	Row Crops - Staight Rows + Crop Residue Cover- Good Condition (1)		64	75	82	85
Commercial	Urban Districts: Commerical and Business	85	89	92	94	95
Forest	Woods(2) - Good Condition		30	55	70	77
Grass/Pasture	Pasture, Grassland, or Range(3) - Good Condition		39	61	74	80
High Density Residential	Residential districts by average lot size: 1/8 acre or less	65	77	85	90	92
Industrial	Urban district: Industrial	72	81	88	91	93
Low Density Residential	Residential districts by average lot size: 1/2 acre lot	25	54	70	80	85
Open Spaces	Open Space (lawns, parks, golf courses, cemeteries, etc.)(4) Fair Condition (grass cover 50% to 70%)		49	69	79	84
Parking and Paved Spaces	Impervious areas: Paved parking lots, roofs, drivesways, etc. (excluding right-of-way)	100	98	98	98	98
Residential 1/8 acre	Residential districts by average lot size: 1/8 acre or less	65	77	85	90	92
Residential 1/4 acre	Residential districts by average lot size: 1/4 acre	38	61	75	83	87
Residential 1/3 acre	Residential districts by average lot size: 1/3 acre	30	57	72	81	86
Residential 1/2 acre	Residential districts by average lot size: 1/2 acre	25	54	70	80	85
Residential 1 acre	Residential districts by average lot size: 1 acre	20	51	68	79	84
Residential 2 acres	Residential districts by average lot size: 2 acre	12	46	65	77	82
Water/ Wetlands		0	0	0	0	0

Percent Impervious Surface to the Soil Group's Average 'CN' Value

Percent Impervious	Soil Group A	Soil Group B	Soil Group C	Soil Group D	Average 'CN' Value for All
1%	30	55	70	77	58.00
12%	46	65	77	82	67.50
20%	51	68	79	84	70.50
25%	54	70	80	85	72.25
30%	57	72	81	86	74.00
38%	61	75	83	87	76.50
65%	77	85	90	92	86.00
72%	81	88	91	93	88.25
85%	89	92	94	95	92.50
99%	98	98	98	98	98.00

Rational 'C' Coefficient with Soil Types

RUNOFF COEFFICIENTS FOR THE RATIONAL FORMULA FOR HYDROLOGIC SOIL GROUP AND SLOPE RANGE												
	A			B			C			D		
Land Use	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+	0-2%	2-6%	6%+
Cultivated Land	0.08	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Residential	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
Lot Size 1/8 acre	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Lot Size 1/4 acre	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Lot Size 1/3 acre	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Lot Size 1/2 acre	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.48
Lot Size 1 acre	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	0.69	0.69	0.69	0.69	0.70
	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.71	0.71	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets	0.70	0.71	0.72	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Open Space	0.05	0.10	0.14	0.08	0.13	0.19	0.12	0.17	0.24	0.16	0.21	0.28
	0.11	0.16	0.20	0.14	0.19	0.26	0.18	0.23	0.32	0.22	0.27	0.39
Parking	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97

TAKEN FROM: "RECOMMENDED HYDROLOGIC PROCEDURES FOR COMPUTING RUNOFF FROM SMALL WATERSHEDS IN PENNSYLVANIA", 1982, The Pennsylvania State University, Chapter 4, pp 4.18-4.19

A Runoff coefficients for storm recurrence intervals less than 25 years

B Runoff coefficients for storm recurrence intervals of 25 years or more

Percent Impervious Surface to the Soil Group's Average 'C' Value

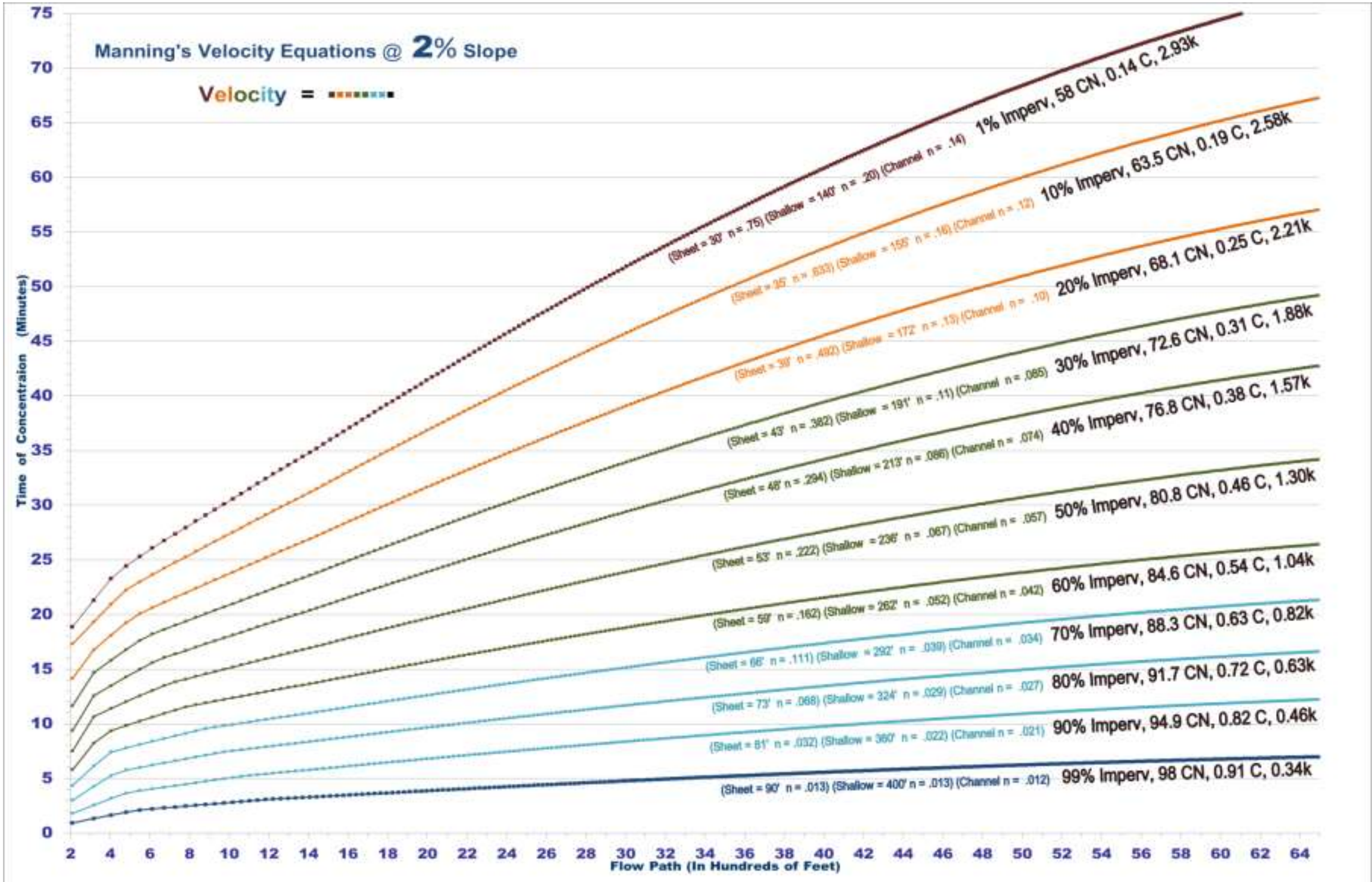
Percent Impervious	Soil Group A	Soil Group B	Soil Group C	Soil Group D	Average 'C' Value for All
1%	0.095	0.125	0.145	0.180	0.137
12%	0.208	0.235	0.277	0.320	0.260
20%	0.225	0.245	0.285	0.320	0.269
25%	0.245	0.275	0.310	0.340	0.293
30%	0.275	0.305	0.335	0.360	0.319
38%	0.300	0.330	0.355	0.380	0.341
65%	0.370	0.400	0.420	0.450	0.410
72%	0.765	0.770	0.775	0.775	0.771
85%	0.795	0.805	0.805	0.805	0.803
99%	0.910	0.910	0.910	0.910	0.910

10% Impervious Surface Increments Normalized to ‘CN’ & ‘C’ Coefficients

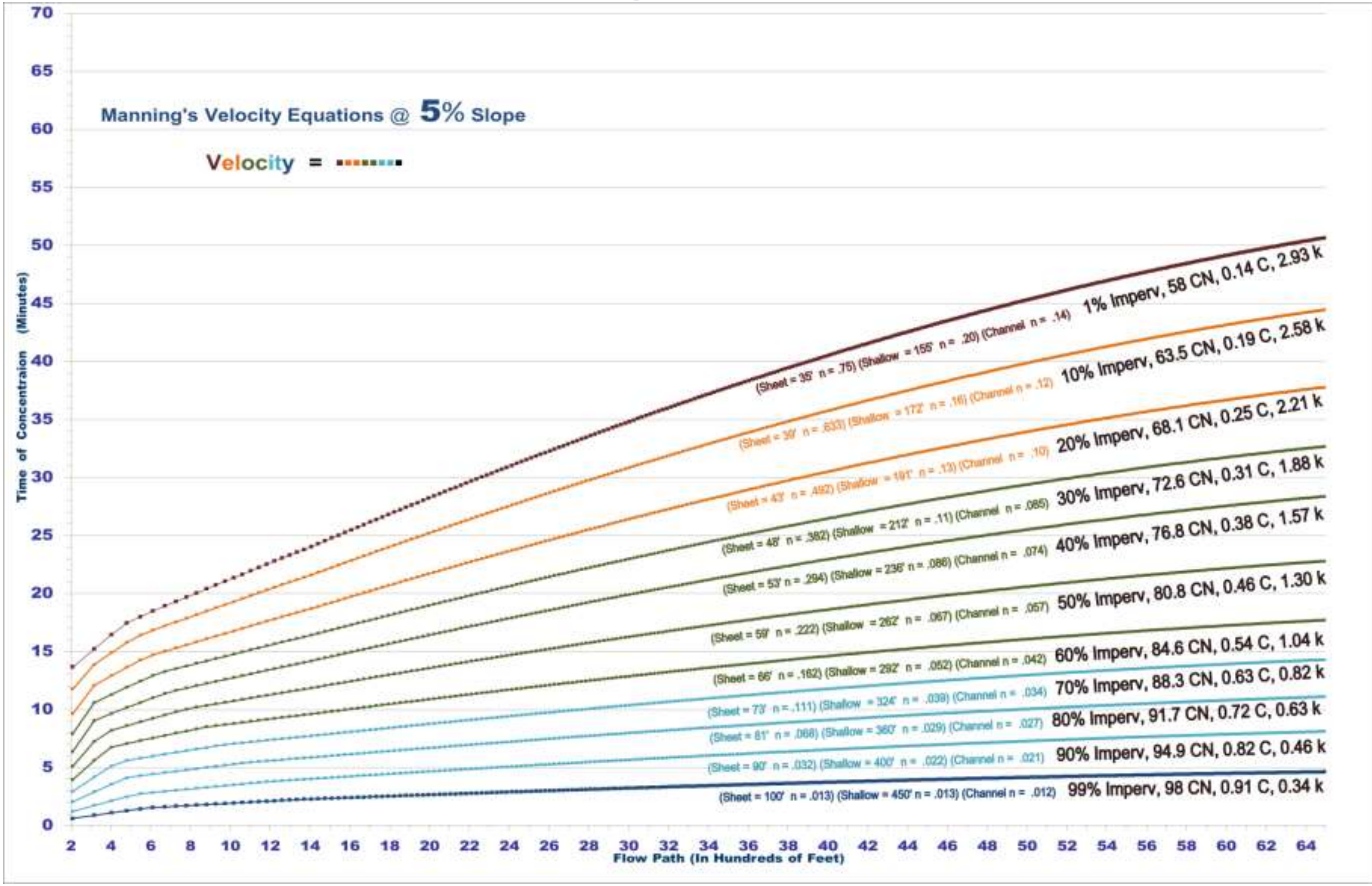
Percent Impervious	Average ‘n’ Sheet Flow Coefficients	Calculated Average ‘CN’ Value from %	Calculated Average ‘C’ Value from %
1%	0.750	58.0	0.14
10%	0.655	63.5	0.19
20%	0.511	68.1	0.25
30%	0.395	72.6	0.31
40%	0.302	76.8	0.38
50%	0.225	80.8	0.46
60%	0.161	84.6	0.54
70%	0.106	88.3	0.63
80%	0.060	91.7	0.72
90%	0.021	94.9	0.82
99%	0.013	98.0	0.91

These Values are Plotted in the Following Graphs:

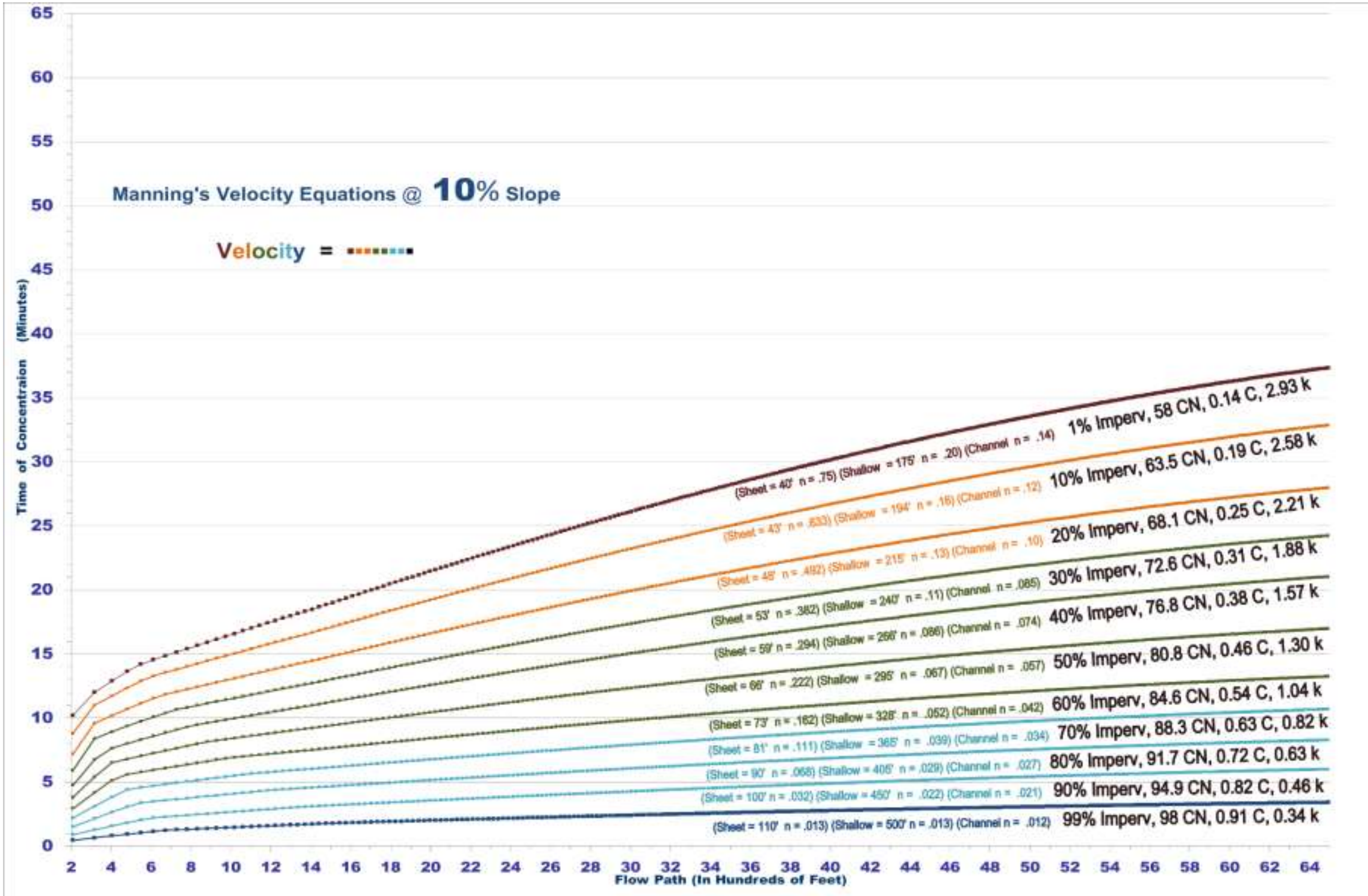
Flow Path vs. T_C for 2% slope path



Flow Path vs. T_C for 5% slope path



Flow Path vs. Tc for 10% slope path



Kirpich Tc Equation

$$T_c = \frac{0.0078\ L_c^{\ 0.77}}{S_c^{\ 0.385}}$$

A Tc equation modeled from channelized basins

- ***Tc*** = minutes, ***Lc*** = flow path length (ft.)

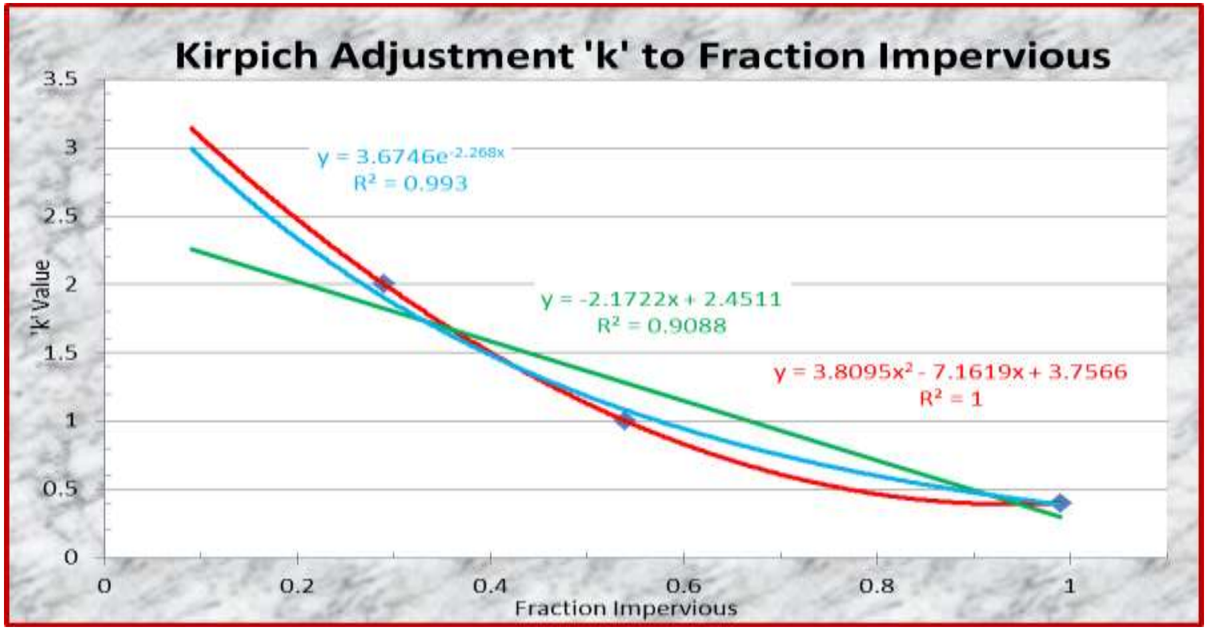
  Sc = flow path slope in (ft./ft.)
- Kirpich is an accepted method in estimating Tc on small basins (1 - 112 acres). It was developed from 7 rural watersheds with basin slopes (3 to 10%) for an assumed **bare soil** flow paths.
- The slope Sc is the elevation difference between the most remote point to the outlet divided by the flow path length *Lc*.

Comparisons of Kirpich Equation Factors to other Runoff Coefficients

Ground Cover	Kirpich Adjustment Factor, 'k' (Chow, 1988; Chin, 2000)
General overland flow and natural grass channels	2.0
Overland flow on bare soil or roadside ditches	1.0
Overland flow on concrete or asphalt surfaces	0.4
Flow in concrete channels	0.2

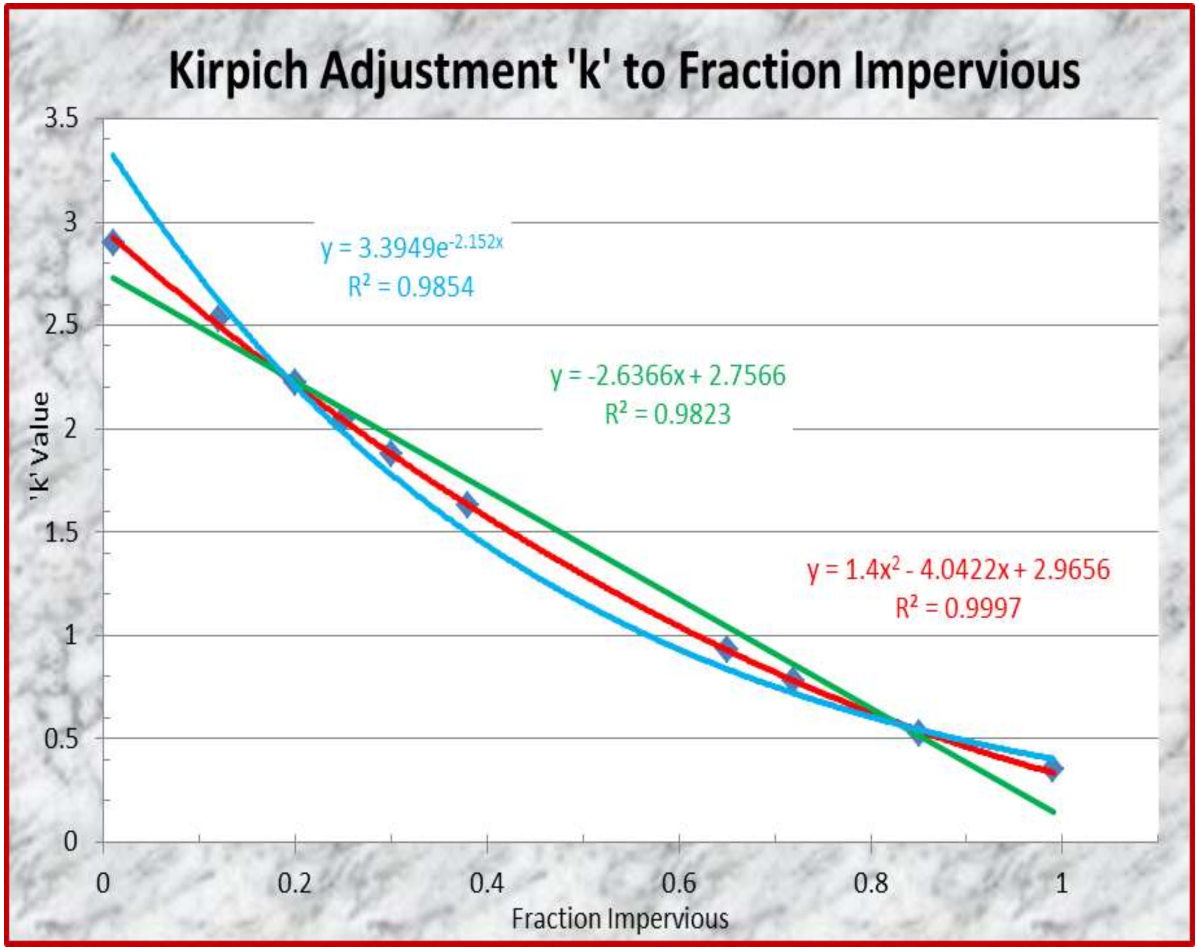
Ground Cover	Kirpich Adjustment Factor, 'k'	Estimated 'C' Value from Cover	Estimated 'CN' Value from Cover	Estimated Percent (%) Impervious
Natural Grass	2.0	.30	72	29
Bare Soil or Roadside ditch	1.0	.49	82	54
Flow on concrete / asphalt surfaces	0.4	.91	98	99

Extrapolation of Kirpich's 'k' Factor



Percent Impervious	Linear 'k' Values	Exponential 'k' Values	Polynomial 'k' Values	Average 'k' Kirpich Adjustment factor
1%	2.43	3.59	3.69	3.24
12%	2.19	2.80	2.95	2.65
20%	2.02	2.33	2.48	2.28
25%	1.91	2.08	2.20	2.07
30%	1.80	1.86	1.95	1.87
38%	1.63	1.55	1.59	1.59
65%	1.04	0.84	0.71	0.86
72%	0.89	0.72	0.57	0.73
85%	0.60	0.53	0.42	0.52
99%	0.30	0.39	0.40	0.36

Extrapolated ‘k’ Factor for Maximum Projected 2.9 ‘k’ & minimum 0.35 ‘k’

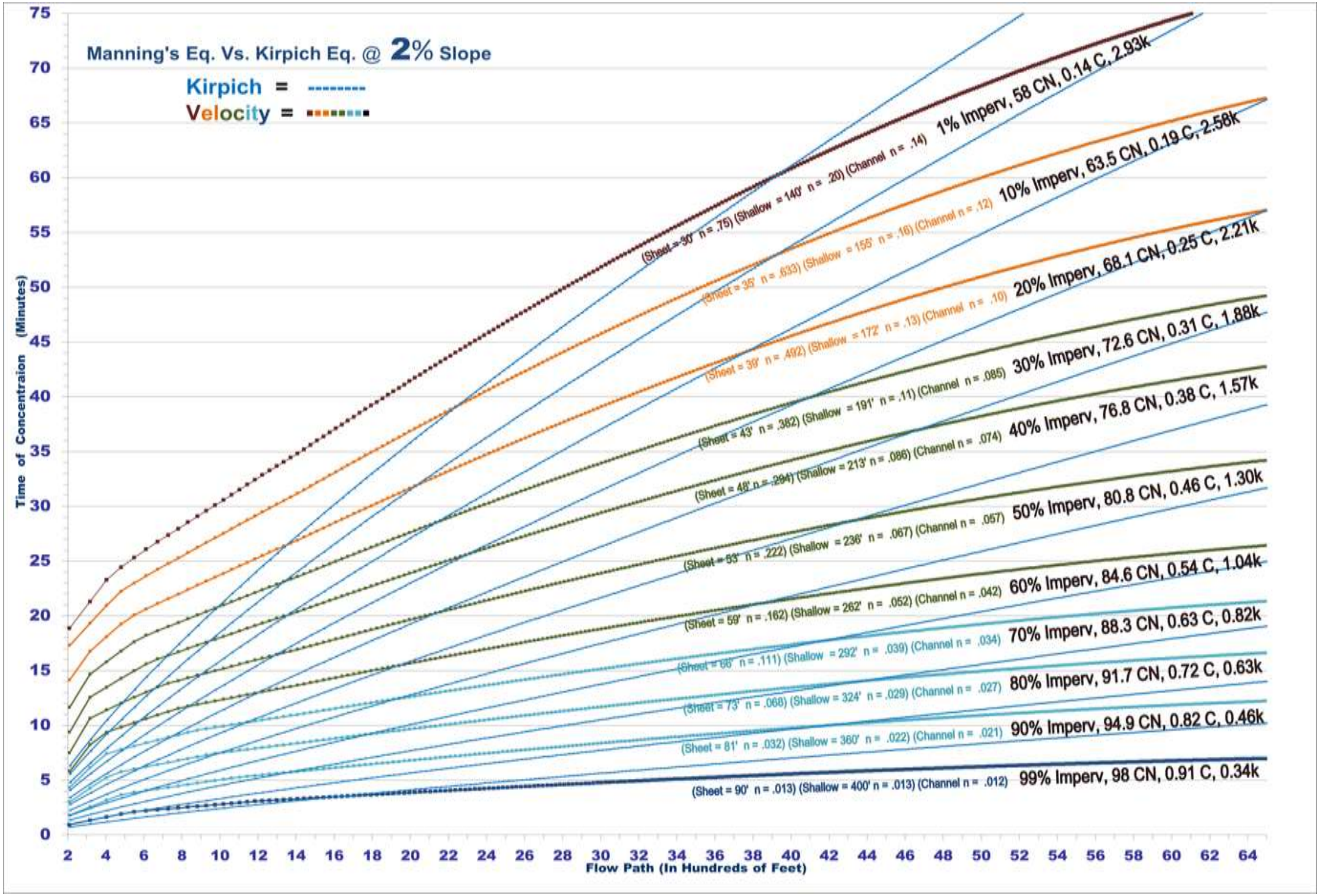


Basin’s Percent Impervious	Kirpich ‘k’ Adjustment factor
1%	2.93
10%	2.58
20%	2.21
30%	1.88
40%	1.57
50%	1.30
60%	1.04
70%	0.82
80%	0.63
90%	0.46
99%	0.34

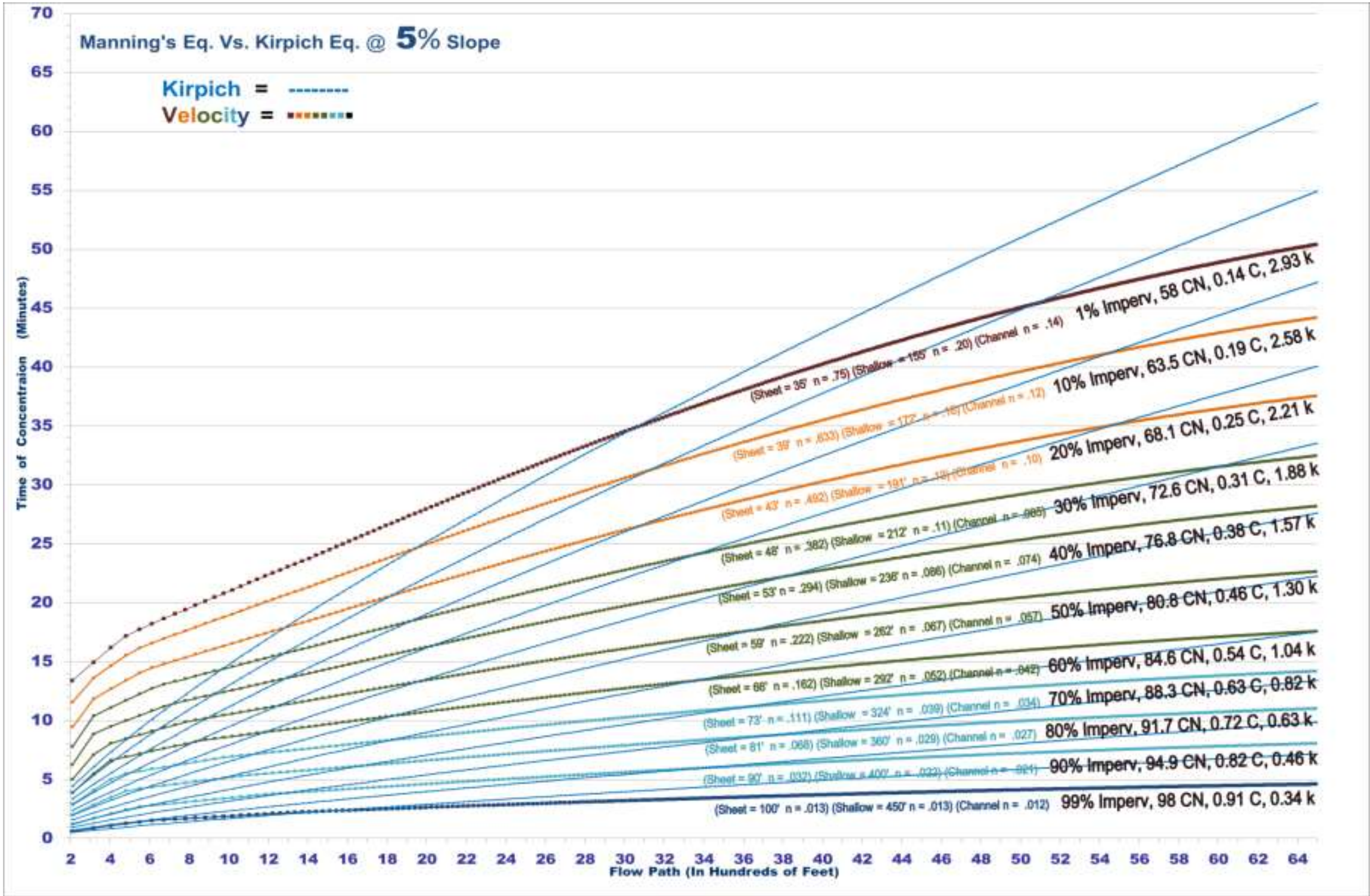
Average 'CN', 'C', 'k', & 'n' Coefficients Normalized to 10% Impervious Surface

Percent Impervious	Calculated 'CN' Values from %	Calculated 'C' Values from %	Kirpich 'k' Values from %	'n' Sheet Flow Coefficients
1%	58.0	0.14	2.93	0.750
10%	63.5	0.19	2.58	0.655
20%	68.1	0.25	2.21	0.511
30%	72.6	0.31	1.88	0.395
40%	76.8	0.38	1.57	0.302
50%	80.8	0.46	1.30	0.225
60%	84.6	0.54	1.04	0.161
70%	88.3	0.63	0.82	0.106
80%	91.7	0.72	0.63	0.060
90%	94.9	0.82	0.46	0.021
99%	98.0	0.91	0.34	0.013

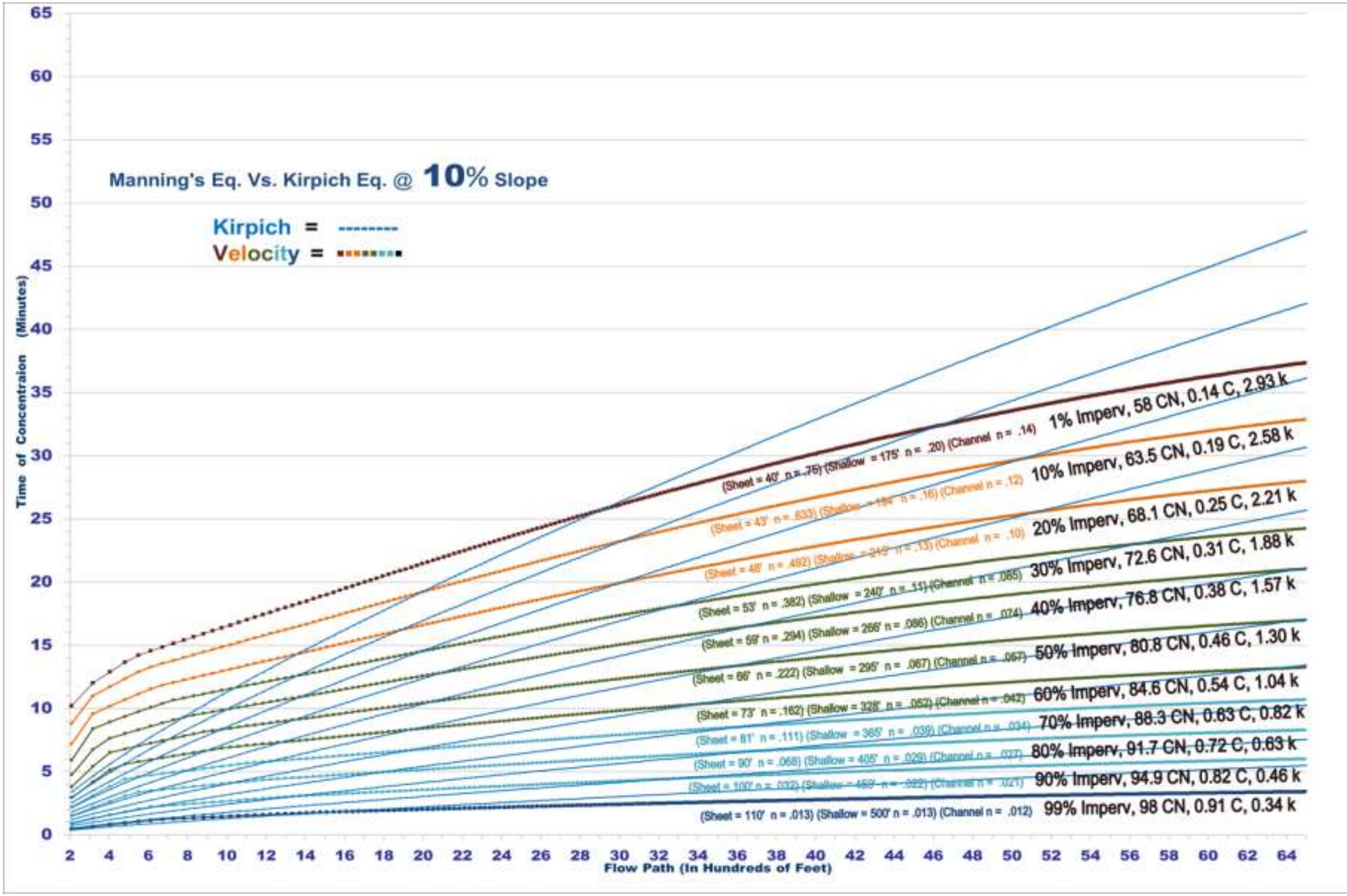
Kirpich & Velocity Eq. Tc's Compared



Kirpich & Velocity Eq. Tc's Compared



Kirpich & Velocity Eq. Tc's Compared



NRCS's LAG Equation

$$T_{lag} = \frac{L_c^{\,0.8}\left(\frac{1000}{CN} - 9\right)^{0.7}}{1900\ Y_c^{\,0.5}}$$

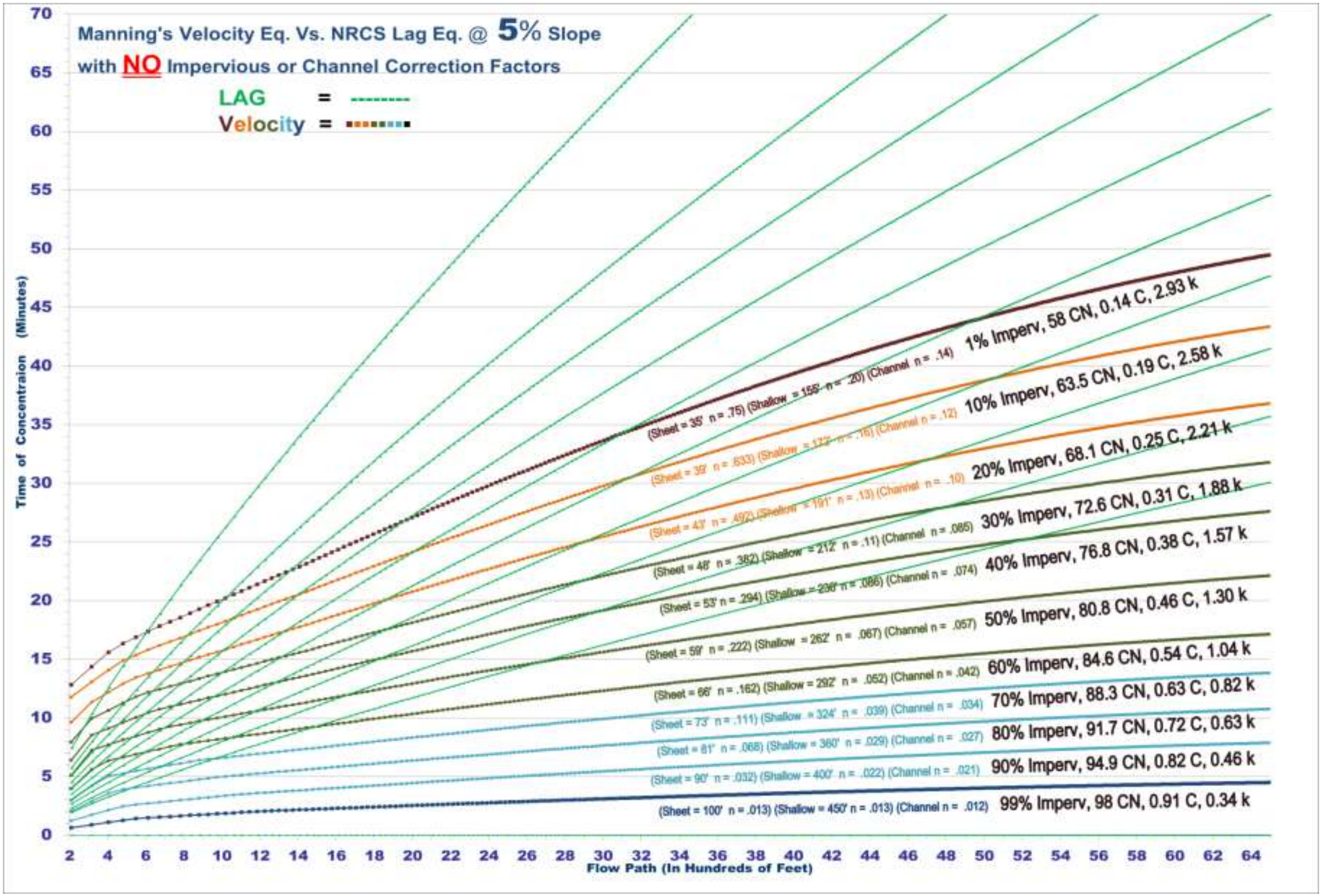
$$T_c = 60\ \frac{T_{lag}}{0.6}\ (\mathrm{IF})(\mathrm{CF})$$

A T_C equation formed with the basin's surface data

- T_{lag} = Lag time (hrs.), L_c = flow path length (ft.)
- Y_c = average watershed slope number percent (%)
- T_c = Time of Concentration (minutes) *IF & CF* = FHWA Adjust. Factors

NRCS lag method was developed by Mockus in 1961 for many conditions from heavy forest, meadows, and paved areas less than 2000 acres. Referenced by NRCS as a T_c.

NRCS Lag & Velocity Tc's Compared

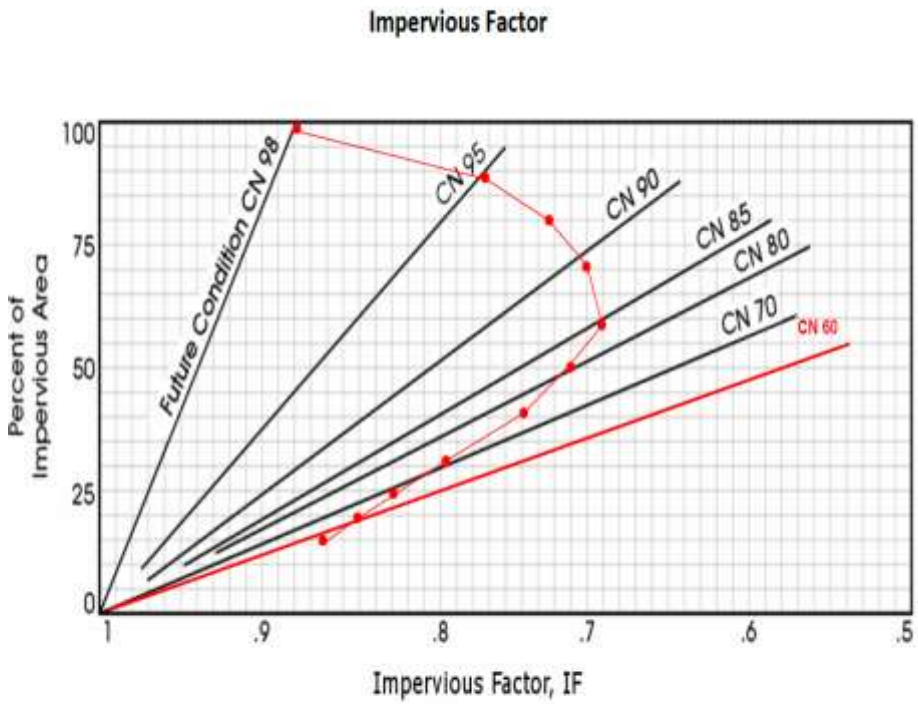


FHWA (HEC19) Adjustment Factors for NRCS Lag Eq. on imperviousness & channel improvements

$$\mathbf{M} = \mathbf{1} - \mathbf{p}\left(\left(-\mathbf{6.8}\,(\mathbf{10})^{-\mathbf{3}}\right) + \left(\mathbf{3.4}\,(\mathbf{10})^{-\mathbf{4}}\boldsymbol{CN}\right) - \left(\mathbf{4.3}\,(\mathbf{10})^{-\mathbf{7}}\boldsymbol{CN}^{\mathbf{2}}\right)\left(\mathbf{2.2}\,(\mathbf{10})^{-\mathbf{8}}\boldsymbol{CN}^{\mathbf{3}}\right)\right)$$

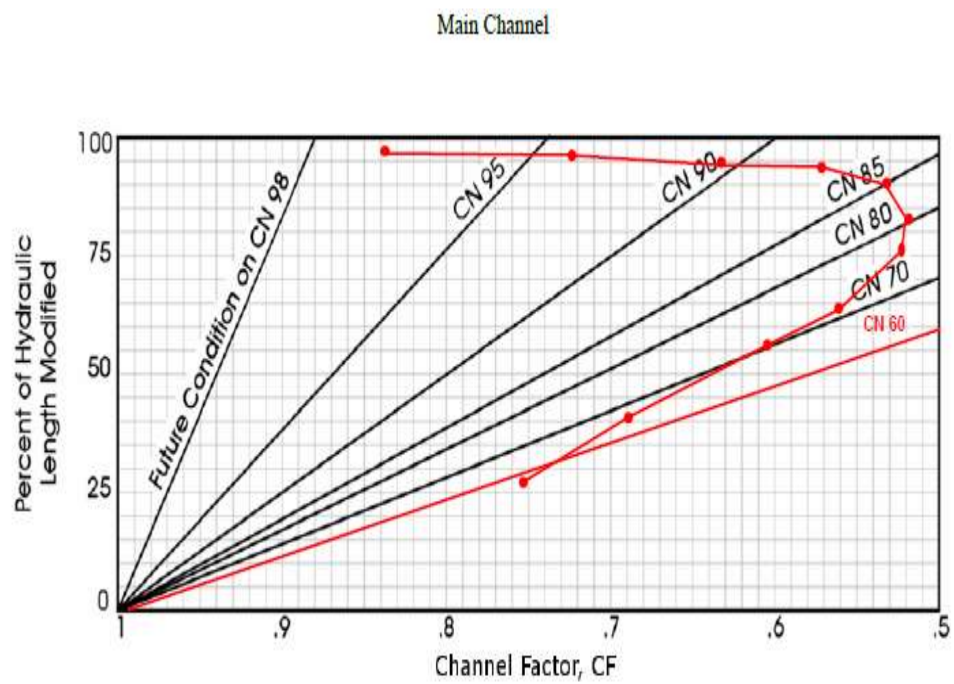
M = NRCS's adjustment factors on Lag Eq. for percent imperviousness and channel improvements

p = the percent imperviousness or percent of main channels that are hydraulically improved beyond natural conditions.



Factors for Adjusting Lag When Impervious Areas Occur in the Watershed

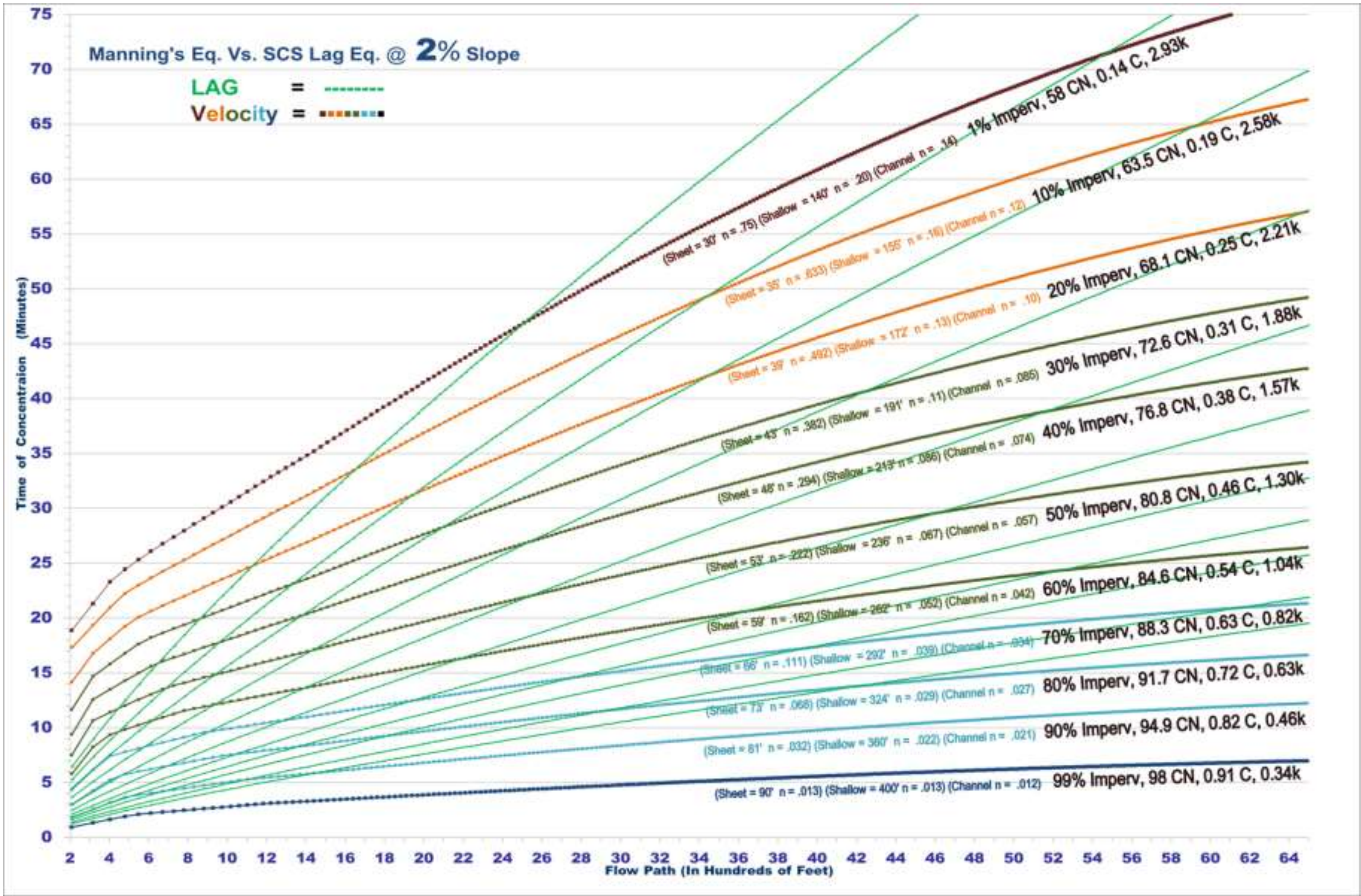
Source: FHWA, HEC-19



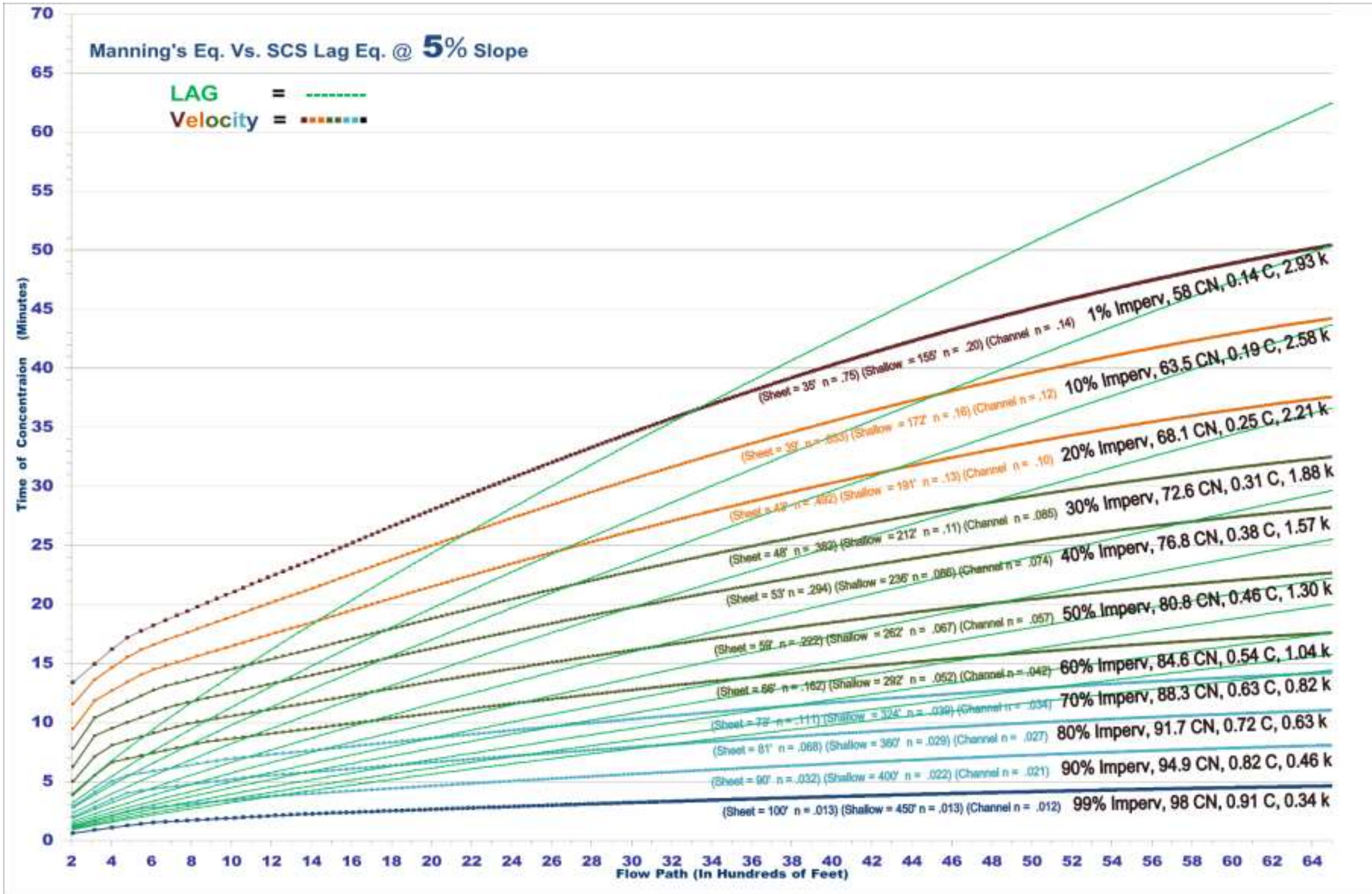
Factors for Adjusting Lag When the Main Channel Has Been Hydraulically Improved

Source: FHWA, HEC-19

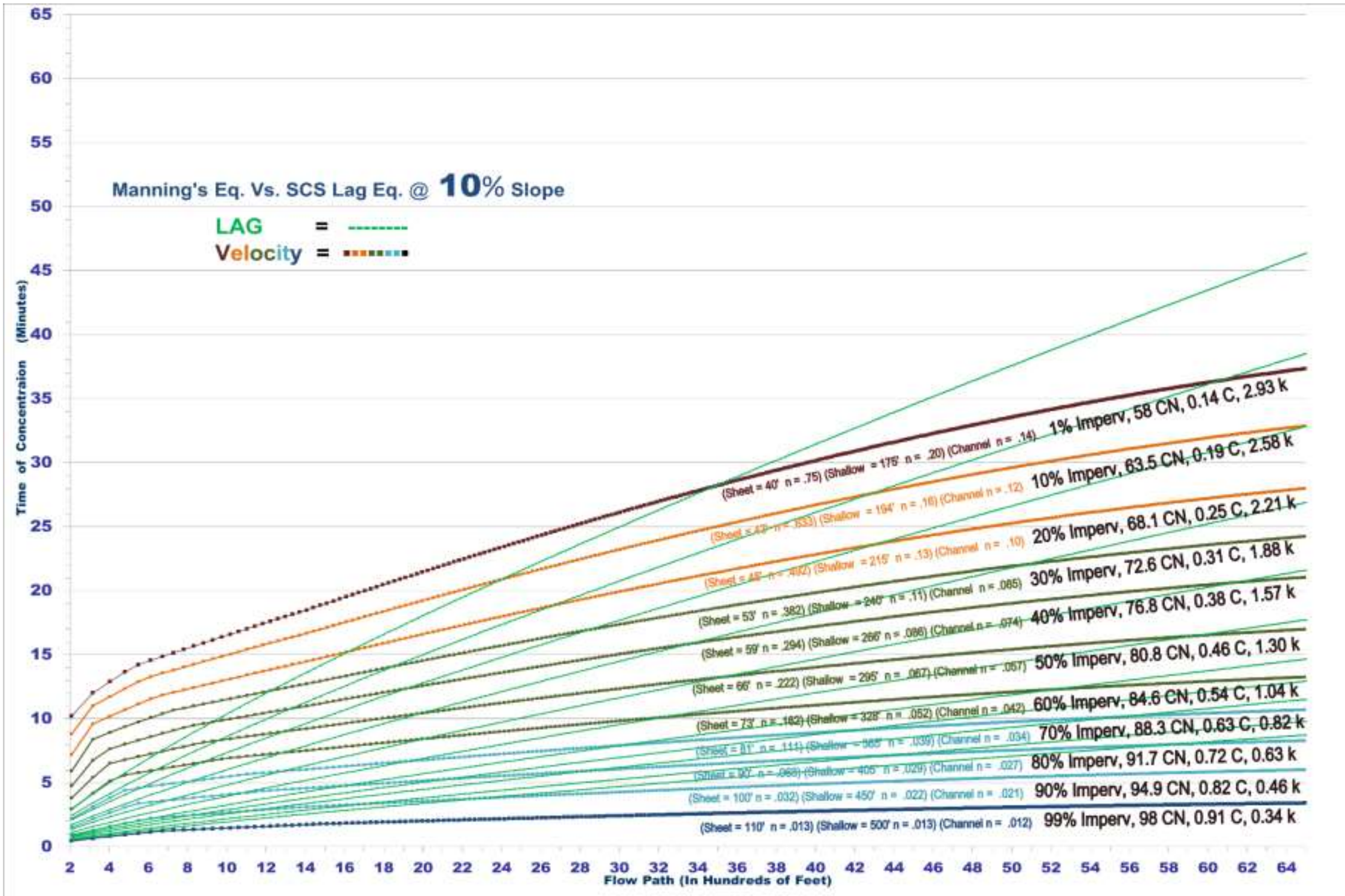
Lag Imp. & Channel Factors vs. Velocity



Lag Imp. & Channel Factors vs. Velocity



Lag Imp. & Channel Factors vs. Velocity



FAA's T_C Equation

$$T_c = 1.8\left((1.1 - C)\frac{{L_c}^{0.5}}{{S_c}^{0.33}}\right)$$

A T_C equation formed with basin's surface data

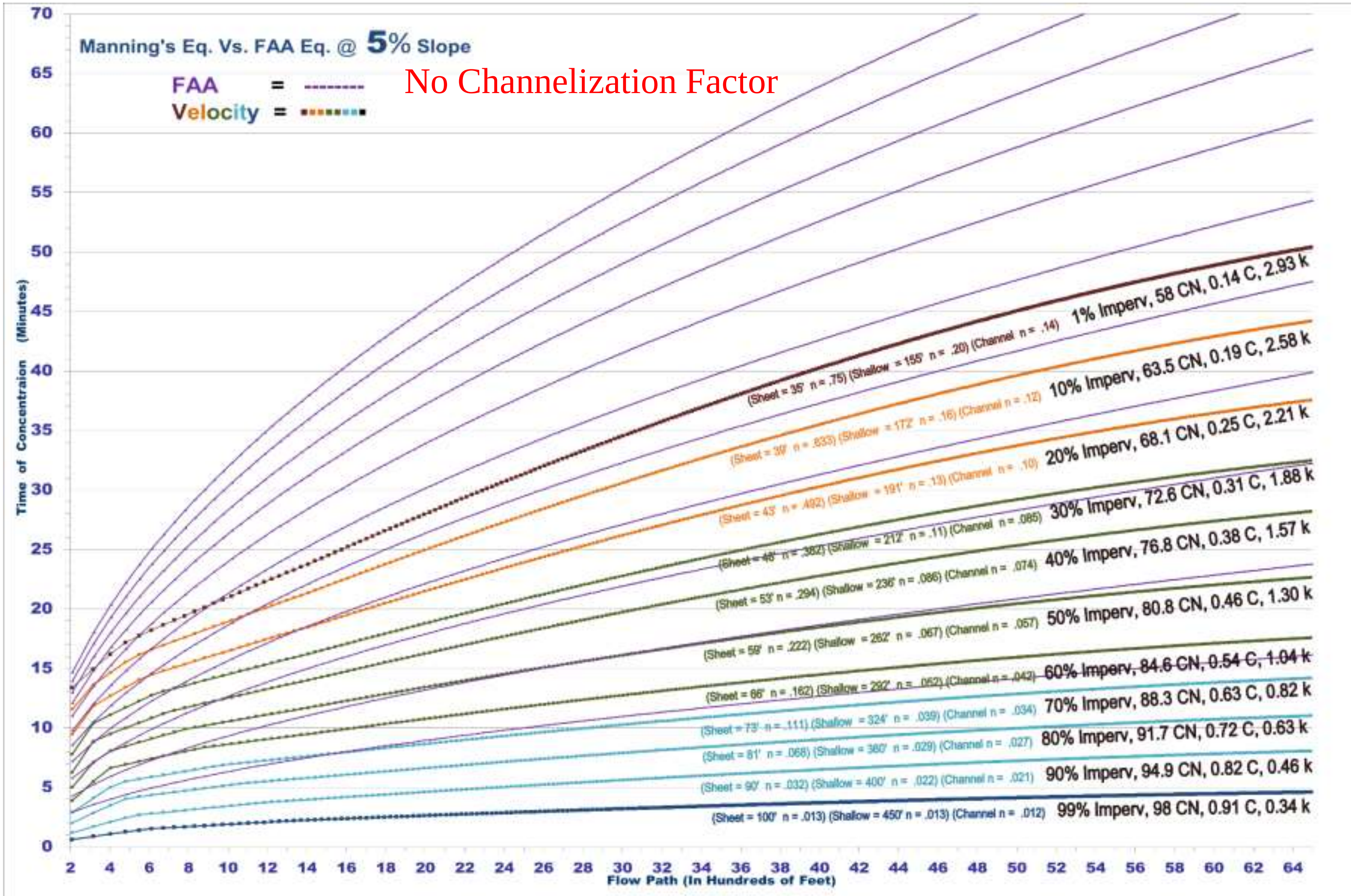
Tc = minutes, Lc = flow path length (ft.)

Sc = flow path slope in (% full number)

C = Rational Runoff Coefficient

- Developed from airfield drainage with data assembled by USACE. It is frequently used on urban watersheds.
- This equation was developed in an environment of primarily sheet & shallow flow, low slopes, higher impervious surfaces, and on small drainage basins.

FAA T_C vs. Velocity T_C's Compared



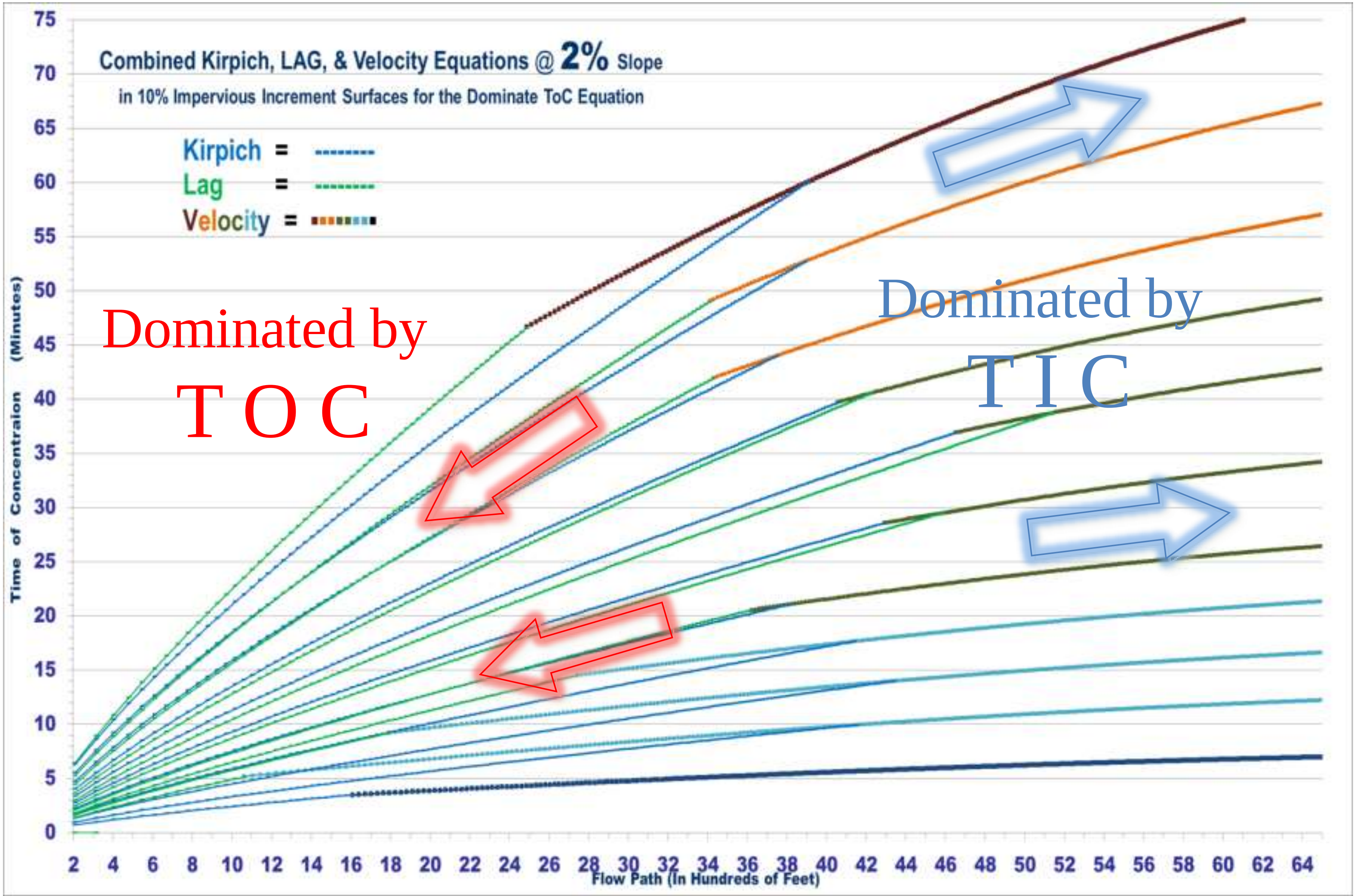
Small Watershed Runoff Response

- T_C comparison graphs between the velocity equations and channelized empirical equations convey a systematic intersect for each related surface coefficient.
- Empirical equations provide a lower T_C in short flow paths while velocity equations for a same flow path exhibits a higher T_C. Empirical equations calculate higher T_C's on longer basin flow paths while velocity equations assess a reduced time for the same longer flow path.
- Runoff time on small basins exhibits a transformation from a "surface" attribute flow dominance to a "channel" attribute flow dominance.

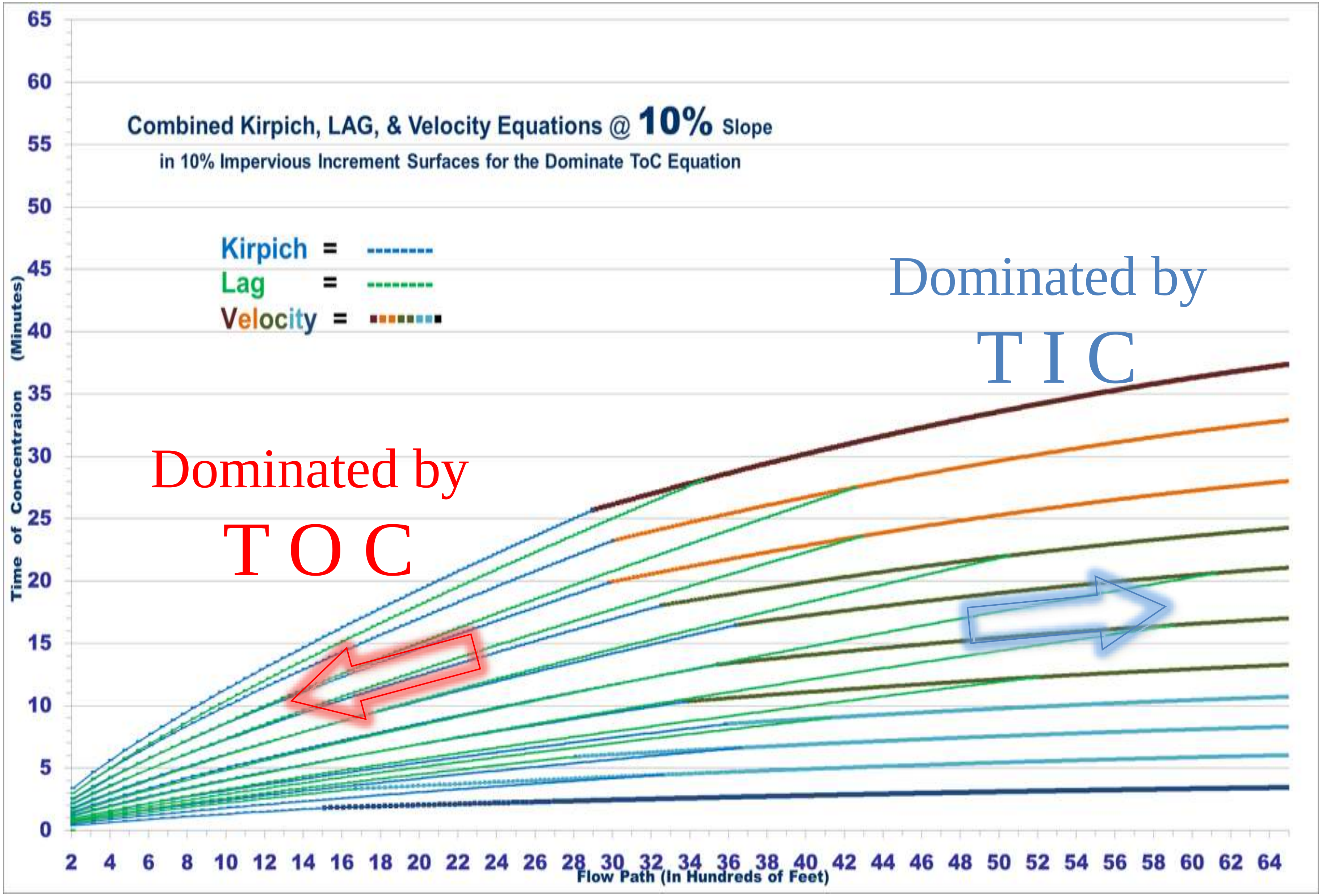
TOC - Timing Outside Channel **TIC - Timing Inside Channel**

- Consider a predictable T_c equation for known observations of related T_c equations in multi-surfaced watersheds from recently acquired graphs.

Combined for a 2% Slope Watershed



Combined for a 10% Slope Watershed

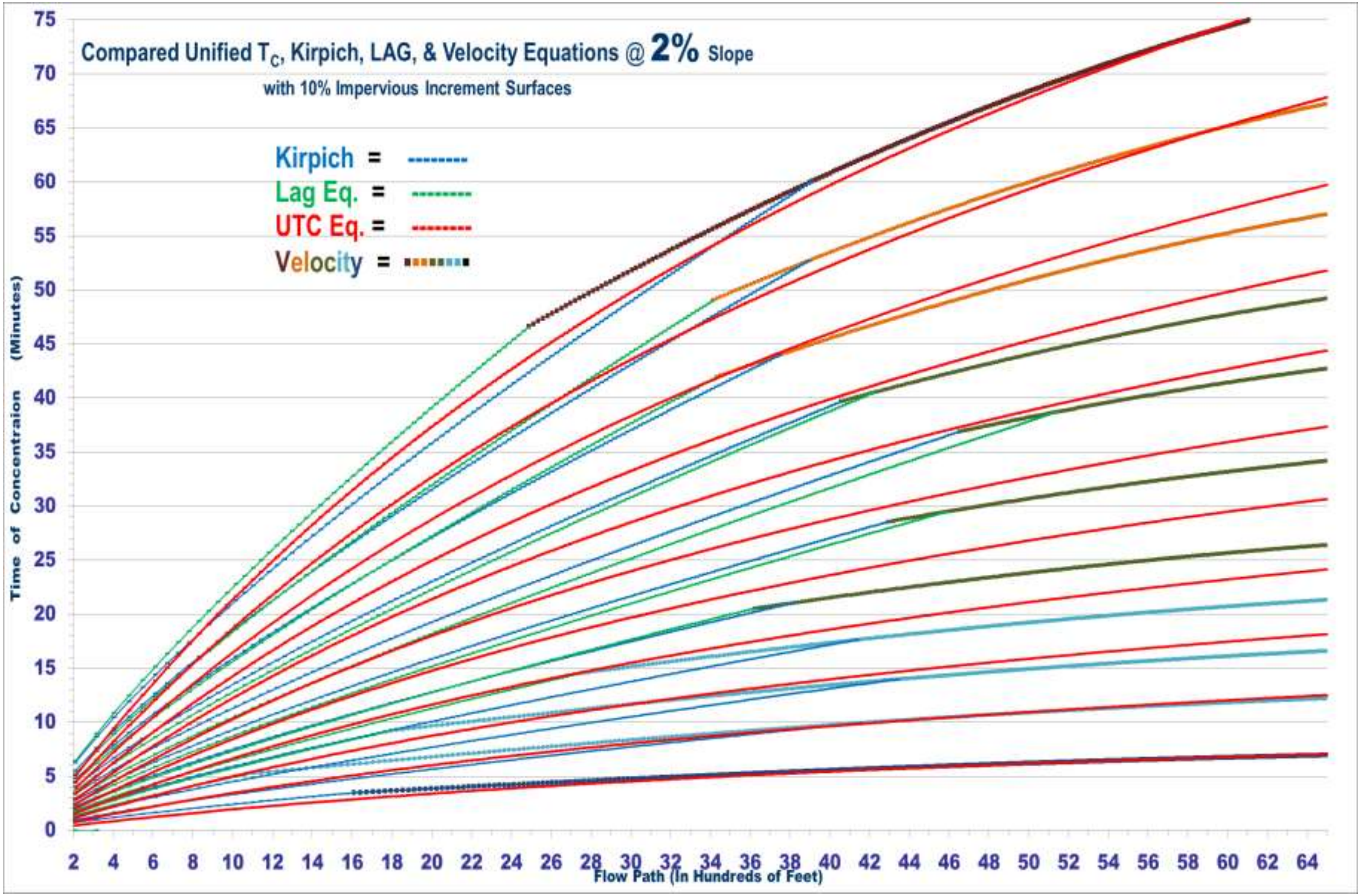


Unified T_C Equation with Channelization using % Impervious Surface

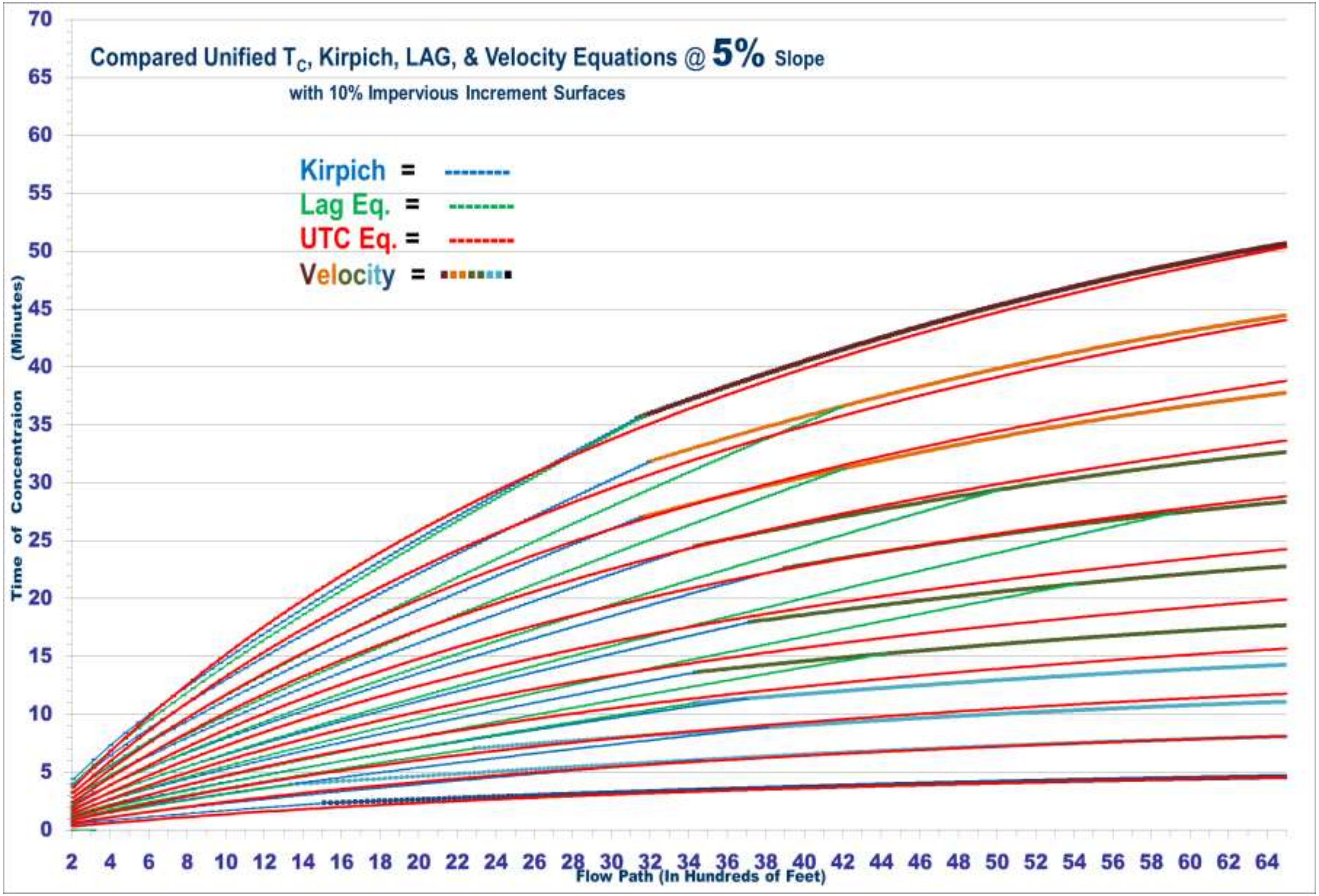
$$T_c = \frac{1.1 - i}{\sqrt[3]{s}\left(\frac{155}{L} + \frac{\sqrt[4]{s}}{14}\right)}$$

- T_c = Time of Concentration (minutes)
- L = Length of Flow Path (feet)
- i = % Impervious Surface (decimal format)
- s = % Slope of Flow Path (decimal format)
- Equation Limits: 1 to 325 acres of drainage basin
  1 to 12 percent slope of flow path
  1 to 99 percent impervious surface

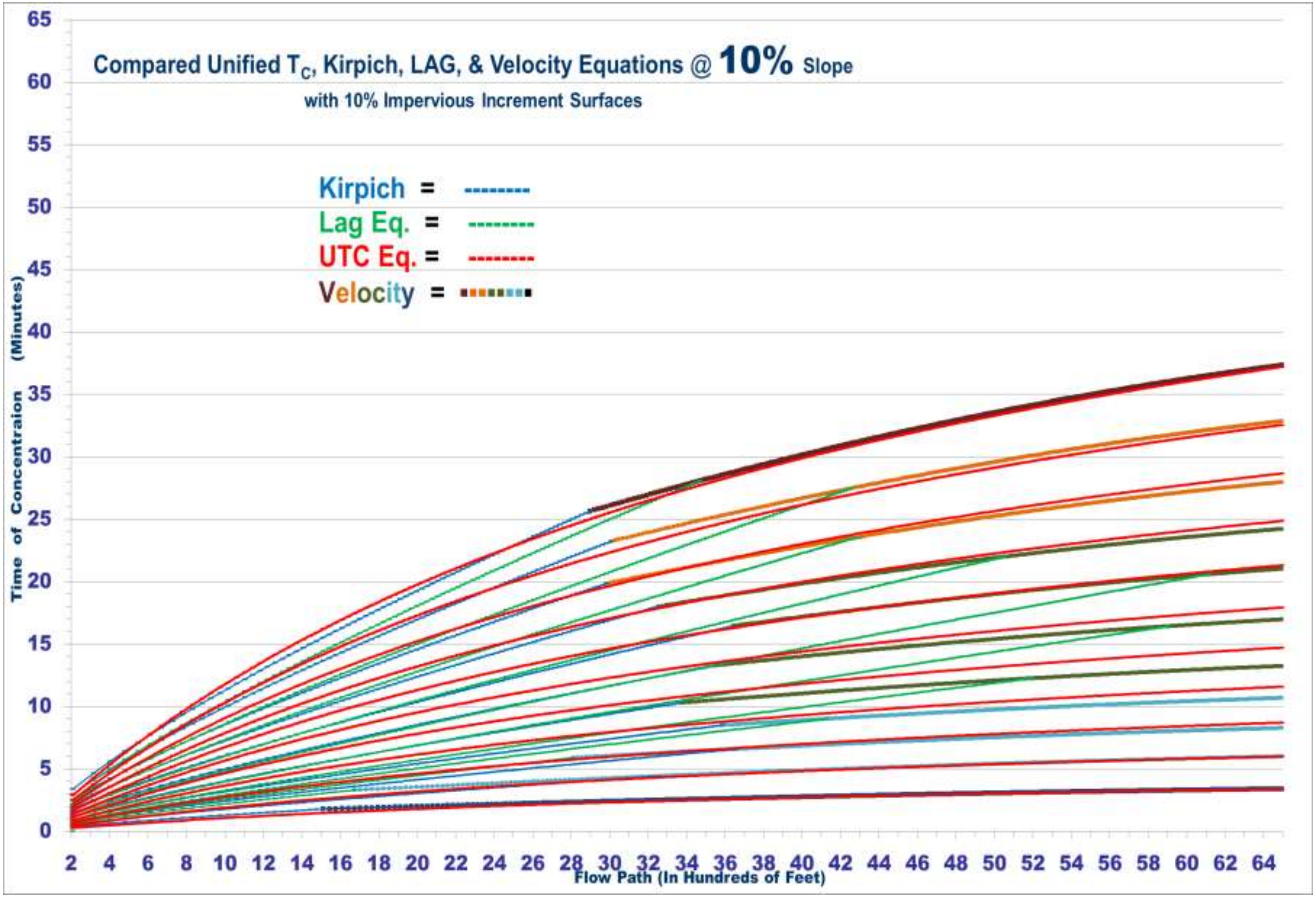
UTC Eq. vs. Lag, Kirpich, & Velocity Curves



UTC Eq. vs. Lag, Kirpich, & Velocity Curves



UTC Eq. vs. Lag, Kirpich, & Velocity Curves

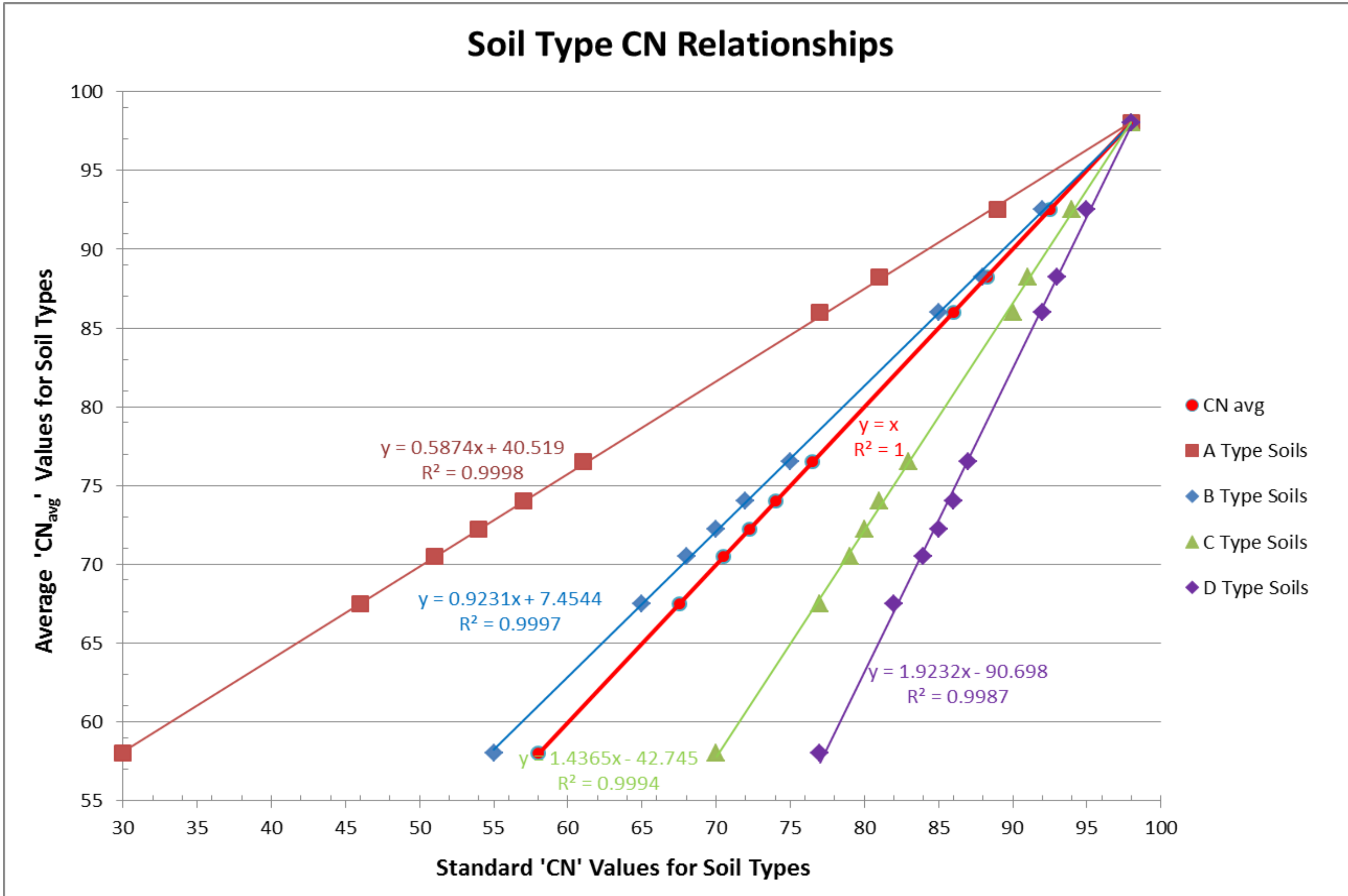


Unified T_C Equation with Channelization using CN Values

$$T_c = \frac{102 - CN_{\mathrm{avg}}}{\sqrt[3]{s}\left(\frac{6500}{L} + 3\sqrt[4]{s}\right)}$$

- T_c = Time of Concentration (minutes)
- L = Length of Flow Path (feet)
- CN_{avg} = NRCS's Average Runoff Curve Number
- s = % Slope of Flow Path (decimal format)
- Equation Limits: 1 to 350 acres of drainage basin
1 to 15 percent slope for flow path
55 to 98 surface runoff curve number

‘CN’ Avg. Relationships for Soil Types



Unified T_C Equation uses an average CN Soil type (near B soil type)

Basin weighed CN value is attained by adjusting CN soil types to a CN_{avg} type

$$\mathbf{CN_{avg}} = \frac{(CN_{type} 1.5^{x}) - 11x^2 - 44x + 63}{1.6}$$

CN_{avg} = Average CN values used in Unified **T_C** Equation

CN_{type} = NRCS's Runoff Curve Number per soil type

x = NRCS's soil type factor shown below

Type **A** Soil: ***x = 0***

Type **B** Soil: ***x = 1***

Type **C** Soil: ***x = 2***

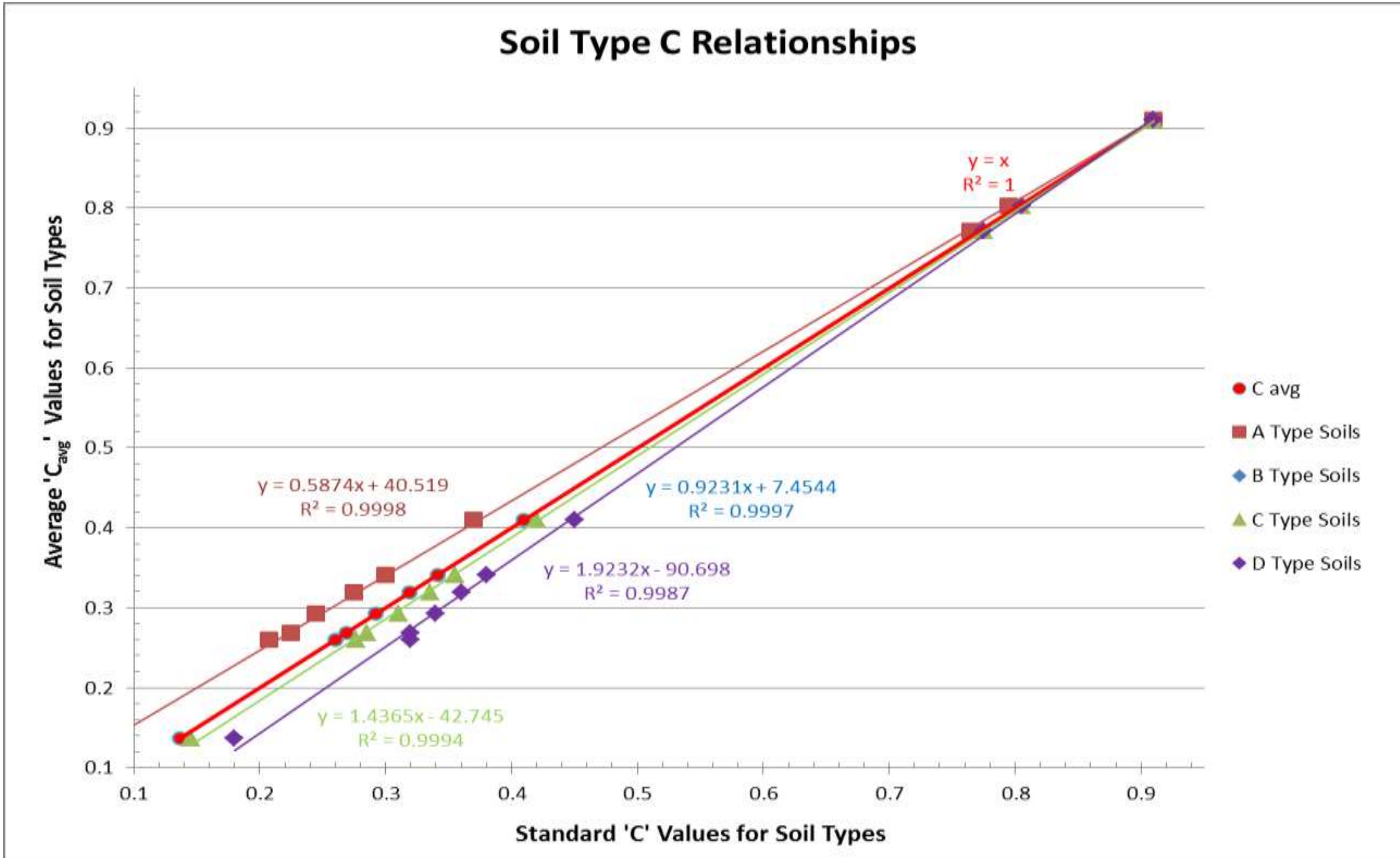
Type **D** Soil: ***x = 3***

Unified T_C Equation for Channelization using 'C'

$$T_c = \frac{1 - C_{\text{avg}}}{\sqrt[3]{s}\left(\frac{125}{L} + \frac{\sqrt[3]{s}}{14}\right)}$$

- T_c = Time of Concentration (minutes)
- L = Length of Flow Path (feet)
- C_{avg} = Rational method's average runoff coefficient
- s = % Slope of Flow Path (decimal format)
- Equation Limits: 1 to 225 acres of drainage basin
  1 to 12 percent slope for flow path
  0.10 to 0.95 rational runoff coefficient

‘C’ Avg. Relationships for Soil Types using a 10yr. Storm Event



Unified T_C Equation uses an average ‘C‘ coefficient (near B soil type)

Basin weighed ‘C’ value is attained by adjusting ‘C’ soil types to a ‘C_{avg}’ type

$$C_{avg} = \frac{C_{type}\left(21+0.7x+0.15x^2\right)-x+1.5}{22.5}$$

C_{avg} = Average C values used in Unified T_C Equation

C_{type} = Rational method’s runoff coefficient per soil type

x = NRCS’s soil type factor shown below

Type **A** Soil: $x = 0$

Type **B** Soil: $x = 1$

Type **C** Soil: $x = 2$

Type **D** Soil: $x = 3$

The Iowa Storm Water Management Manual

Table C3-S4- 1: Runoff coefficients for the Rational method

Hydrologic Soil Group	A			B			C			D		
Recurrence Interval	5	10	100	5	10	100	5	10	100	5	10	100
Land Use Or Surface Characteristics Business:												
A. Commercial Area	.75	.80	.95	.80	.85	.95	.80	.85	.95	.85	.90	.95
B. Neighborhood Area	.50	.55	.65	.55	.60	.70	.60	.65	.75	.65	.70	.80
Residential:												
A. Single Family	.25	.25	.30	.30	.35	.40	.40	.45	.50	.45	.50	.55
B. Multi-Unit (Detached)	.35	.40	.45	.40	.45	.50	.45	.50	.55	.50	.55	.65
C. Multi-Unit (Attached)	.45	.50	.55	.50	.55	.65	.55	.60	.70	.60	.65	.75
D. ½ Lot Or Larger	.20	.20	.25	.25	.25	.30	.35	.40	.45	.40	.45	.50
E. Apartments	.50	.55	.60	.55	.60	.70	.60	.65	.75	.65	.70	.80
Industrial												
A. Light Areas	.55	.60	.70	.60	.65	.75	.65	.70	.80	.70	.75	.90
B. Heavy Areas	.75	.80	.95	.80	.85	.95	.80	.85	.95	.80	.85	.95
Parks, Cemeteries Playgrounds	.10	.10	.15	.20	.20	.25	.30	.35	.40	.35	.40	.45
Schools	.30	.35	.40	.40	.45	.50	.45	.50	.55	.50	.55	.65
Railroad Yard Areas	.20	.20	.25	.30	.35	.40	.40	.45	.45	.45	.50	.55
Streets												
A. Paved	.85	.90	.95	.85	.90	.95	.85	.90	.95	.85	.90	.95
B. Gravel	.25	.25	.30	.35	.40	.45	.40	.45	.50	.40	.45	.50
Drives, Walks, & Roofs	.85	.90	.95	.85	.90	.95	.85	.90	.95	.85	.90	.95
Lawns												
A. 50%-75% Grass (Fair Condition)	.10	.10	.15	.20	.20	.25	.30	.35	.40	.30	.35	.40
B. 75% Or More Grass (Good Condition)	.05	.05	.10	.15	.15	.20	.25	.25	.30	.30	.35	.40
Undeveloped Surface[1] (By Slope)[2]												
A. Flat (0-1%)	0.04-0.09			0.07-0.12			0.11-0.16			0.15-0.20		
B. Average (2-6%)	0.09-0.14			0.12-0.17			0.16-0.21			0.20-0.25		
C. Steep	0.13-0.18			0.18-0.24			0.23-0.31			0.28-0.38		

[1]Undeveloped Surface Definition: Forest and agricultural land, open space.
[2]Source: Storm Drainage Design Manual, Erie and Niagara Counties Regional Planning Board.

UDFCD Runoff Coefficients

Runoff coefficient vs. watershed imperviousness by NRCS HSG's

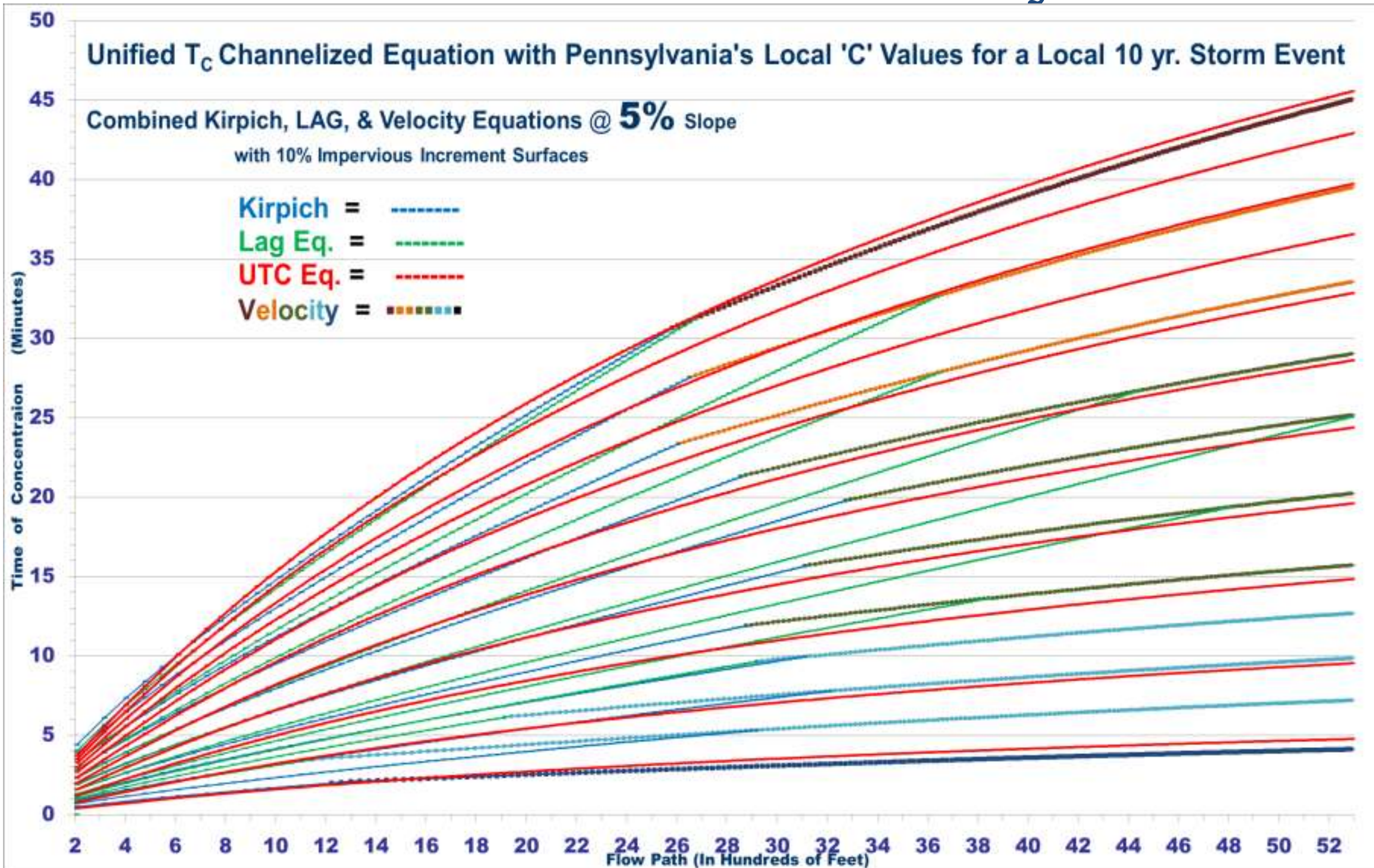
Total or Effective	Runoff coefficients, *c* NRCS Hydrologic Soil Group A					
% Imperviousness	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
1%	0.01	0.01	0.01	0.01	0.01	0.16
10%	0.09	0.09	0.09	0.09	0.10	0.23
20%	0.18	0.19	0.19	0.19	0.19	0.32
30%	0.27	0.28	0.28	0.28	0.29	0.40
40%	0.36	0.37	0.38	0.38	0.38	0.48
50%	0.45	0.47	0.47	0.47	0.48	0.56
60%	0.53	0.56	0.56	0.57	0.57	0.64
70%	0.62	0.65	0.66	0.66	0.67	0.72
80%	0.71	0.74	0.75	0.76	0.76	0.80
90%	0.80	0.84	0.85	0.85	0.86	0.88
99%	0.88	0.92	0.93	0.93	0.94	0.95

Total or Effective	Runoff coefficients, *c* NRCS Hydrologic Soil Group B					
% Imperviousness	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
1%	0.01	0.01	0.13	0.24	0.37	0.46
10%	0.09	0.09	0.21	0.30	0.42	0.50
20%	0.18	0.19	0.29	0.37	0.48	0.55
30%	0.27	0.28	0.37	0.44	0.54	0.60
40%	0.36	0.37	0.45	0.51	0.60	0.65
50%	0.45	0.47	0.53	0.58	0.66	0.70
60%	0.53	0.56	0.61	0.65	0.72	0.75
70%	0.62	0.65	0.69	0.72	0.78	0.80
80%	0.71	0.74	0.77	0.79	0.84	0.85
90%	0.80	0.84	0.85	0.86	0.89	0.90
99%	0.88	0.92	0.93	0.93	0.94	0.94

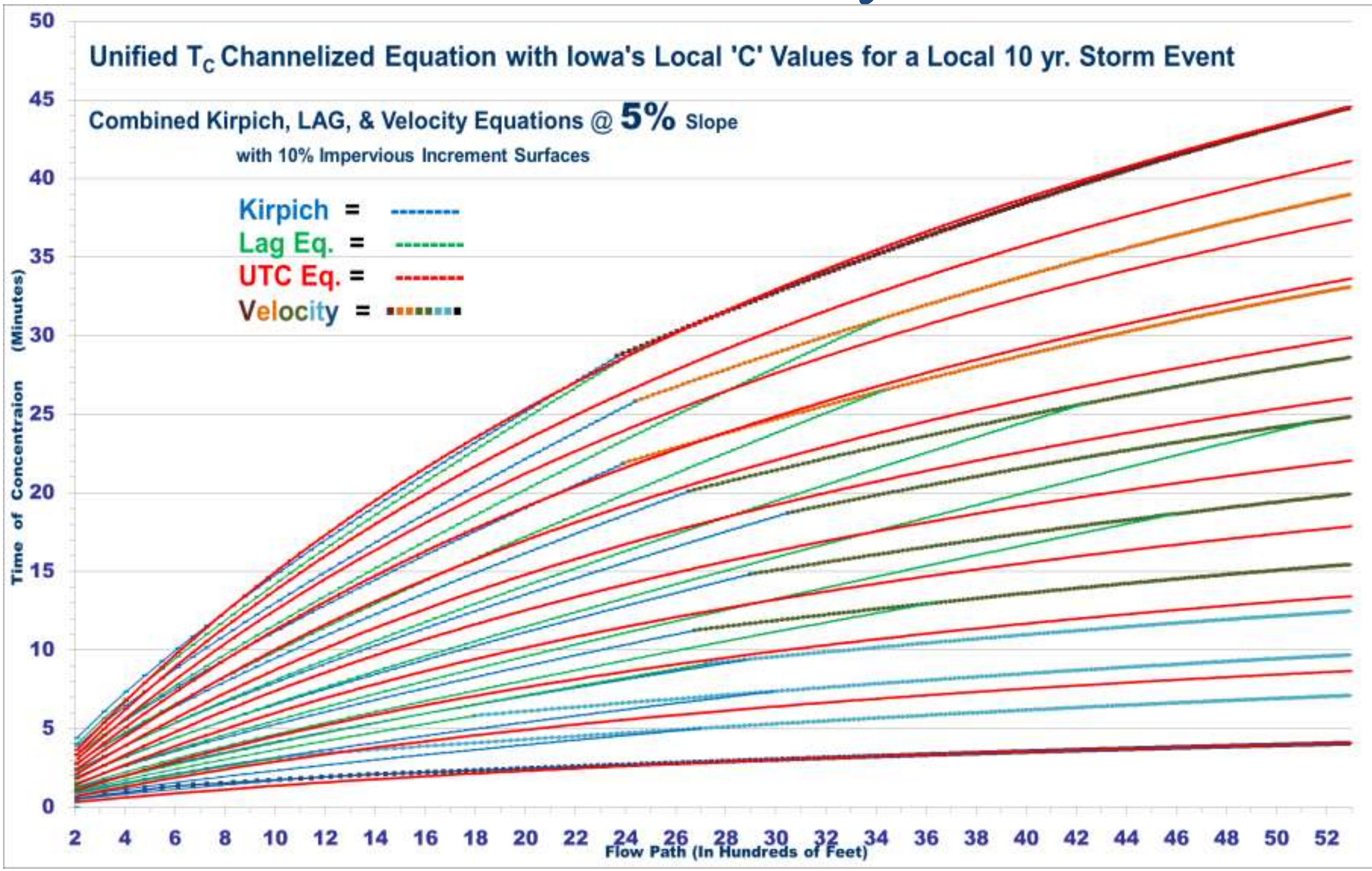
Total or Effective	Runoff coefficients, *c* NRCS Hydrologic Soil Groups C and D					
% Imperviousness	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
1%	0.01	0.06	0.21	0.32	0.42	0.51
10%	0.09	0.14	0.27	0.37	0.47	0.55
20%	0.18	0.23	0.35	0.44	0.53	0.60
30%	0.27	0.31	0.42	0.50	0.58	0.64
40%	0.36	0.40	0.50	0.57	0.63	0.69
50%	0.45	0.49	0.57	0.63	0.69	0.73
60%	0.53	0.57	0.64	0.69	0.74	0.78
70%	0.62	0.66	0.72	0.76	0.80	0.82
80%	0.71	0.75	0.79	0.82	0.85	0.87
90%	0.80	0.83	0.87	0.89	0.90	0.91
99%	0.88	0.91	0.93	0.94	0.95	0.95

Urban Drainage and Flood Control District January 2016
Urban Storm Drainage Criteria Manual Volume 1

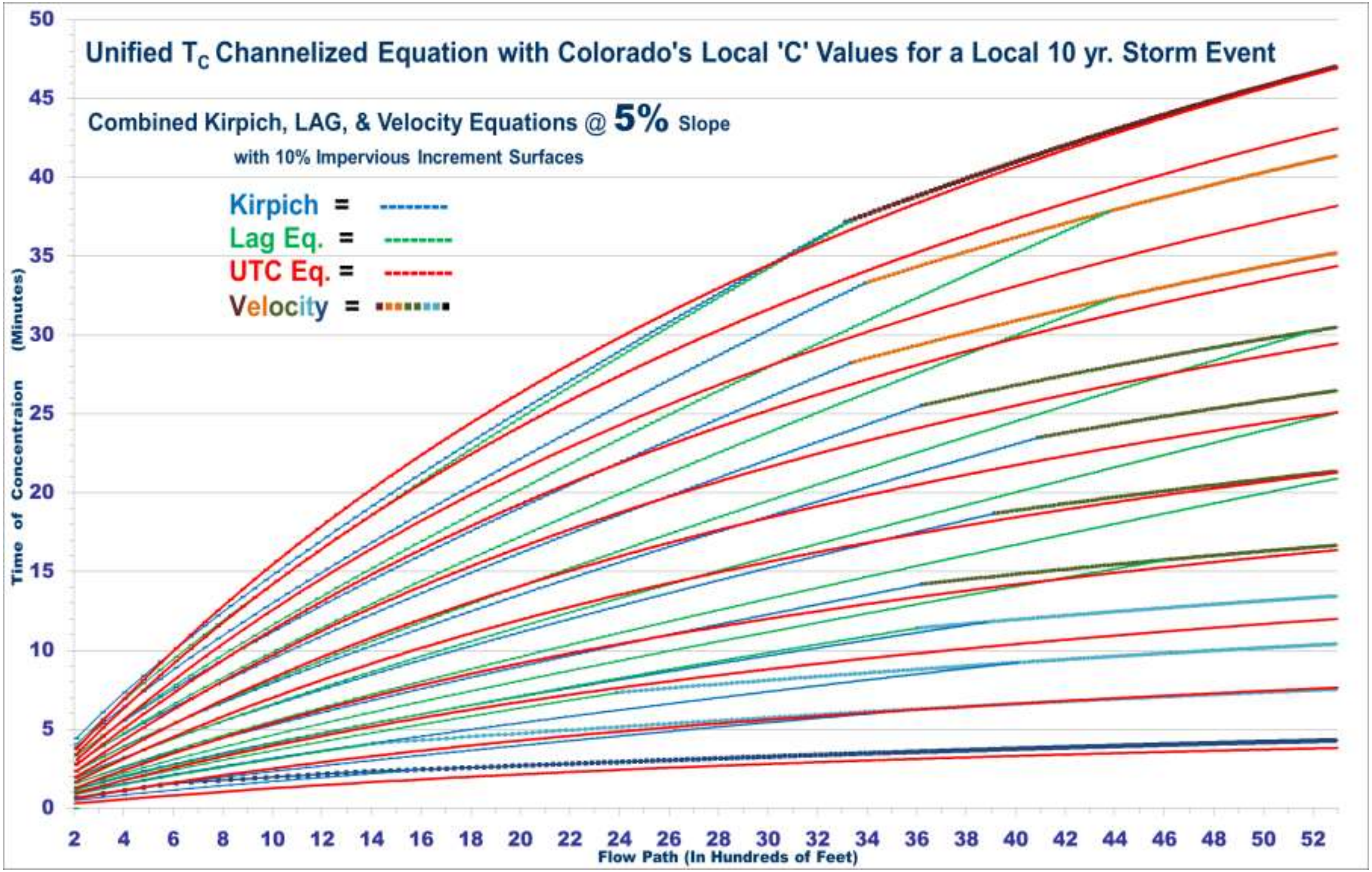
Unified T_C C Equation with Pennsylvania's local 'C' Value for a Local 10 yr. Event



Unified T_C 'C' Equation with Iowa's local 'C' values for a 10 yr. Event



Unified T_C ‘C’ Equation with Colorado’s Local ‘C’ values for a Local 10 yr. Storm



Kinematic Wave Theory is Significant in Prevailing Hydrology Flow Equations

- Kinematic wave method relates flows to the basin characteristics.
- Kinematic basin routing parameters define the channel shape, boundary roughness, and slope of the flow routing surface.
- Flood runoff waves are defined by two studies of motion kinematic and dynamic (changes in discharge, velocity, & surface elevations) wave equations.
- Kinematic wave equations govern flow with forces essentially from flow of fluid weight balanced by surface resistive forces.
- Kinematic wave approximation is an accurate & efficient method of modeling storm water runoff for both overland flow & channel routing. **(Overton & Meadows, 1976)**

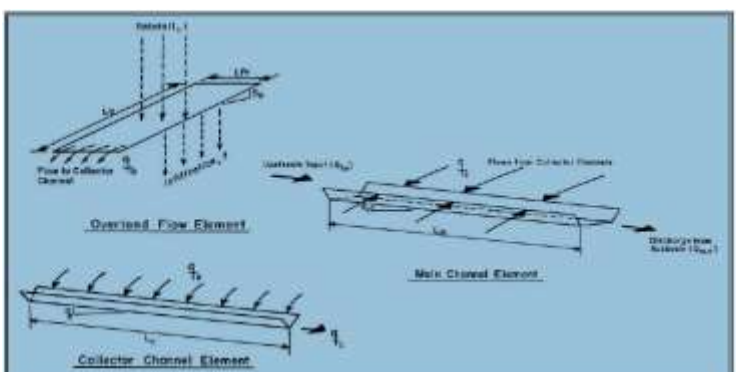


Figure 3 Elements Used in Kinematic Wave Calculations

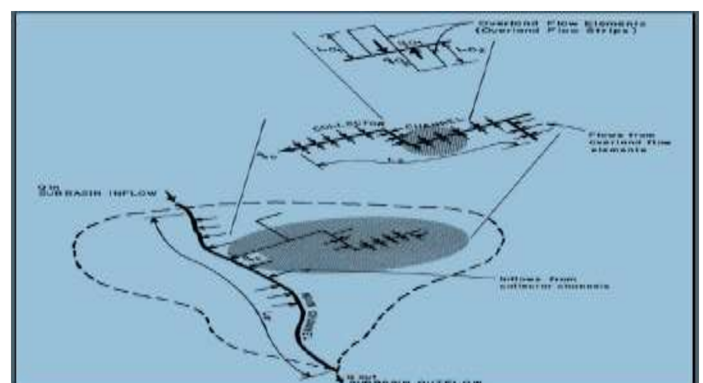


Figure 4 Relationships Between Flow Elements

Papadakis-Kazan T_C Equation

$$T_c = \frac{k\,(L)^a\,(n)^b}{(i)^z\;\;(S)^y} \qquad\qquad T_c = \frac{0.66\,(L)^{0.5}\,(n)^{0.52}}{(i)^{0.38}\;\;(S)^{0.31}}$$

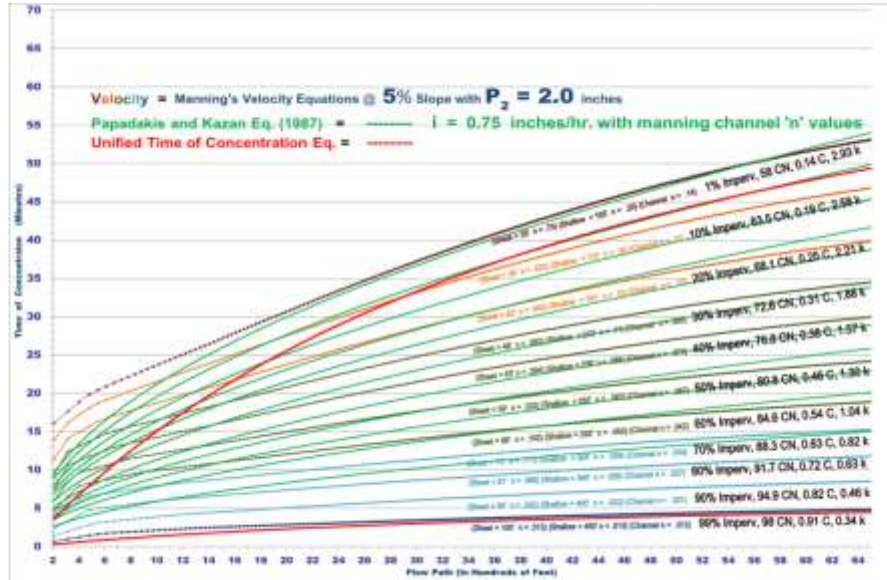
A global regression equation derived from eleven T_C equations

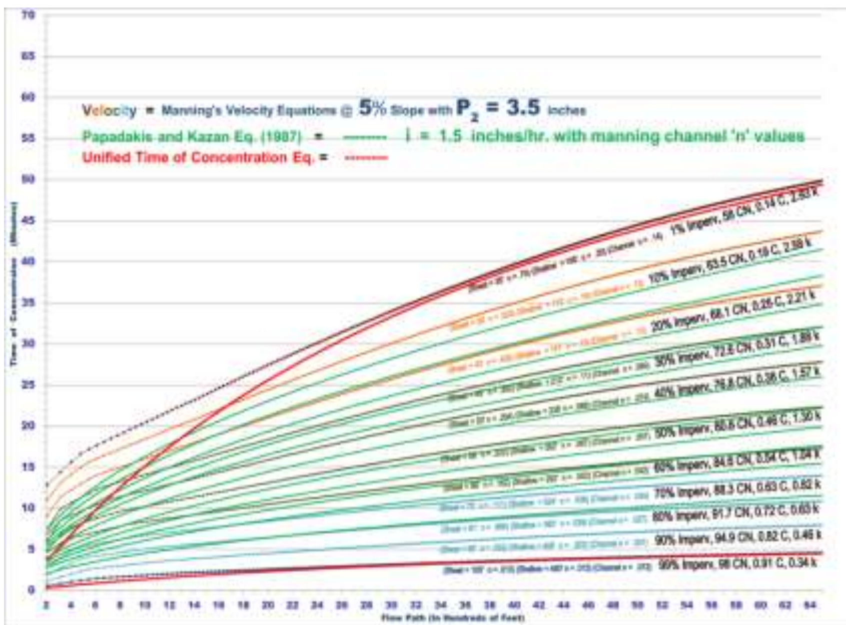
T_c = minutes, L = flow path length (ft.)
n = Manning's Coefficient, S = flow path slope in (ft./ft.)
i = Rainfall Intensity (in./hr.), k = Constant

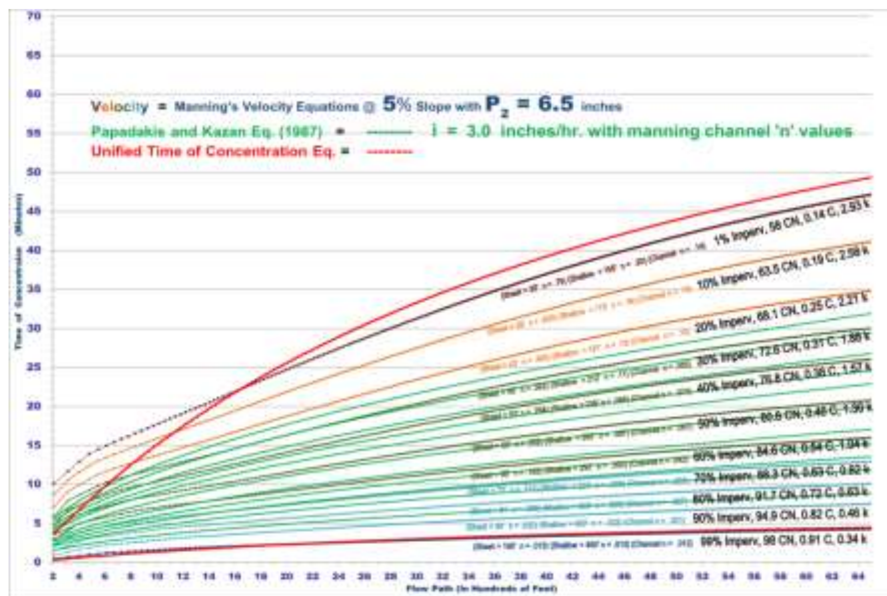
- Developed from frequent T_C equations that includes Kirpich, Izzard, Kerby/Hathaway, Carter, Eagleson, Kinematic Wave, Morgali, Linsley, FAA, SCS Velocity , SCS Curve (Lag), and Singh's Kinematic Wave/Chezy equations.
- Examination of existing equations used for time of concentration revealed a shared a general format. The resulting upper right equation right provides an general applicable Tc equation with a predetermined degree of confidence.
- The common exponents a, b, y, z, and the constant k for the 4 variables were formed from 375 data points on natural and experimental watersheds of less than 500 acres. A regression analysis was performed for each with a best fit.

Papadakis-Kazan T_C with Manning's Channel 'n' Value Compared to Velocity & UTC Equations

Percent Impervious	'n' Sheet Coefficients	'n' Shallow Coefficients	'n' Channel Coefficients
1%	0.750	0.200	0.140
10%	0.655	0.160	0.120
20%	0.511	0.130	0.100
30%	0.395	0.110	0.085
40%	0.302	0.086	0.074
50%	0.225	0.067	0.057
60%	0.161	0.052	0.042
70%	0.106	0.039	0.034
80%	0.060	0.029	0.027
90%	0.021	0.022	0.021
99%	0.013	0.013	0.012

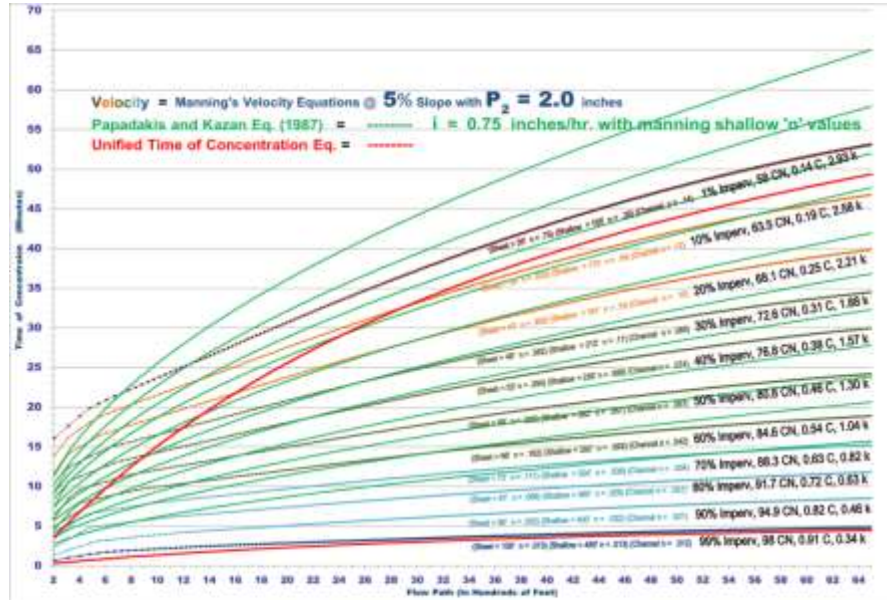


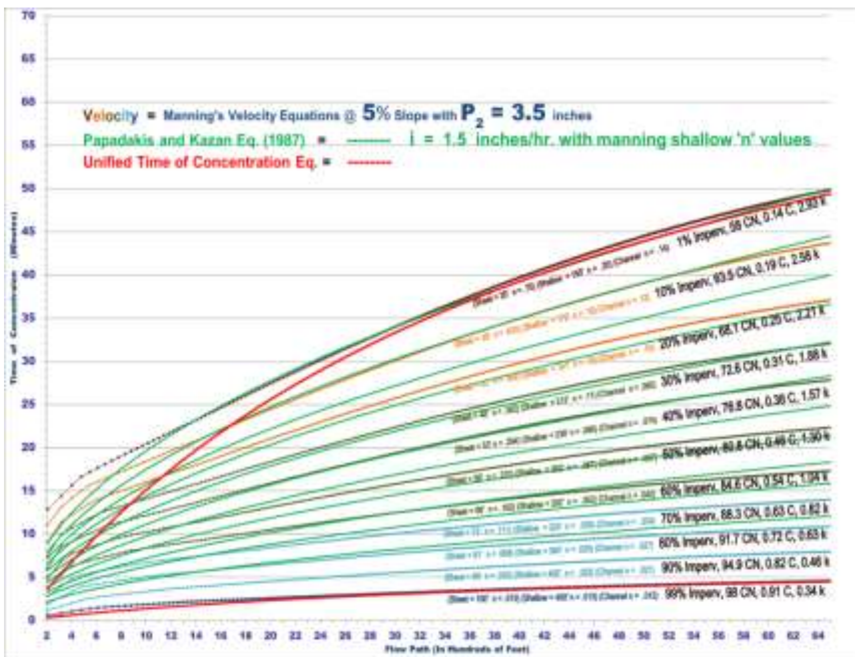


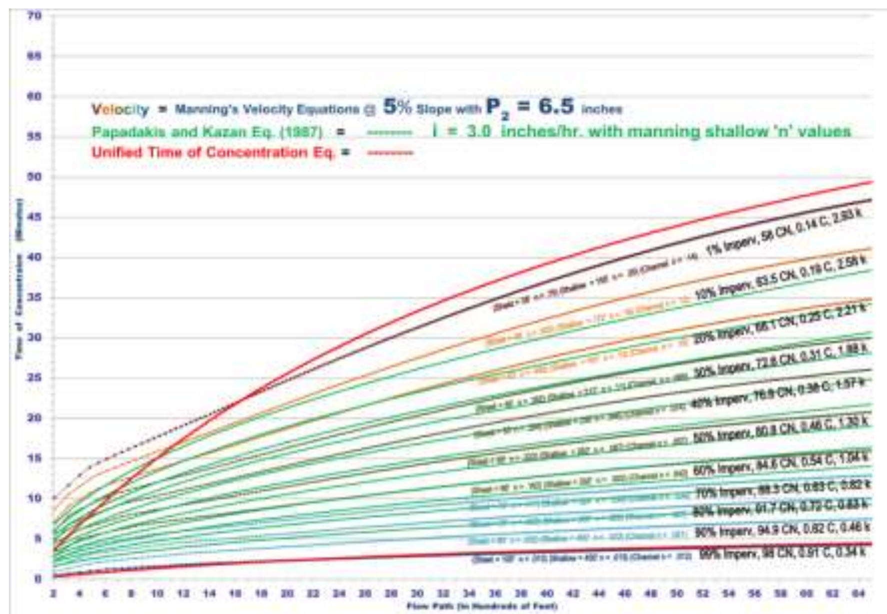


Papadakis-Kazan T_C with Manning's Shallow 'n' Value Compared to Velocity & UTC Equations

Percent Impervious	'n' Sheet Coefficients	'n' Shallow Coefficients	'n' Channel Coefficients
1%	0.750	0.200	0.140
10%	0.655	0.160	0.120
20%	0.511	0.130	0.100
30%	0.395	0.110	0.085
40%	0.302	0.086	0.074
50%	0.225	0.067	0.057
60%	0.161	0.052	0.042
70%	0.106	0.039	0.034
80%	0.060	0.029	0.027
90%	0.021	0.022	0.021
99%	0.013	0.013	0.012

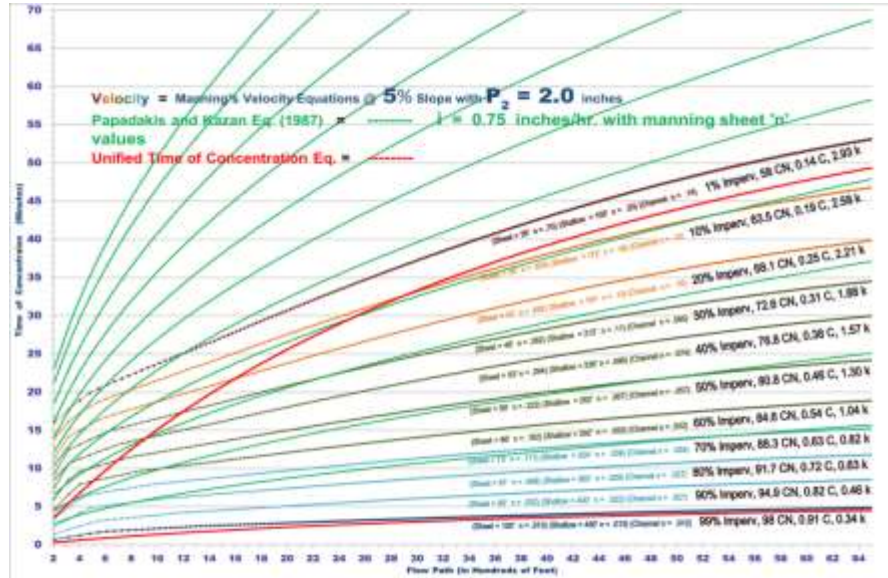


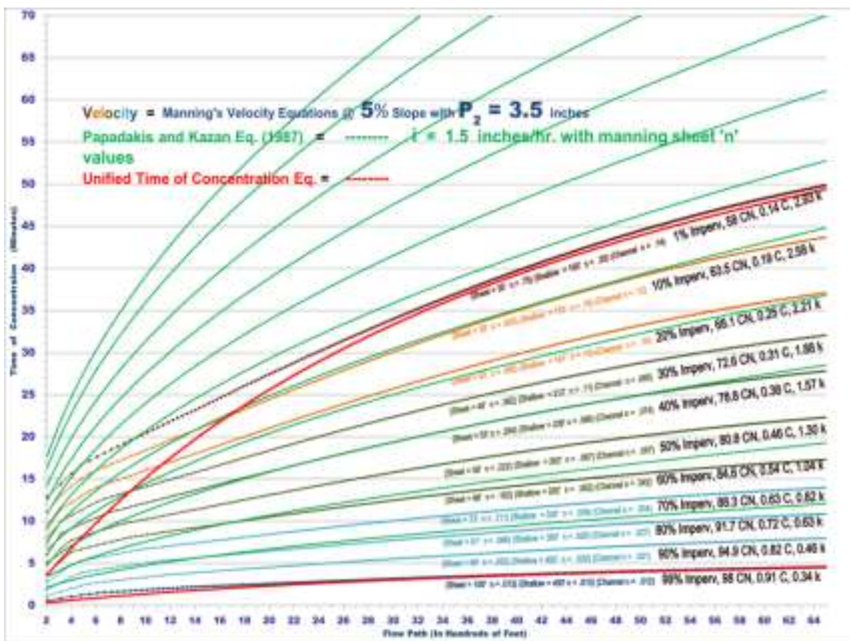


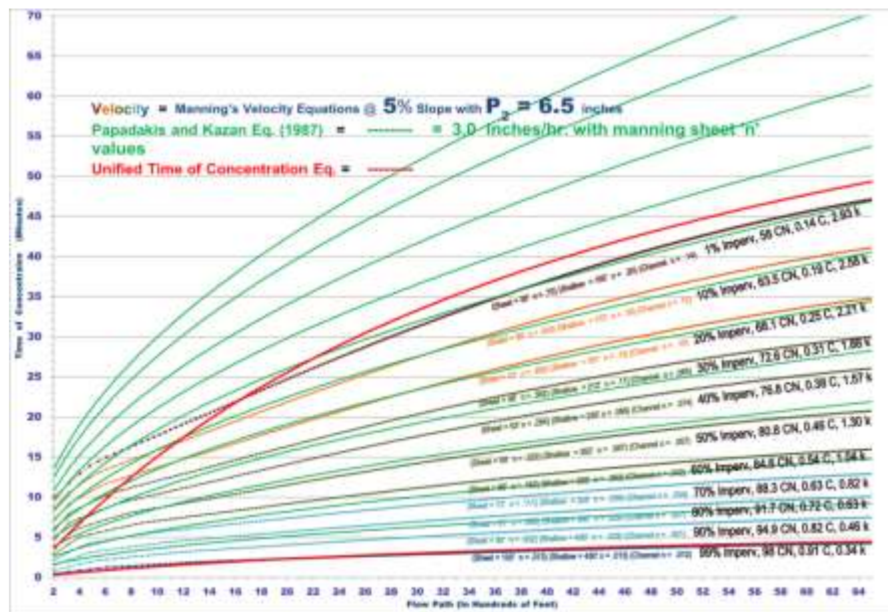


Papadakis-Kazan T_C with Manning's Sheet 'n' Value Compared to Velocity & UTC Equations

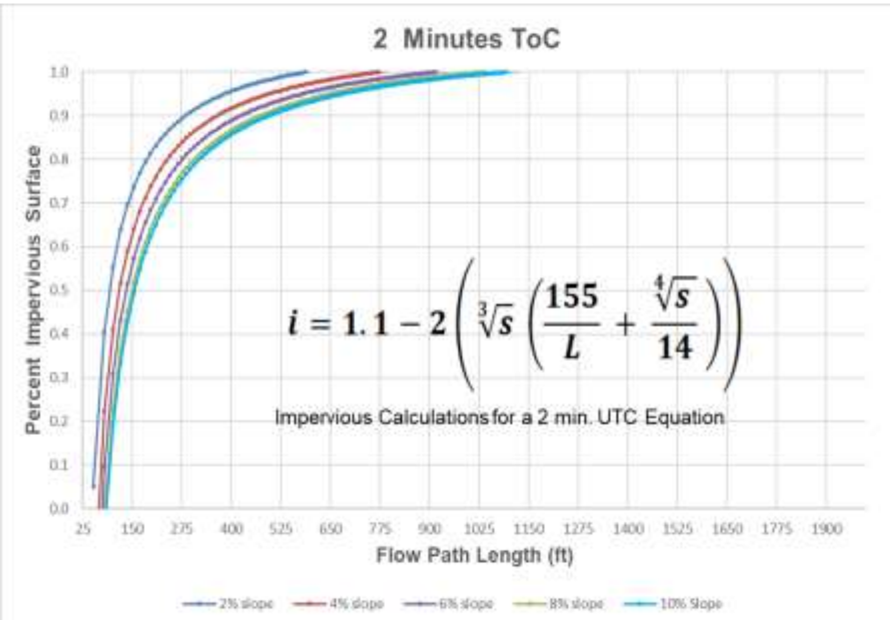
Percent Impervious	'n' Sheet Coefficients	'n' Shallow Coefficients	'n' Channel Coefficients
1%	0.750	0.200	0.140
10%	0.655	0.160	0.120
20%	0.511	0.130	0.100
30%	0.395	0.110	0.085
40%	0.302	0.086	0.074
50%	0.225	0.067	0.057
60%	0.161	0.052	0.042
70%	0.106	0.039	0.034
80%	0.060	0.029	0.027
90%	0.021	0.022	0.021
99%	0.013	0.013	0.012



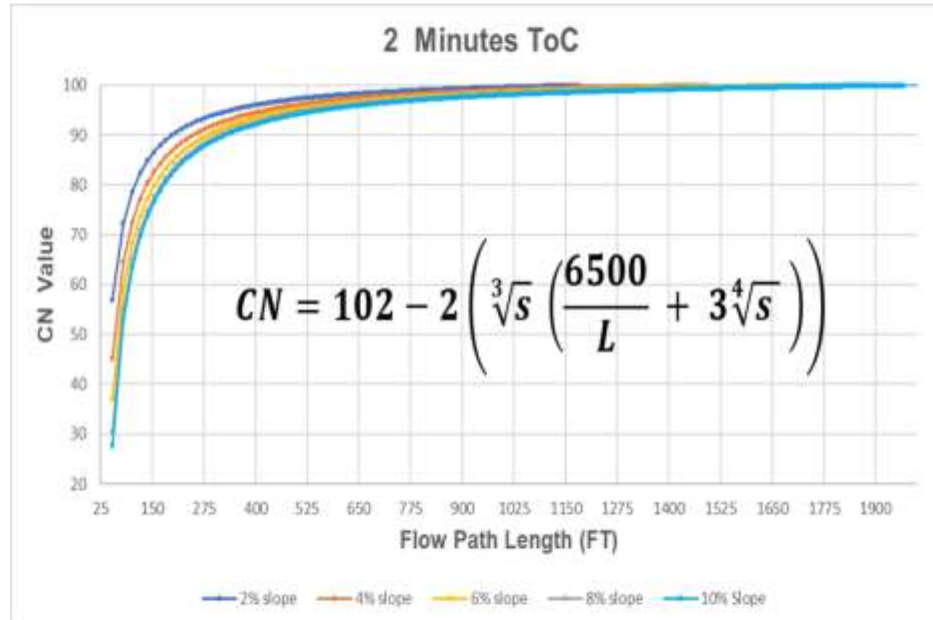




Mathematical Boundaries of Variables in the UTC, Kinematic Wave Flow, and Papadakis-Kazan Equations



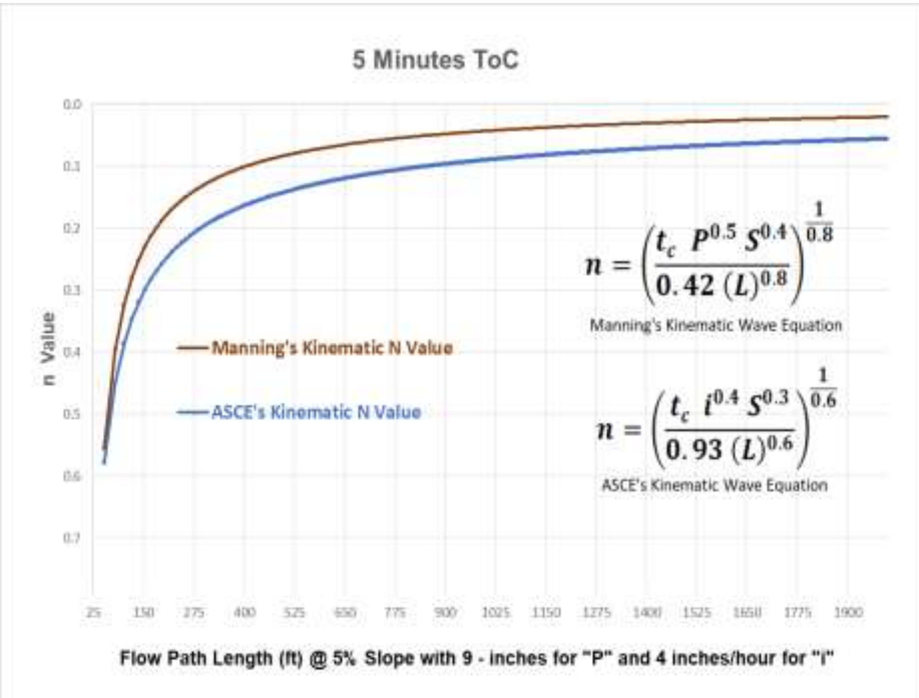
UTC Eq. plotted for Impervious Surface Boundary



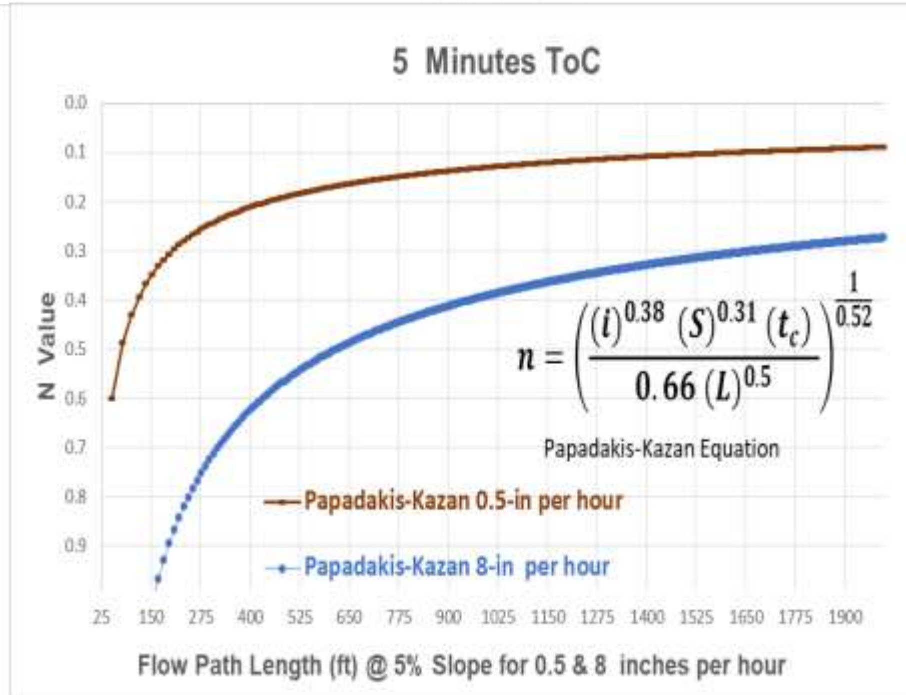
UTC Eq. plotted Surface Boundary of NRCS CN Values

Surface Boundary Coefficient's have Hydrologic Value Limits by Hydrology Definitions. However, These Limits May Not Exist within a Mathematic Equation.

Mathematical Boundaries of Variables in the UTC, Kinematic Wave Flow, and Papadakis-Kazan Equations



Kinematic Equations plotted for Surface Boundary of Manning's 'n' Value



Papadakis-Kazan Equation plotted for Surface Boundary of Manning's 'n' Value

Surface Boundary Coefficient's 'n' at the Vertical Axis can be Estimated with a Range of Limits for 's' and 'i' for the Entire Limits of the Mathematic Equation.

An Evaluation of the Papadakis-Kazan T_C Equation for a Full Range of Manning's Sheet Flow 'n' Values

$$T_c = \frac{k\,(L)^a\,(n)^b}{(i)^z\,(S)^y} \qquad T_c = \frac{0.66\,(L)^{0.5}\,(n)^{0.52}}{(i)^{0.38}\,(S)^{0.31}}$$

Papadakis-Kazan Equation Arranged for Rainfall Intensity

$$\mathbf{i} = \left(\frac{0.66\,(L)^{0.5}\,(n)^{0.52}}{(t_c)\,(S)^{0.31}}\right)^{\frac{1}{0.4}}$$

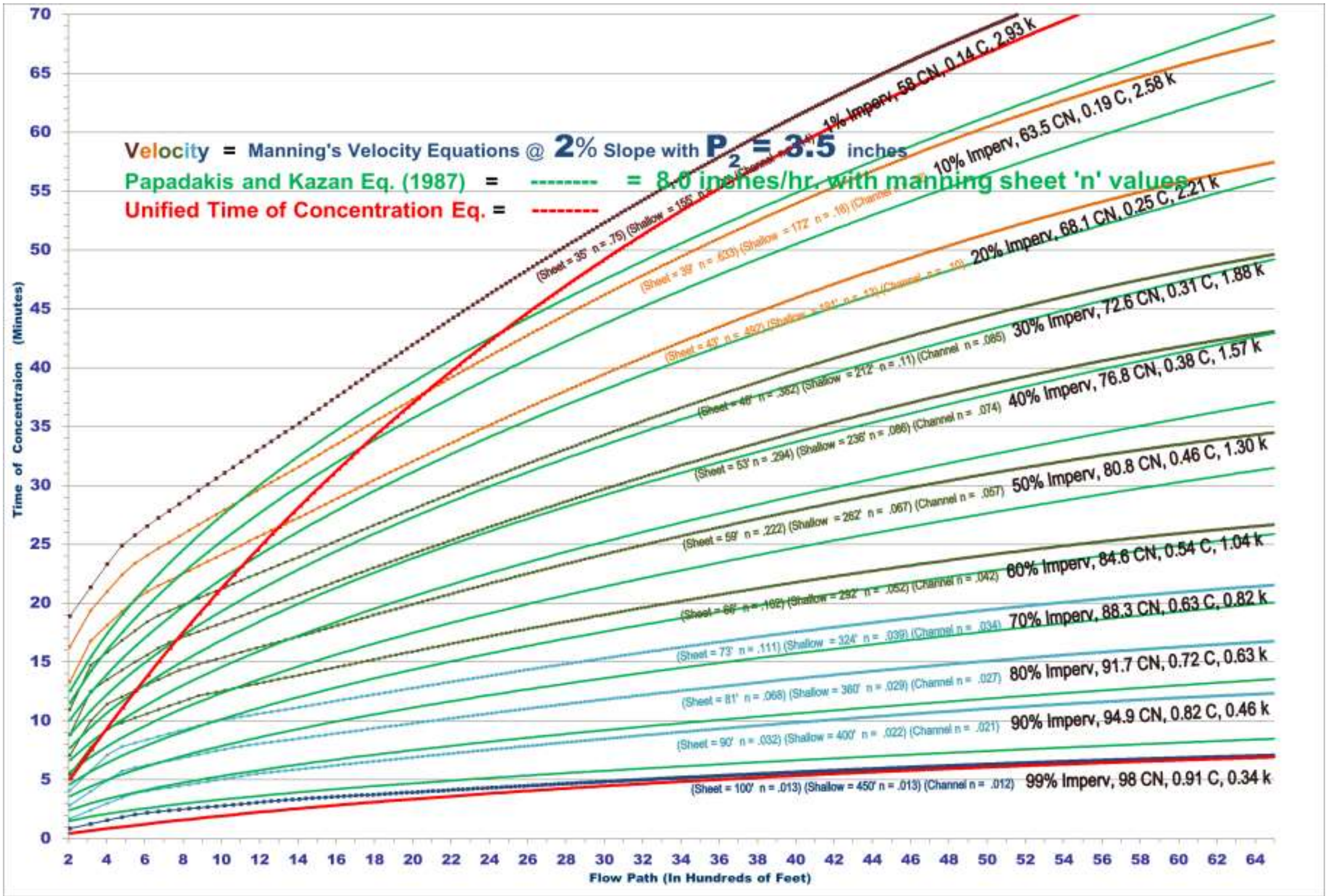
Partial Multi-Variable Derivative of Papadakis-Kazan Eq. with respect to 'L'

$$f_L\,(L,t,s) = \frac{\partial f}{\partial L} = \lim_{n \to 0.75} \left(\frac{0.66\,(L)^{0.5}\,(n)^{0.52}}{(t_c)\,(S)^{0.31}}\right)^{\frac{1}{0.4}}$$

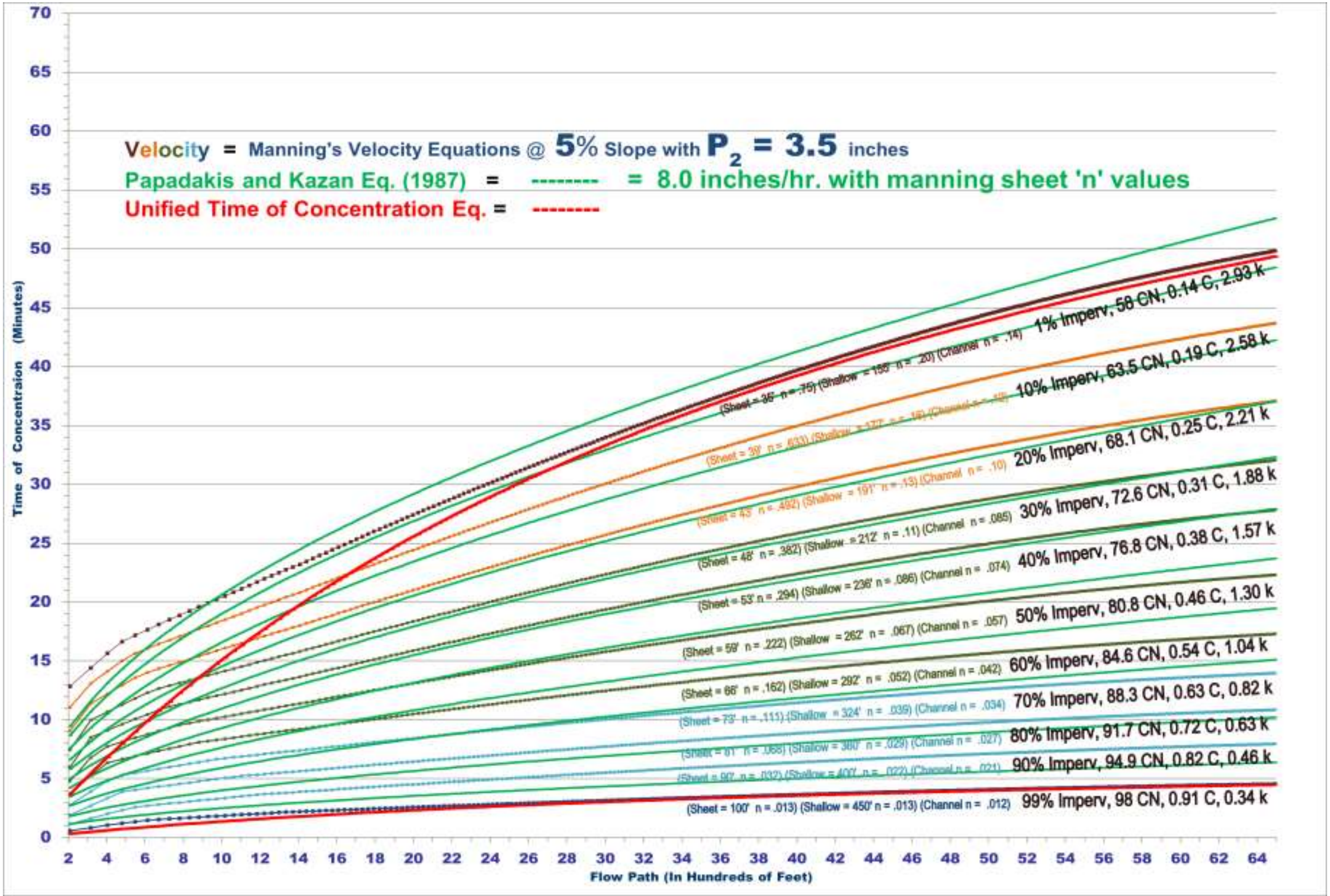
Papadakis-Kazan 'i' Optimized for Manning's Sheet Flow 'n' Values

$$T_c = \frac{0.66\,(L)^{0.5}\,(n)^{0.52}}{(8)^{0.38}\,(S)^{0.31}} = \frac{0.3\,(L)^{0.5}\,(n)^{0.52}}{(S)^{0.31}}$$

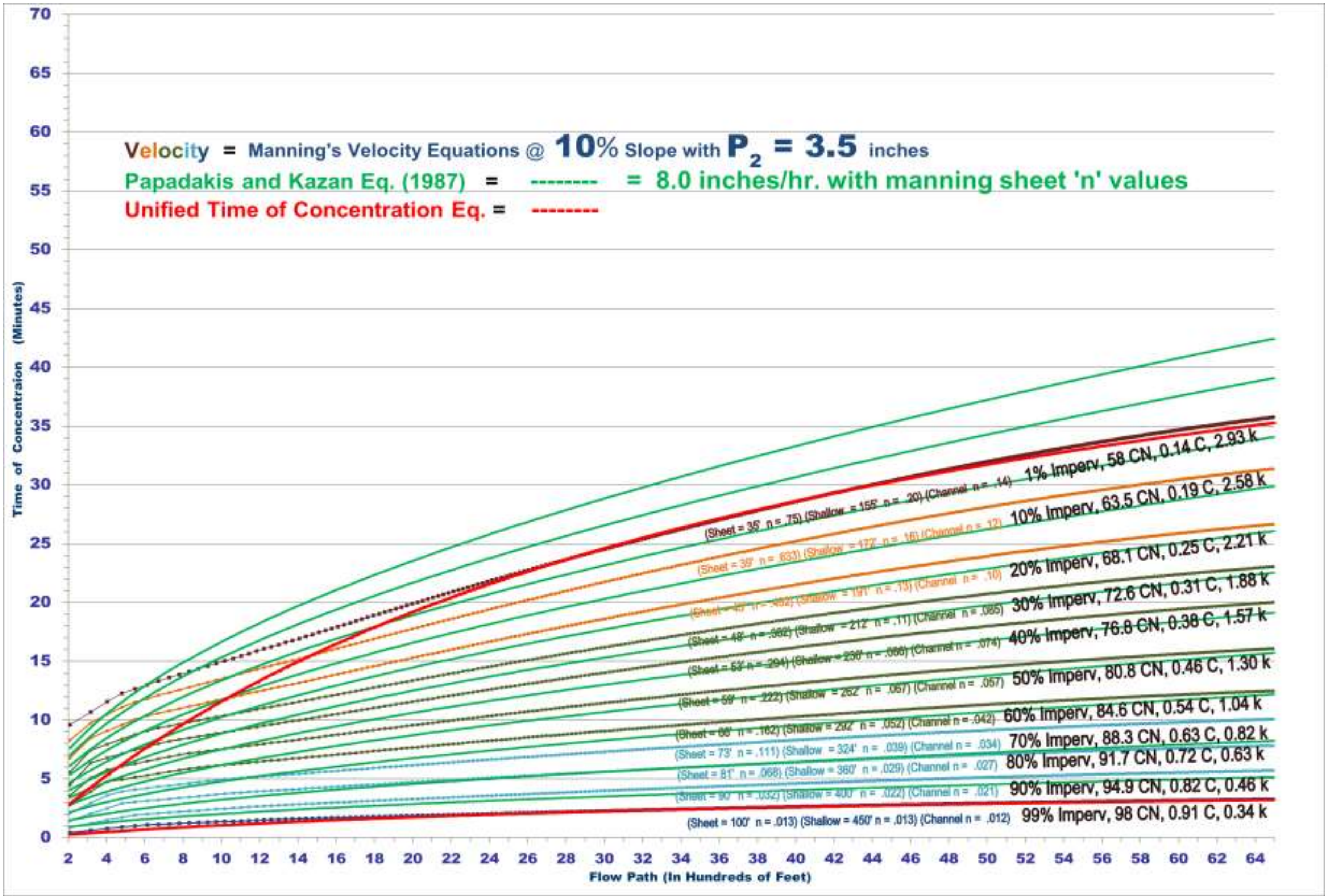
Papadakis-Kazan T_C Compared to Velocity & UTC Eqs.



Papadakis-Kazan T_C Compared to Velocity & UTC Eqs.



Papadakis-Kazan T_C Compared to Velocity & UTC Eqs.



Papadakis-Kazan T_C Equation for Surface Boundary Conditions with Manning's 'n' Sheet Flow Coefficients

Percent Impervious	'n' Sheet Coefficients
1%	0.750
10%	0.655
20%	0.511
30%	0.395
40%	0.302
50%	0.225
60%	0.161
70%	0.106
80%	0.060
90%	0.021
99%	0.013

$$T_c = \frac{0.3\,(L)^{0.5}\,(n)^{0.52}}{(S)^{0.31}}$$

. Papadakis-Kazan with surface and channelization attributes

- T_c = Time of Concentration (minutes)
- L = Length of Flow Path (feet)
- n_{avg} = Manning's Sheet Flow Coefficient
- s = % Slope of Flow Path (decimal format)
- Equation Limits: 1 to 500 acres of drainage basin
  1 to 12 percent slope for flow path
  0.013 to 0.75 Manning's sheet surface 'n' value

The Complexities of a T_c Equation when Properly Applied to a Basin's Attributes Can Reasonably Estimate a Response Time for Storm Water Runoff

Time of Concentration is Vital to Hydrograph Peak Flow Assessment And a Reasonably Estimated T_c can Vary Peak Flows by $\pm$ 300%.

The Accuracy of Time Equations are Improved with the following:

- Understanding the required variables in a time of concentration equation.
- Understanding the limits to each variable in a time of concentration equation.
- Understanding a basin's flow path with its flow type, length, depth, and slope.
- Apply acceptable surface roughness **T_c** coefficients that correlate to equivalent hydrology's surface roughness conditions used to calculate the hydrograph.

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