VERMONT
VTrans

Hydraulics Engineering Instructions (HEI)

Distribution: Structures, Bureau Chiefs, Chief of Contract Admin., Consultants

DocuSigned by:

Approved: Jeff DeGraff **Date:** 11/8/2024

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Subject: **Hydrology Updates**

Administrative Information:

Effective Date: This HEI shall be considered effective for the Structures & Hydraulics Section from the date of approval.

Superseded HEI: None.

Exceptions: None.

Disposition of HEI Content: The technical information transmitted by this HEI will be incorporated into the next revision of the VTrans Hydraulics Manual.

Purpose:

This HEI will update guidance and equations found in section 4.5.5 Time of Concentration Analysis of the VTrans Hydraulics Manual.

This HEI will add guidance for determining the average rainfall intensity found in Section 4.6.3 of the VTrans Hydraulics Manual.

This HEI will update the values to be used in the Area-Relationship Adjustment Technique Method 1 exponent term, *b,* found in section 4.10.3.1 of the VTrans Hydraulics Manual.

This HEI will update guidance and equations found in section 4.12.2.2 Computational Regression Analysis of the VTrans Hydraulics Manual.

This HEI will update Table 6-3 and will update allowable headwater guidance for culvert design found in Section 6.4.2.1 of the VTrans Hydraulics Manual.

This HEI will update section 6.6.4.2 Tailwater Conditions of the VTrans Hydraulics Manual.

The VTrans Hydraulics Manual does not provide guidance on the selection of design flows for riverine watersheds. VTrans will now provide such guidance.

The VTrans Hydraulics Manual does not provide guidance on applying bulking factors for riverine watersheds that have the potential for highly concentrated sediment, hyper-concentrated, mud and debris flows. VTrans will now provide such guidance.

Technical Information:

References:

Olson, S.A., 2014, Estimation of flood discharges at selected annual exceedance probabilities for unregulated, rural streams in Vermont, with a section on Vermont regional skew regression, by Veilleux, A.G.: U.S. Geological Survey Scientific Investigations Report 2014–5078, 27 p. plus appendixes.

Estimating Joint Probabilities of Design Coincident Flows at Stream Confluences, NCHRP Report 15-36

Manual Updates:

4.5.5 Time of Concentration Analysis

Drainage Area Equation

The following drainage area equation may be used when applying the Rational or TR-55/20 method for small watersheds. This approach is recommended as a check or for quick analyses.

$$T_c = 0.9A^{0.6}$$

Where:
T_c = time of concentration, hrs
A = drainage area, mi^2

SCS-Lag Method

The SCS-Lag method may be used when applying the Rational or TR-55/20 method for small watersheds. The SCS-Lag method variables may be determined with the use of Watershed Modeling System (WMS) or applicable GIS software. WMS is not necessarily free but a “community version” is available to the public.

1. Delineate the watershed.
2. Determine watershed length and slope.
3. Determine the composite Curve Number of the watershed with the use of the 2021 National Land Cover Dataset (2021 NLCD) and Curve Number Table below.
    a. The 2021 NLCD Curve Number Table assumes an Antecedent Moisture Condition II
4. Using the variables calculated above, determine the time of concentration with the use of the SCS-Lag method. The equation below has been converted to calculate time of concentration.

$$T_c = l^{0.8}\frac{(S+1)^{0.7}}{1140Y^{0.5}}$$

$$S = \frac{1000}{CN_{composite}} - 10$$

Where:
T_c = time of concentration, hrs
l = flow length, ft
Y = average watershed land slope, %
S = maximum potential retention, in
$CN_{composite}$ = composite curve number of the watershed

2021 NLCD Curve Number Table

NLCD Code	Description	HSG A	HSG B	HSG C	HSG D
11	*Open Water*	98	98	98	98
21	*Developed, Open Space*	39	61	74	80
22	*Developed, Low Intensity*	61	75	83	87
23	*Developed, Medium Intensity*	77	85	90	92
24	*Developed High Intensity*	89	92	94	95
31	*Barren Land (Rock/Sand/Clay)*	77	86	91	94
41	*Deciduous Forest*	30	55	70	77
42	*Evergreen Forest*	30	55	70	77
43	*Mixed Forest*	32	58	72	79
52	*Shrub/Scrub*	49	68	79	84
71	*Grassland/Herbaceous*	39	61	74	80
81	*Pasture/Hay*	39	61	74	80
82	*Cultivated Crops*	65	75	82	86
90	*Woody Wetlands*	84	89	90	92
95	*Emergent Herbaceous Wetlands*	60	78	87	90

Kirpich Equation

The Kirpich Equation was derived from examining the required time from the stream to rise from the low to maximum stage during a storm, and was assumed to be the time of concentration. This description indicates that this equation computes the lag to peak (lag time). The original hypothesis assumed that there was very little difference between the lag time and time of concentration for small watersheds. For this reason, the Kirpich Equation will be converted to Time of Concentration ($T_{lag} \sim 0.6T_c$) as shown below.

$$T_{lag} = 0.0078 l^{0.77} S^{-0.385}$$

$$T_c = \frac{mT_{lag}}{0.6}$$

Where:

T_c = time of concentration, mins
l = channel flow length, ft
S = slope of terrain conveying the channel, ft/ft $\left(\frac{\Delta h}{l}\right)$
m = overland flow correction factor

m is a correction factor that can be applied to account for watershed and/or channel roughness.

For overland flow on grassy surfaces, *m* is 2.0
For overland flow on bare earth, *m* is 1.0
For overland flow on concrete or asphaltic/smooth surfaces, *m* is 0.4

4.6.3 Description

In addition to the current method for determining rainfall intensity, the following preferred method may also be used.

The Vermont County Intensity Duration Frequency (IDF) Curve equations have been developed with the use of the Nelder-Mead method in conjunction with the NOAA Atlas 14 precipitation frequency estimates. The point precipitation frequency estimates were extrapolated at the centroid of each VT County. The VT County IDF equations are a function of time (time of concentration) and follow this general equation.

$$I = \frac{a}{(T_c + b)^c}$$

Where:

I = the average rainfall intensity for a duration equal to the time of concentration for a selected AEP, in/hr
T_c = time of concentration, mins
a = coefficient a
b = coefficient b
c = coefficient c

Table 4-8a below lists the coefficients to be used for each county and annual exceedance probability. The IDF equations are valid between 5 to 1440 minutes.

Table 4-8a VT County IDF Equation Coefficients

County	**Coeff.**	**50% AEP**	**20% AEP**	**10% AEP**	**4% AEP**	**2% AEP**	**1% AEP**	**0.5% AEP**	**0.2% AEP**
Addison	a =	16.49	21.33	25.39	30.75	35.04	38.68	42.52	47.19
	b =	2.57	2.77	2.84	2.90	2.95	2.89	2.84	2.76
	c =	0.68	0.69	0.70	0.70	0.70	0.70	0.70	0.69
Bennington	a =	14.35	18.34	21.43	25.97	29.21	32.79	36.12	42.20
	b =	1.75	1.81	1.80	1.85	1.84	1.87	1.74	1.94
	c =	0.63	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Caledonia	a =	17.00	19.76	21.99	25.07	27.63	30.06	31.84	34.58
	b =	2.71	2.53	2.38	2.22	2.16	2.10	1.92	1.82
	c =	0.69	0.68	0.67	0.67	0.66	0.66	0.65	0.64
Chittenden	a =	17.20	21.98	26.01	31.05	35.49	39.36	43.92	48.77
	b =	2.54	2.66	2.74	2.74	2.82	2.81	2.94	2.86
	c =	0.68	0.69	0.69	0.69	0.69	0.69	0.70	0.69
Essex	a =	16.54	19.15	21.21	24.37	26.68	29.30	32.32	36.99
	b =	2.64	2.46	2.27	2.19	2.13	2.11	2.07	2.04
	c =	0.69	0.68	0.67	0.66	0.66	0.66	0.66	0.66

County	**Coeff.**	**50% AEP**	**20% AEP**	**10% AEP**	**4% AEP**	**2% AEP**	**1% AEP**	**0.5% AEP**	**0.2% AEP**
Franklin	a =	16.71	21.53	25.95	31.48	35.75	40.41	45.53	51.17
	b =	2.61	2.72	2.93	2.98	3.00	3.09	3.22	3.12
	c =	0.69	0.69	0.70	0.71	0.71	0.71	0.72	0.71
Grand Isle	a =	16.69	21.80	26.24	32.05	36.81	41.13	46.90	53.42
	b =	2.68	2.81	2.91	2.93	3.03	2.99	3.14	3.03
	c =	0.69	0.69	0.69	0.70	0.70	0.70	0.70	0.70
Lamoille	a =	18.51	22.74	26.18	30.95	34.81	38.39	41.63	45.08
	b =	2.80	2.83	2.80	2.78	2.78	2.77	2.71	2.61
	c =	0.71	0.71	0.71	0.71	0.71	0.71	0.70	0.69
Orange	a =	17.30	21.75	25.58	30.71	34.58	38.89	43.53	50.29
	b =	2.77	2.71	2.69	2.65	2.63	2.66	2.63	2.65
	c =	0.70	0.69	0.69	0.69	0.69	0.69	0.69	0.68
Orleans	a =	17.14	20.33	22.86	26.58	29.31	31.99	34.93	38.24
	b =	2.72	2.62	2.51	2.43	2.38	2.30	2.26	2.10
	c =	0.70	0.69	0.69	0.68	0.68	0.68	0.67	0.67
Rutland	a =	15.89	20.10	23.63	28.49	32.16	36.20	40.89	45.47
	b =	2.42	2.45	2.50	2.53	2.55	2.60	2.74	2.50
	c =	0.68	0.68	0.68	0.68	0.68	0.69	0.69	0.68
Washington	a =	18.43	22.28	25.32	29.87	33.35	36.74	39.52	43.70
	b =	2.95	2.85	2.75	2.75	2.72	2.69	2.58	2.55
	c =	0.71	0.70	0.70	0.70	0.70	0.70	0.69	0.69
Windham	a =	13.34	16.76	19.29	23.23	25.85	29.05	31.92	36.17
	b =	1.67	1.75	1.67	1.75	1.68	1.76	1.70	1.75
	c =	0.62	0.62	0.62	0.63	0.62	0.63	0.62	0.62
Windsor County	a =	13.86	17.87	21.07	25.48	28.90	32.60	36.48	40.79
	b =	1.89	2.07	2.11	2.17	2.21	2.29	2.31	2.11
	c =	0.64	0.64	0.65	0.65	0.65	0.65	0.66	0.65

IDF Equation Example:

Givens:

Crossing is in Addison County
Time of concentration was determined to be 30 mins.

Determine the intensity at the 1% AEP.

Solution:
From Table 4-8a, the 1% AEP coefficients are

a = 38.68
b = 2.89
c = 0.70

$$\boldsymbol{I} = \frac{38.68}{(30 + 2.89)^{0.70}} = \mathbf{3.35}\ \boldsymbol{in}/\boldsymbol{hr}$$

<u>4.10.3.1 Method 1</u>

$$Q_{AEP_1} = \left[\frac{A_1}{A_2}\right]^b Q_{AEP_2}$$

Where:
Q_{AEP_1} = the peak runoff rate (at the selected AEP) for the watershed of unknown flows, cfs
Q_{AEP_2} = the peak runoff rate (at the selected AEP) for the watershed of known flows, cfs
A_1 = the drainage area to the location where flow is unknown, mi^2
A_2 = the drainage area to the location where flow is known, mi^2
b = the exponent to the drainage area ratio $(\frac{A_1}{A_2})$ at the selected AEP using Table 4-10c

Table 4-10c or b may be directly computed if there is a USGS gage found upstream and downstream of location being analyzed

Table 4-10c Method 1 Exponent to the Drainage Area Ratio Term

Annual Exceedance Probability (%)	**b[1]**
50%	0.869
20%	0.855
10%	0.847
4%	0.838
2%	0.833
1%	0.827
0.5%	0.822
0.2%	0.816

1 See "Drainage-Area-Only Regression Equations" section in *Olson, S.A., 2014*

4.12.2.2 Computational Regression Analysis

4.12.2.2.1 Gumbel

Specialized statistical software is not necessary to perform a regression analysis based on the Gumbel distribution. Use common spreadsheet software (e.g. MS Excel) to plot flow rate (Q_{AEP}) vs. the Gumbel reduced variate (y_{AEP}).

$$y_{AEP} = -\ln\left[-\ln(q_{AEP})\right]$$

$$q_{AEP} = 1 - \frac{AEP}{100}$$

Where:

Q_{AEP}	=	the peak flow rate at annual exceedance probability AEP, cfs
y_{AEP}	=	Gumbel reduced variate
q_{AEP}	=	probability
AEP	=	Annual Exceedance Probability, %

Apply a trendline (linear, polynomial, exponential, power, or logarithmic) to the plot. Choose the trendline that produces a R^2 value nearest to 1 and use the properties of the trend line (i.e. slope, intercept) to determine the flow rate for the AEP(s) of interest.

4.12.2.2.2 Log-Normal

Specialized statistical software is not necessary to perform a regression analysis based on the Log-Normal distribution. Use common spreadsheet software (e.g. MS Excel) to determine flow rates assuming a Log Normal distribution.

$$\mu = \log Q_{50\%}$$

$$\sigma = \frac{\log Q_{0.2\%} - \mu}{Z_{0.2\%}}$$

$$\log Q_{AEP} = \mu + Z_{AEP}\sigma$$

$$Q_{AEP} = 10^{\log Q_{AEP}}$$

$$q_{AEP} = 1 - \frac{AEP}{100}$$

Where:

μ	=	log of the mean peak flow rate at 50% AEP, cfs
σ	=	estimated log normal standard deviation
Q_{AEP}	=	the peak flow rate at annual exceedance probability AEP, cfs
$Q_{0.2\%}$	=	the peak flow rate at annual exceedance probability 0.2%, cfs
$Z_{0.2\%}$	=	Standard Normal Variable at annual exceedance probability 0.2%
q_{AEP}	=	Cumulative probability at annual exceedance probability AEP
AEP	=	annual exceedance probability, %

To determine the Standard Normal Variables, Z, found in the Table 4-13 below, simply use the NORM.INV excel function, with the use of the cumulative probability, and a mean and standard deviation value of 0.0 and 1.0 respectively.

The log normal standard deviation calculated above assumes that the flow curve follows a log normal distribution between the assumed mean value and 2% AEP flow and standard normal variable.

Table 4-13 Annual Exceedance Probability vs. Standard Normal Variable, Z

Annual Exceedance Probability (%)	Standard Normal Variable, Z
80%	-0.842
50%	0.000
20%	0.842
10%	1.282
4%	1.751
2%	2.054
1%	2.326
0.5%	2.576
0.2%	2.878

6.4.2.1 Allowable Headwater and Backwater, Table 6-3

The allowable headwater for a given crossing structure has been updated to better reflect the practices the VTrans Hydraulics unit has been following due to increased precipitation intensity rates and extreme storm events seen in Vermont. The headwater to depth ratios recorded in Table 6-3. "Hydraulic Criteria for Allowable Headwater at Culverts" will be revised to the following:

Table 6-3 Hydraulic Criteria for Allowable Headwater at Culverts

Stream Type	Allowable Headwater[1]
Perennial Stream	≤ 0.8 times the culvert rise at the design frequency (HW/D ≤ 0.8) ≤ 1.0 times the culvert rise at the check frequency (HW/D ≤ 1.0)
Intermittent Stream	≤ 1.0 times the culvert rise at the design frequency (HW/D ≤ 1.0) ≤ 1.2 times the culvert rise at the check frequency (HW/D ≤ 1.2)
Ephemeral Stream / Roadway Ditch	
Culvert Rise	
≤ 36 inches	≤ 1.5 times the culvert rise at the design frequency ($HW/D \leq 1.5$)
> 36 inches	≤ 1.2 times the culvert rise at the design frequency ($HW/D \leq 1.2$)
≥ 60 inches	≤ 1.2 times the culvert rise at the design frequency ($HW/D \leq 1.2$). In addition, check that $HW/D \leq 1.5$ during the 1% AEP storm event regardless of performance at other frequencies

[1] For culverts on NHS with long term woody debris/aggradation and maintenance issues consider a HW/D for 1% AEP (Q100) of ≤ 0.8

Regardless of the allowable headwater criteria found in Table 6-3, it is recommended that roadway overtopping is avoided for flood events equal or less than the 1% AEP (Q100) event.

If the criteria above can't be met or if there is reason for adjustment, written justification is to be provided and shall be approved by the VTrans Hydraulics Engineer.

6.6.4.2 Tailwater Conditions

Table 6-6 will be superseded with Table 6-6a, Table 6-6b, Table 6-6c. If a more refined analysis is necessary, Tables H.3, H.4, H.5, and H.6 found in NCHRP Report 15-36 may be used. Written justification is to be provided regarding which approach is to be used and shall be approved by the VTrans Hydraulics Engineer prior to using Table H.3 through H.6.

The method described below is intended to be used for sites with no or limited peak flow regulation.

Table 6-6a Watershed Categories

Drainage Area Ratio	A_{TOT} < 350 mi²	A_{TOT} ≥ 350 mi²
$RA < 7$	SS	SL
$RA \geq 7$	LS	LL

$$RA = \frac{A_{Main}}{A_{Tributary}}$$

$$A_{TOT} = A_{Main} + A_{Tributary}$$

Where:

A_{Main} = watershed area of Main river, mi^2

$A_{Tributary}$ = watershed area of Tributary river, mi^2

A_{TOT} = total watershed area, mi^2

RA = Drainage Area Ratio

The first letter found in Table 6-6a references the drainage area ratio. If the RA is less than 7, the ratio is small and is indicated by an "S." If RA is greater than or equal to 7 then the ratio is large and is indicated by an "L." The second letter in the code references A_{TOT}. If A_{TOT} is less than 350 mi^2, the letter "S" is assigned for small. Otherwise, the letter "L" is assigned for large for the second letter.

Combinations for individual annual exceedance probabilities on the tributary and main river for the 10%, 4%, 2%, 1%, and 0.2% AEP are summarized in Table 6-6b and Table 6-6c. The simplified analysis is to be used when the design AEP freeboard requirements are met without significantly increasing project costs with the use of Table 6-6b. The refined analysis is recommended to be used if there will be significant project cost increases to meet the design AEP freeboard requirements of the simplified analysis. The flow combinations found in Table 6-6c are to be used to determine a design water surface elevation for Watershed Category LL only for the 2%, 1% and 0.2% AEP. All other Watershed Categories (SS, SL, LS) will be analyzed using Table 6-6b regardless of the simplified or refined approach.

To determine the 80% AEP (1.25yr) discharge, the procedure in section *4.12.2.2.2 Log-Normal,* is recommended.

Table 6-6b Simplified Joint Probability Analysis

Category	Location	10% AEP Combination			4% AEP Combination			2% AEP Combination			1% AEP Combination			0.2% AEP Combination		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
SS	*Tributary*	50%	10%	10%	20%	4%	4%	10%	2%	2%	4%	1%	1%	1%	0.2%	0.2%
	Main	10%	10%	50%	4%	4%	20%	2%	2%	10%	1%	1%	4%	0.2%	0.2%	1%
SL	*Tributary*	50%	10%	10%	50%	4%	4%	20%	2%	2%	10%	1%	1%	2%	0.2%	2%
	Main	10%	10%	50%	4%	4%	50%	2%	2%	20%	1%	1%	10%	0.2%	0.2%	0.2%
LS	*Tributary*	50%	10%	10%	20%	4%	4%	10%	2%	2%	4%	1%	1%	1%	0.2%	0.2%
	Main	10%	10%	50%	4%	4%	20%	2%	2%	10%	1%	1%	4%	0.2%	0.2%	1%
LL	*Tributary*	80%	10%	10%	80%	4%	4%	50%	2%	2%	50%	1%	1%	20%	0.2%	0.2%
	Main	10%	10%	80%	4%	4%	80%	2%	2%	50%	1%	1%	50%	0.2%	0.2%	20%

Simplified Joint Probability Analysis Procedure:

To evaluate tailwater conditions for structures located within the influence of a downstream river confluence:

- Evaluate the joint probability of flood magnitudes based on Table 6-6a and Table 6-6b
- Water Surface Elevations are to be determined using combination 2 for all annual exceedance probabilities and watershed categories.
    1. For example, to evaluate a 2% AEP storm event for a RA ≥ 7 and A_{TOT} ≥ 350 mi^2. Category "LL" is to be used from Table 6-6a in conjunction with Table 6-6b.
        - Evaluate a 2% AEP discharge occurring in the tributary and a 2% AEP discharge occurring in the main river. This is the design combination for determining water surface elevations.
- For scour evaluation and countermeasure design, all combinations are to be assessed.
    1. For example, to evaluate a 2% AEP storm event for a RA ≥ 7 and A_{TOT} ≥ 350 mi^2. Category "LL" is to be used from Table 6-6a in conjunction with Table 6-6b.
        - Combination 1: Evaluate a 50% AEP discharge occurring in the tributary and a 2% AEP discharge occurring in the main river.
        - Combination 2: Evaluate a 2% AEP discharge occurring in the tributary and a 2% AEP discharge occurring in the main river.
        - Combination 3: Evaluate a 2% AEP discharge occurring in the tributary and a 50% AEP discharge occurring in the main river.
        - The combination resulting in the largest scour depth and/or highest velocity (or unit discharge) at the bridge/location of interest is the design combination.

Table 6-6c Refined Joint Probability Analysis: Watershed Category LL Only

Category	Location	2% AEP Combination					1% AEP Combination					0.2% AEP Combination				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
LL	*Tributary*	50%	4%	4%	2%	2%	50%	2%	2%	1%	1%	20%	1%	1%	0.2%	0.2%
	Main	2%	2%	4%	4%	50%	1%	1%	2%	2%	50%	0.2%	0.2%	1%	1%	20%

Refined Joint Probability Analysis Procedure:

To evaluate tailwater conditions using the refined joint probability analysis for structures located within the influence of a downstream river confluence and have a Watershed Category LL:

- Evaluate the joint probability of flood magnitudes for the 10% and 4% AEP based on Table 6-6a and Table 6-6b.
  - Water Surface Elevations are to be determined using Combination 2 for the 10% and 4% annual exceedance probabilities and watershed categories.
- Evaluate the joint probability of flood magnitudes for the 2%, 1% and 0.2% AEP based on Table 6-6c and Watershed Category LL.
  2. For example, to evaluate a 2% AEP storm event for a RA ≥ 7 and A_{TOT} ≥ 350 mi^2. Category “LL” is to be used from Table 6-6a in conjunction with Table 6-6c.
     - Combination 1: Evaluate a 50% AEP discharge occurring in the tributary and a 2% AEP discharge occurring in the main river.
     - Combination 2: Evaluate a 4% AEP discharge occurring in the tributary and a 2% AEP discharge occurring in the main river.
     - Combination 3: Evaluate a 4% AEP discharge occurring in the tributary and a 4% AEP discharge occurring in the main river.
     - Combination 4: Evaluate a 2% AEP discharge occurring in the tributary and a 4% AEP discharge occurring in the main river.
     - Combination 5: Evaluate a 2% AEP discharge occurring in the tributary and a 50% AEP discharge occurring in the main river.
     - The combination resulting in the largest water surface elevation is to be used for setting low beam elevations.
     - The combination resulting in the largest scour depth and/or highest velocity (or unit discharge) at the bridge/location of interest is the design combination for scour evaluation and countermeasure design.

Riverine Design Flow Guidance:

The following methods are listed in order of preference

1. USGS Gage Flows
2. FEMA Flood Insurance Study (FIS) Peak Discharges
3. USGS Regression Equations
4. Other

The Design flows chosen can be vetted by calibrating a hydraulic model to highwater marks. Highwater marks for past flood events may be viewed on USGS Flood Event Viewer.

USGS Gage Flows

Design flow rates at USGS Gage(s) of interest have been determined using statistical methods, including the Bulletin 17B or 17C method. PeakFQ may be used to perform the updated Bulletin 17B or 17C analysis.

Skew

When implementing Bulletin 17B or 17C, the weighted skew is recommended to be used.

If the Station Skew is significantly different than the Regional Skew, more consideration should be taken into choosing either the Station or Regional Skew. The Station Skew may be used if the peak flows are highly regulated. The Regional Skew may be used for sites that have limited data and meet the criteria explained below.

Regional Skew Criteria

The regional skew was generated using sites with no or limited peak flow regulation. When regional skew for VT was determined, site selection criteria included a maximum of 4.5 million cubic feet of usable storage per square mile. This criteria was based on a study titled Factors influencing the occurrence of floods in a humid region of diverse terrain (Water Supply Paper 1580-B). Water Supply Paper 1580-B found that in New England, storage less than 4.5 million cubic feet of usable storage per square mile affected peak flows by less than 10%.

Regional Skew

A regional skew of 0.44 with an average variance of prediction equal to 0.078 is to be used. The average variance of prediction corresponds to the Mean Square Error (MSE) in Bulletin 17B. The Regional Skew Standard Error used is determined by taking the square root of the average variance of prediction as shown in the Figure 1 below.

Regional Skew	Reg Skew Std Error	Mean Sqr Err
0.44	0.2793	0.078

Figure 1 – Regional Skew and Standard Error

Area-Relationship Adjustment

When USGS Gage Flows are available, the flow values shall be adjusted with the use of the Area-Relationship Adjustment Technique Method 1. See section 4.10.1 for Method 1 applicability.

FEMA Flood Insurance Study (FIS)

Regardless of the design flows chosen, the FEMA Flood Insurance Study (FIS) 1% AEP (100-yr) Peak Discharge is to be used when determining potential impacts to 100-yr base flood elevations (BFEs).

When USGS Gage Flows are not available, the flow values from the applicable FEMA Flood Insurance Study Peak Discharges Table shall be used. If FIS Peak Discharges are not used, written justification is to be provided and shall be approved by the VTrans Hydraulics Engineer.

Curve Fitting

FIS Peak Discharges are typically reported at the 10%, 2%, 1% and 0.2% AEP. To determine intermediate flow values, VTrans recommends that the Log-Normal Distribution in section 4.12.2.2 shall be used. To determine the 50% AEP flow value, an iterative approach may be implemented such that the difference between a known flow value at the 2% or 1% AEP and the calculated value is within 5%.

Area-Relationship Adjustments

For crossings located in Zone A without BFEs and/or No Delineated Floodplain; Zone X, FIS Peak Discharges may need to be adjusted with the use of the Area-Relationship Adjustment Technique Method 1.

The following applies when using Method 1:

- The drainage area to the location of unknown flows is 0.5 to 1.5 times the drainage area to the location of known flows.
- There are no significant tributaries between the Peak Discharge location and the area of interest, especially if they originate in different types of terrain, or if they are subject to dam and reservoir controls.

USGS Regression Equations

When USGS Gage Flow or FEMA FIS Peak Discharges are not available, or Method 1 is not applicable, the use of the current USGS Regression equations (Table 4-9b) may be used within their application.

For Drainage Areas greater than 0.30 sq. mi. and less than 4.5 sq. mi. the following procedure is recommended to transition between the Rational Method and the current USGS Regression Equation:

1. Using the same mean annual precipitation and %wetlands for the watershed of interest, determine the upper limit flow for a drainage area equal to 0.3 sq. mi.

$$Q_{AEP_{A=0.3}} PUI_{AEP}$$

2. Using the same mean annual precipitation and %wetlands for the watershed of interest, determine the flow (with no flow value adjustments, Table 4-9b) for a drainage area equal to 4.5 sq. mi.

$$Q_{AEP_{A=4.5}}$$

3. To determine the flow at the project site, use linear interpolation as shown below.

$$Q_{AEP_{site}} = Q_{AEP_{A=0.3}} PUI_{AEP} + (A_{site} - 0.3\ sq.mi.)\left(\frac{Q_{AEP_{DA=4.5}} - Q_{AEP_{DA=0.3}} PUI_{AEP}}{4.5\ sq.mi. - 0.3\ sq.mi}\right)$$

Where:

$Q_{AEP_{site}}$	=	the peak flow rate at annual exceedance probability AEP, cfs at the site of interest
$Q_{AEP_{A=0.3}}$	=	the peak flow rate at annual exceedance probability AEP, cfs for a watershed area equal to 0.3 sq. mi.
$Q_{AEP_{A=4.5}}$	=	the peak flow rate at annual exceedance probability AEP, cfs for a watershed area equal to 4.5 sq. mi.
PUI_{AEP}	=	Upper Prediction Interval multiplier at annual exceedance probability AEP
A_{site}	=	Watershed area at the site of interest, sq. mi.
AEP	=	annual exceedance probability, %

The Upper 90% Prediction Interval Flow Value ($Q_{AEP} PUI_{AEP}$) may be taken directly from the StreamStats Report, or the Upper 90% Prediction Interval Flow values may be estimated by multiplying the USGS Regression Equation Flow Value (see Table 4-9b) at annual exceedance probability AEP by the corresponding PIU multiplier at annual exceedance probability AEP. (see Table 4-9d below)

Table 4-9d 90% Confidence Prediction Interval Multipliers

Annual Exceedance Probability (%)	**Lower Prediction Interval (PIL)**	**Upper Prediction Interval (PIU)**
50%	0.57	1.75
20%	0.56	1.79
10%	0.54	1.85
4%	0.51	1.96
2%	0.49	2.06
1%	0.48	2.10
0.5%	0.45	2.21
0.2%	0.43	2.35

Other

For Drainage Areas less than 0.30 sq. mi. the Rational Method is recommended for use.

All other methods not listed above that are found in Table 4-3 may be used with a written justification and approved by the VTrans Hydraulics Engineer.

The TR-55 or TR-20 method may be used in urban watersheds with written justification and shall be approved by the VTrans Hydraulics Engineer.

If an unsteady state flow model is warranted, the SCS or Snyder Unit hydrograph may be used in conjunction with the SCS Curve Number method, and Type II 24-hour SCS Hyetograph to estimate inflow hydrographs. An alternate design hyetograph may be used with written justification and shall be approved by the VTrans Hydraulics Engineer.

Bulking Factor & Design Flow Adjustment:

Mud and debris flows transport large volumes of solid material that the liquid/solid mixture volume is increased significantly and is known as “bulking”. In watersheds that are known (or prone) to have high concentrations of sediment (mud and debris) in the flow, the design flows may need to be adjusted with the use of a Bulking Factor. The **Bulking Factor** is the ratio of bulked discharge to clear-water discharge which aids in hazard assessments to help determine the potential impacts and reduce the risk of damage to the transportation infrastructure. The volumetric sediment flow can be back calculated for a known or approximated clear-water discharge.

The designer may reference ANR’s GIS Landslide Dataset to determine if a bulking factor should be incorporated into the analysis.

The equation for bulking factor is:

$$BF = \frac{Q + Q_s}{Q} = 1 + \frac{C_v}{1 - C_v} = 1 + \frac{C_w}{S_g(1 - C_w)}$$

Where:

BF	=	Bulking Factor
Q	=	clear water discharge, cfs
C_v	=	concentration by volume (sediment volume/total volume)
C_w	=	concentration by weight (sediment weight/total weight)
S_g	=	sediment specific gravity

The design discharge is then determined by the following equation

$$Q_{design_{AEP}} = Q_{AEP} * BF$$

Where:

BF	=	Bulking Factor
Q_{AEP}	=	the peak (clear water) flow rate at annual exceedance probability AEP, cfs
Q_{design_AEP}	=	the design peak flow rate at annual exceedance probability AEP, cfs

Figure 2 shows the range of taxonomies of geophysical flows as a function of concentration percent by volume.

Blue indicates clear water flow with sediment.
Light to Dark Brown indicates hyper-concentrated to mud flow
Light to Dark Gray indicates debris to land slide flows

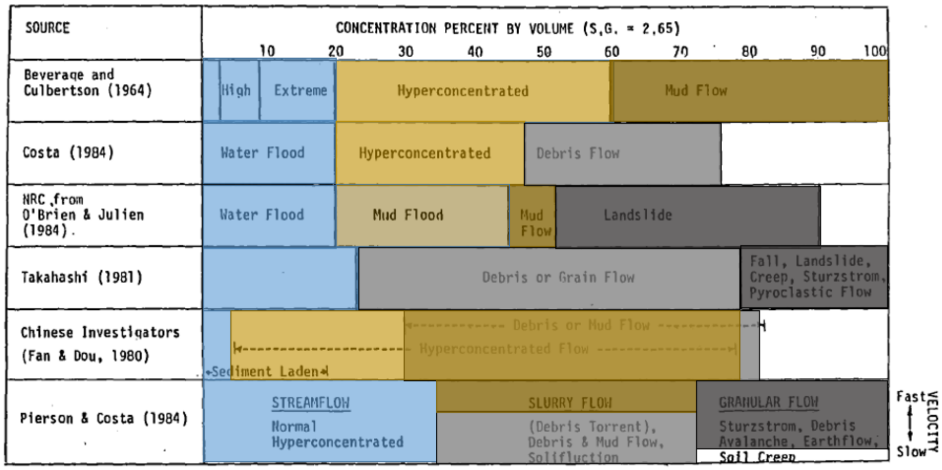

Figure 2 - ***Various taxonomies of geophysical flows illustrating the diversity of definitions (modified from Philips (1888) after Bradley and McCutcheon, 1985)).***

Implementation:

The content of this HEI will be implemented immediately on all projects.

Transmitted Materials:

No supplemental materials are transmitted with this HEI.