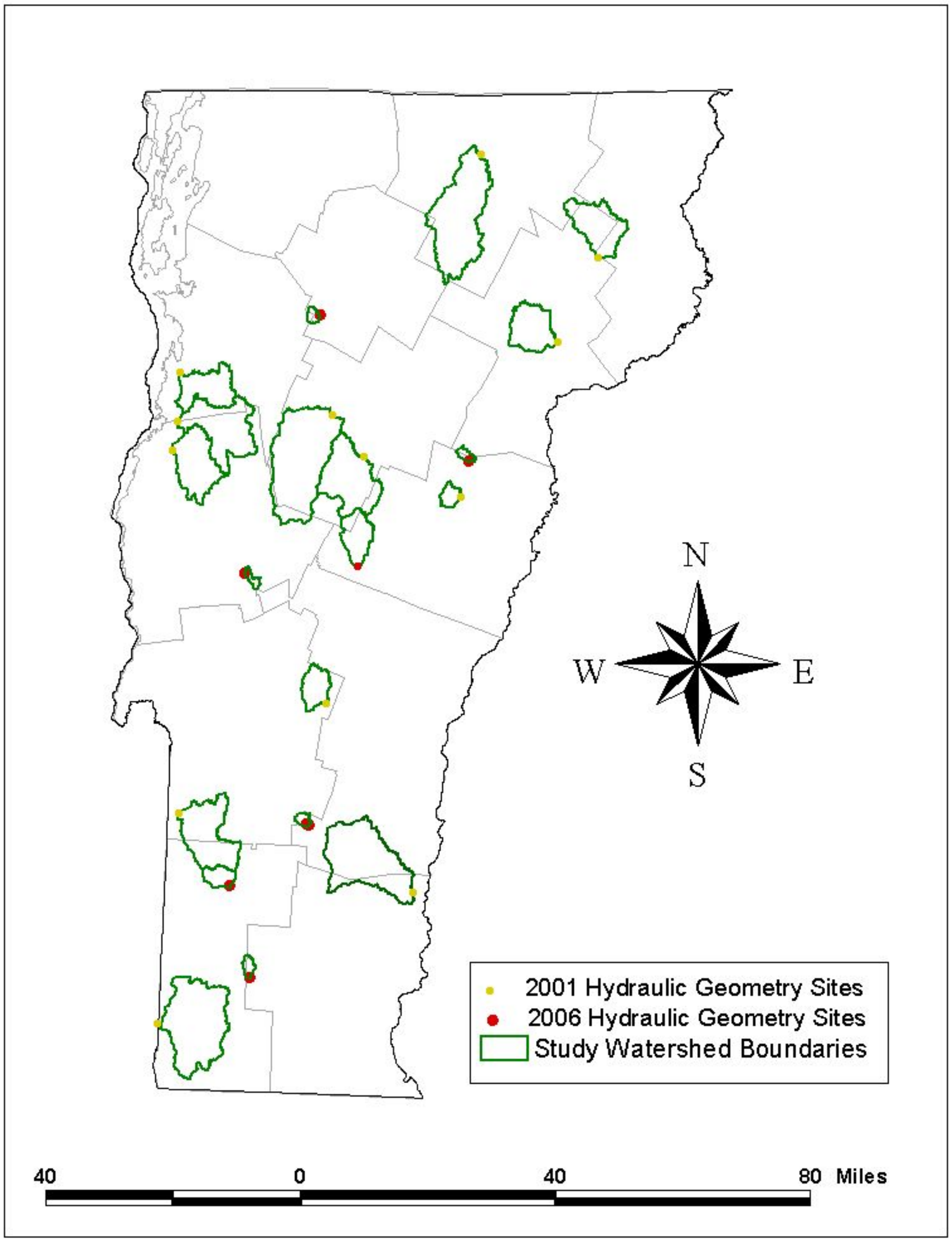
Vermont Stream Geomorphic Assessment

Appendix J



Vermont Regional Hydraulic Geometry Curves

River Management Program
Vermont Agency of Natural Resources
January, 2006

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Abstract

Hydraulic geometry data from six ungaged streams in Vermont, ranging from four to 13 square miles of drainage area, were gathered and added to hydraulic geometry curves previously developed by the Vermont Department of Environmental Conservation (Vermont DEC, 2001). Four of the surveyed stream reaches have entrenchment ratios less than 2.2 and width to depth ratios greater than 12 which places them in the Rosgen B-stream type category (Rosgen, 1998). Two of the stream reaches have entrenchment ratios greater than 2.2 and width to depth ratios greater than 12 which places them in the Rosgen C-stream type category (Rosgen, 1998).

To verify that the flow frequency of the identified bankfull stage at each reach was within reasonable proximity to the theoretical value of 1.5 years the discharge associated with the identified bankfull stage was determined using stage discharge relations developed during this study and compared to the predicted 2-yr. recurrence interval flow as calculated using a regression equation developed by the United States Geological Survey (Olson, 2002) to calculate peak flow frequency characteristics of Vermont streams. Bankfull values extrapolated from the stage discharge curves fell within the standard error of prediction of the Olson equation.

Addition of the new data points to the previously developed Vermont Hydraulic Geometry Curves (Vermont DEC 2001) significantly strengthened the regressions describing the relation between drainage area and bankfull hydraulic geometry. Considering the typical application of and standard error of prediction associated with the regional curves, the change in predicted bankfull dimension values (cross section, width and depth) resulting from the addition of the 2006 data points are not substantial.

Flow measurement and hydraulic geometry data was used to test the applicability of an equation relating friction factor to relative roughness presented in Rosgen (1998). The test showed that the Rosgen (1998) friction factor equation does not accurately predict friction factor of the study streams. Velocities calculated using the Rosgen (1998) based friction factor vary from measured velocities by 33% on average. The equation was revised using flow measurement data from this study and used to recalculate velocities. The average variation between calculated and measured velocity decreased to 16%. These results are encouraging in that they suggest locally derived relative roughness friction factor relationships may lead to improved accuracy in velocity calculations. The revised relation should be tested on streams outside of the study streams.

Study Objectives

Bankfull hydraulic geometry relationships, otherwise known as regional curves were presented by Dunne and Leopold (1978). Regional hydraulic geometry curves describe the relation between drainage area of a channel and the bankfull hydraulic characteristics of discharge, cross-sectional area, width and depth of the channel. Hydraulic geometry curves developed by the Vermont Department of Environmental Conservation (VT DEC, 2001) have proven to be a useful tool in predicting the equilibrium condition hydraulic geometry of streams in Vermont.

Use of the hydraulic geometry curves has assisted in: geomorphic assessment, regulatory activities, flood recovery, fluvial conflict management and stream corridor protection and restoration design. Empirical evidence has verified that the curves' accuracy of prediction when applied to streams of the same size and morphologic type as those used to develop the curves is sufficient for the intended applications. Users of the curves have reported that the curves appear to under predict hydraulic geometry characteristics, particularly width, when applied to higher gradient streams draining an area less than the lower limit of the range of those used to develop the curves. The primary purpose of this study was to obtain and add data points from small streams in Vermont to improve the accuracy of prediction of the 2001 Vermont Hydraulic Geometry Curves when applied to small streams.

Flow velocity is strongly related to flow resistance (Knighton, 1998). Boundary resistance is the component of flow resistance that has been shown to have the most affect on velocity. Grain roughness is a component of boundary resistance and has been shown to be a function of relative roughness wich is the ratio of mean flow depth (d) to D84 (the diameter at which 84 percent of the particles are finer). Rosgen (1998) presents a plot of the relation between relative roughness and the ratio of velocity to shear velocity (v/v*). The data on the plot is from Leopold et. al (1964) and Limerinos (1970). The equation describing the line fit to the data is given as:

$$v/v^* = 2.83 + 5.7\mathrm{Log}(d/D84).$$

The Vermont DEC Phase 3 stream geomorphic assessment spreadsheet calculates flow velocity using the above equation. Because the data sets used to develop the equation do not originate in the north eastern U.S. the applicability of this relationship to Vermont rivers has been questioned. A secondary purpose of this study is to verify the applicability of the above relationship to Vermont Rivers.

Site Selection

Several criteria were established for use in site selection. To qualify as study sites, candidate sites needed to: be of reference condition (see, 2001 Vermont Regional Hydraulic Geometry Curves), drain an area of less than 15 square miles, have a slope less than three percent and have well developed bankfull indicators. Data for the development of the 2001 Vermont regional curves was collected near active flow gages. Because of the lack of active USGS flow gages on small streams in Vermont we decided that study sites did not need to be in the vicinity of active gages.

Because sites were not required to be in the proximity of active flow gages possible site locations included nearly any reach of river in Vermont that met the above criteria. Remote screening data used to iteratively reduce the number of candidate sites included: Emergency 911 GIS data as an indicator of existing development, Vermont Biophysical Regions Data (Sorenson and Thompson, 2000) as an indicator of bedrock surficial geology and topographic characteristics, Vermont Road data (Vermont Center for Geographic Information) as an indicator of roadway encroachments, ortho-photographs (1990's) as an indicator of surrounding land use and information on Vermont's flood history (Cahoon, 2004 personal communication) as an indicator of potential historic flood damage and mitigation related alterations. Information provided by the Green Mountain National Forest helped to identify sites with a high probability of meeting the established criteria. A list of likely study sites was developed and field visits made to each to verify the suitability of each as a study site.

Verifying Correct Identification of Bankfull Stage

Data for the development of hydraulic geometry curves is typically collected at locations of flow gages with a period of record longer than 20 years. This allows for the bankfull stage selected by observation of field indicators to be correlated to a flow recurrence interval as calculated from the long term flow data. It has been shown that the bankfull or channel forming flow of different streams within a hydrophysiographic region will have a common recurrence interval which is typically in the proximity of 1.5 years (Leopold, etc, etc). Using this principle the researchers are able to verify that they have correctly identified the bankfull stage by comparing the flow frequency of the bankfull discharge to the theoretical value of 1.5.

Of the six sites selected only the Ranch Brook site, which has been in operation for four years, is in the proximity of an active USGS flow gage. None of the remaining study sites were located in the proximity of a gaging station. The absence of long term flow gages near the study sites prevented the standard practice of using long term flow data to calculate a recurrence interval for the field identified bankfull stage at each site. As an alternative means of providing some level of verification that the recurrence interval of the field identified stage was within the proximity of that which was expected the Vermont Flow Frequency Tool (Olson, 2003) was used to predict the 2-year discharge for each site. Stage discharge rating curves were developed and used to determine bankfull discharge and the bankfull discharge was then compared to the 2-year flow predicted by the Vermont Flow Frequency Tool (Olson, 2003).

Stage Discharge Rating Curves

Table 1 presents flow measurement data that was collected during the study. Because the Ranch brook site was in close proximity to a gage it was unnecessary to make flow measurements there. Two to three flow measurements were made at each of the other sites. This allowed for development of preliminary stage-discharge rating curves from which bankfull discharge could be extrapolated. Because the two measurements from the Waits river site were made during very similar discharges a rating curve could not be developed for this site.

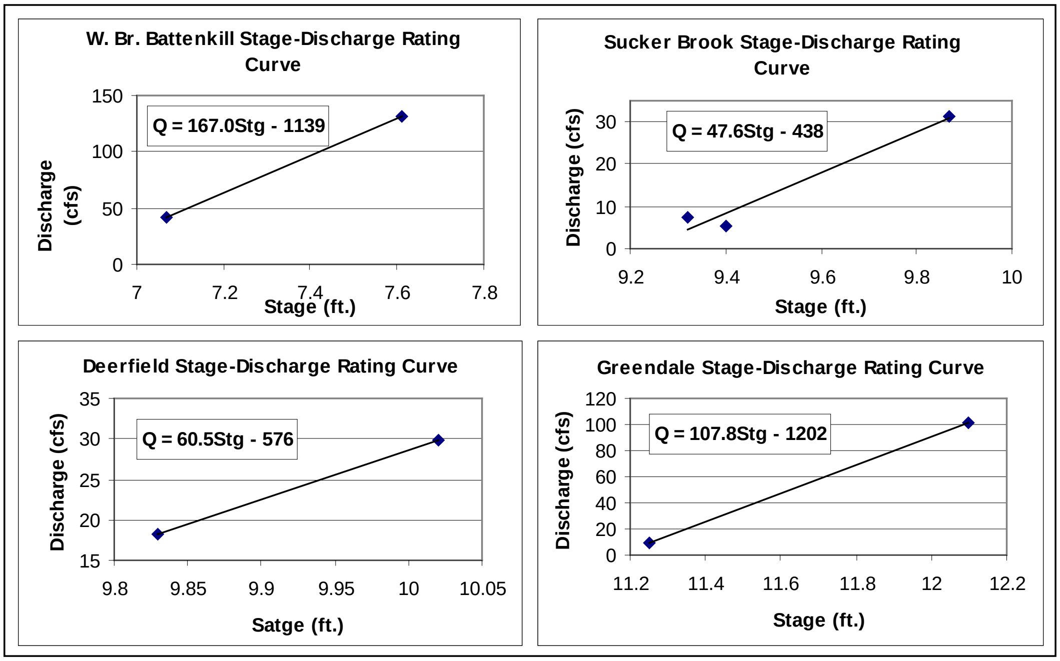
Table 1. Flow Measurement Data**.**

Stream	Date	Stage	Mean Depth (ft.)	Width (ft.)	Cross Sectional Area (sq.ft.)	Velocity (ft/sec)	Discharge (cfs)	Manning's n
Battenkill W. Br.	10/11/2005	7.07	1	29	28.89	1.45	41.9	0.06
Battenkill W. Br.	10/25/2005	7.61	1.55	31	48.05	2.75	132.1	0.07
Deerfield	5/25/2004	10.02	1.04	22.3	23.2	1.28	29.8	0.12
Deerfield	10/11/2005	9.83	0.78	21	16.4	1.12	18.3	0.11
Greendale Brook	10/11/2005	11.25	0.36	23	8.21	1.19	9.77	0.084
Greendale Brook	10/25/2005	12.1	1.22	23.5	28.69	3.53	101.37	0.063
Sucker Brook	5/25/2004	9.32	0.54	16.75	9.06	0.8	7.22	0.19
Sucker Brook	8/13/2004	9.87	1.07	17.4	18.58	1.68	31.25	0.14
Sucker Brook	9/1/2005	9.4	0.45	15	6.8	0.8	5.43	0.16
Waits River	4/28/2005	6.28	0.82	22.6	18.62	2.11	39.39	0.08
Waits River	10/17/2005	6.22	0.9	21	18.95	2.18	41.24	0.09

Figure 1 shows the four stage discharge rating curves that were developed for the remaining sites. These curves should be considered preliminary. Due to the few data points on each plot there can be little confidence in discharge values both interpolated and extrapolated from these curves. The presentation of these curves and use of values extrapolated from them in this report is done out of absolute necessity. As more data points are added to these plots this report will be updated.

Table 2 presents the bankfull values derived by extrapolation from the preliminary state discharge rating curves, the 2-year flow calculated using the Olson equation, and the difference between the two as a percentage of the Olson Q2 prediction for each site. The data neither verifies nor disproves the accuracy of the field determination of bankfull stage.

Figure 1. Stage-discharge rating curves for study sites.



While there is up to 45 percent difference between the bankfull discharge and predicted 2-yr discharges it must be noted that the typical standard error of prediction for the 2-year discharge using the Vermont Flow Frequency Tool (Olson, 2003) is +48.2 percent and -32.5 percent and the probability that the actual 2 year discharge falls within this range is only 68 percent. Table 2 shows that the bankfull values fall within this standard error of prediction. The fact that the identified bankfull discharge falls within the standard error of prediction of the 2-yr flow does indicate a good probability that the bankfull stage was correctly identified.

Table 2. Difference between bankfull discharge determined by extrapolation of preliminary rating curves and calculation using Olson, 2003 regression equations.

Stream	**Qbkf from Rating Curve (cfs)**	**Q2-Olson (cfs)**	**Difference as % of Q2-Olson**
Sucker Brook	79	98	-19
Greendale Brook	171	157	9
Ranch Brook	*N/A	147	N/A
Waits River	N/A	131	N/A
Deerfield	104	189	-45
Battenkill W. Br.	206	320	-36

*The reason that there is no bankfull for Ranch brook is that the need to correlate flow stage at the measurement cross section to flow stage at the USGS gage was overlooked. This data will be gathered in the upcoming field season.

Channel Morphology of Study sites

Hydraulic geometry and several morphologic characteristics of the study sites and surrounding valleys were surveyed in the field following established protocols and using standard laser level survey equipment. See, 2002 Vermont Regional Hydraulic Geometry Curves (VT DEC, 2002) for further description of field survey techniques.

Table 3. Compiled 2001 and 2006 hydraulic geometry dataset.

Table 4 presents the primary parameters that describe stream morphology for each of the sites. Research has shown that channel geometry has an influence on hydraulic geometry. For this reason it is common practice to use streams of a single valley type and boundary condition when developing regional hydraulic geometry curves. The Rosgen stream classification system (Rosgen, 1996) provides a useful method for identifying streams of similar type. In developing the 2002 Vermont regional hydraulic geometry curves (VT DEC, 2001) an effort was made to obtain data from unconfined streams with slopes less than three percent (Rosgen C-type streams) because in Vermont these are the types of streams that are most frequently degraded and in need of restoration. Due to topographic characteristics of Vermont it is uncommon for small catchments to be drained by C-type streams. For this reason the common morphology criterion was relaxed to allow for streams of narrower valleys and steeper slopes to be included in the study.

Table 4. Morphologic characteristics of 2006 study sites.

Stream Name	Entrench-ment Ratio	W/D Ratio	Reach Slope (ft./ft.)	D50 (mm)	Rosgen Stream Type
Greendale Brook	1.64	20.78	0.0184	31	B4c
Sucker Brook	1.74	16.50	0.0292	32.00	B4
Ranch Brook	1.48	24.88	0.0193	53.00	B4
Waits River	4.18	16.00	0.0195	35.00	C4b
Deerfield River	1.88	21.00	0.0104	74.00	B3c
W Br. Bkill	4.89	25.22	0.0070	43.00	C3

Site Name**	Drainage Area (sq.mi.)	Bankfull Discharge (cfs)*	XS Area (sq.ft.)	Width (ft.)	Depth (ft.)
Sucker Brook	3	79	27	22	1.25
Greendale Brook	4	171	30	20	1.49
Ranch Brook	4	147	37	27	1.40
Waits River	4	131	34	25	1.34
Deerfield	5	104	57	32	1.8
East Orange Br.	9	187	53	28	1.9
W. Br. Bkill	13	206	63	40	1.58
Ottauquechee	23	661	201	63	3.2
Ayers	31	621	146	41	3.6
Sleepers R.	43	1312	214	69	3.1
Laplatte	45	734	197	77	2.5
E Br Passumpsic	54	854	224	72	3.1
Little Otter	57	1122	265	92	2.9
Mettawee	70	3300	337	95	3.5
Dog	76	1537	277	78	3.6
Lewis	77	1850	244	89	2.7
Walloomsac	111	1879	410	110	3.7
Williams	112	5490	650	133	4.9
Black River	122	1726	304	71	4.3
Mad River	139	4960	559	138	4.0

* For 2006 sites except Ranch brook and Waits river bankfull discharge was determined by extrapolation from preliminary stage discharge rating curves. Bankfull discharge for Ranch brook and Waits river were calculated using the VT Flow Frequency Tool. For all other sites bankfull discharge was determined using USGS stage discharge relation for the particular gage.

** Sites in bold were used for development of 2001 Regional Hydraulic Geometry Curves. All other sites were surveyed in 2004

2006 Hydraulic Geometry Curves

The complete 2001 and 2006 hydraulic geometry dataset is presented in Table 3. The 2001 and the new 2006 curves (the 2006 curves are based on the compiled 2001 and 2006 data sets) are shown in Figure 2. Plotting both the 2001 and the 2006 curves on the same graph allows for a visual analysis of the affect that the 2006 data has on the previously plotted 2001 regressions. Because the discharge data collected for the 2006 sites is unreliable bankfull discharge data was not plotted. The addition of the 2006 data to the 2001 data set resulted in a:

- 0.17 increase in intercept and no change in slope and of the area regression,
- 2.92 increase in intercept and a 0.16 decrease in slope of the width regression, and
- 0.26 increase in intercept and a 0.05 increase in slope of the depth regression.

Addition of the 2006 data to the 2001 VT Hydraulic Geometry Curves resulted in a rise in r-squared values for each curve. R-squared values increased from:

- 0.85 to 0.95 for the area regression,
- 0.78 to 0.91 for the width regression and
- 0.59 to 0.87 for the depth regression.

These high r^2 values reveal that drainage area is a very good predictor of bankfull width, depth and cross-sectional area.

To quantify the effect of the 2006 data on bankfull dimension predictions, an analysis of prediction difference was conducted. The results of the analysis are presented in Table 5.

- The difference in predicted cross sectional area, ranges from 0.57 square feet at five square miles to 6.16 square feet at 120 square miles.
- The difference in predicted width decreases from 3.83 feet at five square miles to zero at 66 square miles and then increases to 3.84 feet at 120 square miles.
- The difference in predicted depth decreases from 0.27 feet at five square miles to zero at 120 square miles.

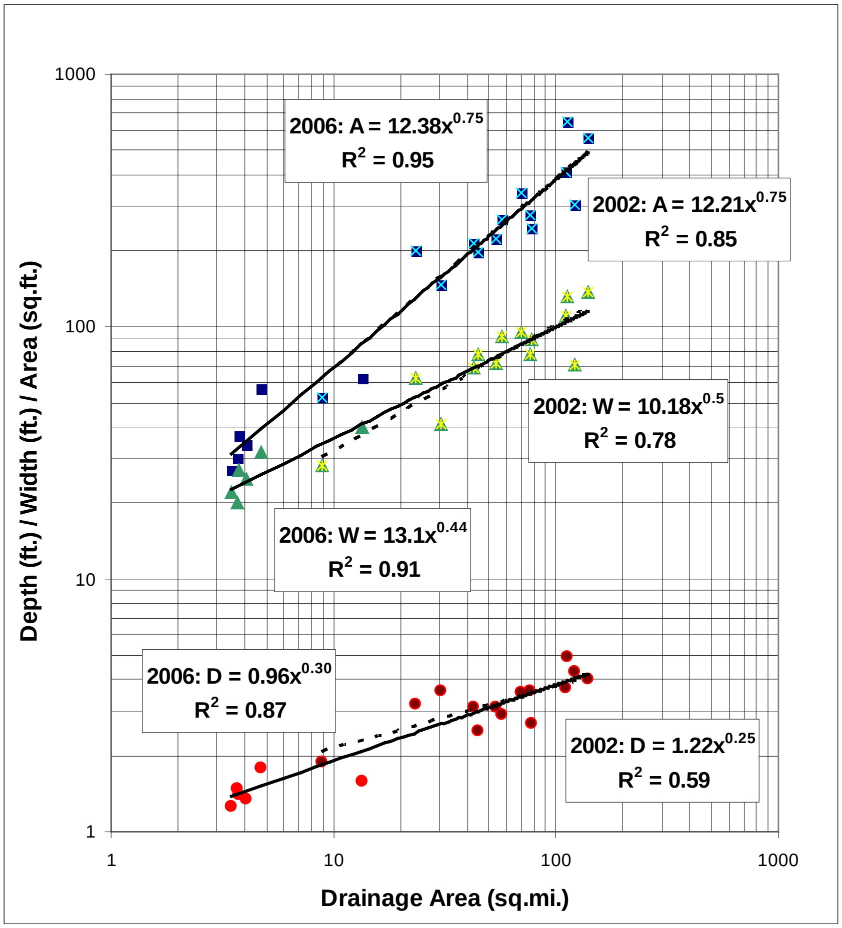


Figure 2. 2001 and 2006 Vermont Hydraulic Geometry Curves. The 2001 curves are presented as dashed lines and 2006 curves as solid lines. 2001 data are presented as dual-colored points and 2006 data as mono-colored points.

Table 5. Analysis of difference in geometry predictions between 2001 and 2006 curves.

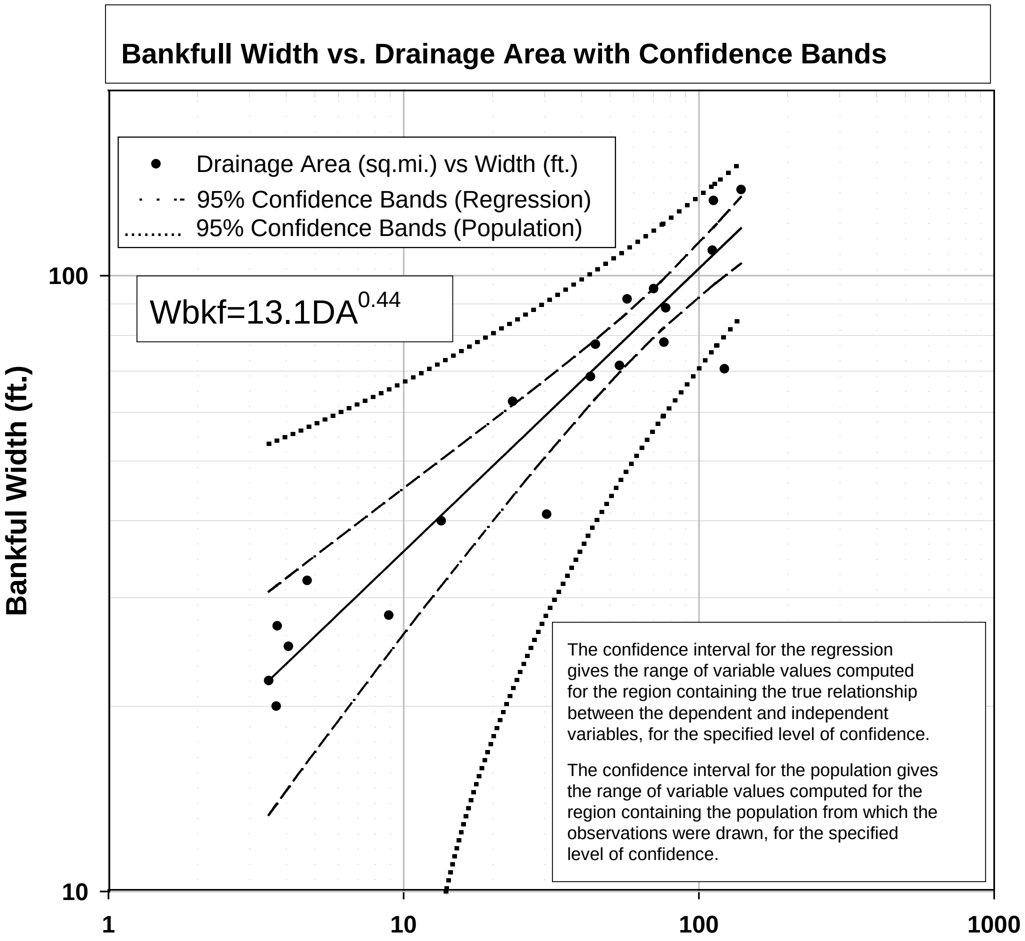
	Area (sq. ft.)			Width (ft.)			Depth (ft.)		
Drainage Area	**2006 Prediction**	**2001 Prediction**	**Diff.**	**2006 Prediction**	**2001 Prediction**	**Diff.**	**2006 Prediction**	**2001 Prediction**	**Diff.**
5	41.40	40.83	0.57	26.60	22.76	3.83	1.56	1.82	-0.27
10	69.62	68.66	0.96	36.08	32.19	3.89	1.92	2.17	-0.25
20	117.08	115.48	1.61	48.95	45.53	3.42	2.36	2.58	-0.22
40	196.91	194.21	2.70	66.40	64.38	2.02	2.90	3.07	-0.16
60	266.89	263.23	3.66	79.37	78.85	0.52	3.28	3.40	-0.12
80	331.16	326.61	4.55	90.08	91.05	-0.97	3.57	3.65	-0.07
100	391.49	386.11	5.38	99.37	101.80	-2.43	3.82	3.86	-0.04
120	448.86	442.69	6.16	107.67	111.52	-3.84	4.04	4.04	0.00

The increase in predicted width that resulted from addition of the 2006 is in agreement with past reports that the 2001 curves under-predict channel width when applied to small streams. Yet the increase in predicted width is at only 3.83 feet for streams draining five square miles.

The 95% interval confidence bands around the width curve are shown in Figure 3. The figure shows that the possible prediction values associated with a 95% confidence level range from:

- 15 to 33 feet at four square miles,
- 51 to 68 feet at 30 square miles,
- 79 to 95 feet at 70 square miles and
- 105 to 134 feet at 143 square miles.

Considering this range of predicted values within the 95% confidence limits and the typical applications of the curves the change in predicted bankfull geometry values when the 2006 data is added to the 2001 curves is not substantial.



The confidence interval for the regression gives the range of variable values computed for the region containing the true relationship between the dependent and independent variables, for the specified level of confidence.

The confidence interval for the population gives the range of variable values computed for the region containing the population from which the observations were drawn, for the specified level of confidence.

Figure 3. Width vs. drainage area data and regression lines with confidence

Testing the Rosgen (1998) Friction Factor Equation

The flow measurement and hydraulic geometry data gathered during this study provided an opportunity to test the applicability of the friction factor relative roughness relation presented in Rosgen (1998) and used in the Vermont DEC Phase 3 stream geomorphic assessment spreadsheet to Vermont streams. The relationship is of the form,

$$v/v^* = 2.83 + 5.7\log(d/D84)$$

Where; v is velocity, and
d is mean depth and
v* is shear velocity.

The calculation of shear velocity is possible with basic channel geometry data.

$$V^* = (gSR)^{0.5}$$

Where, g = the acceleration due to gravity,
S = channel slope, and

R= hydraulic radius.

The friction factor relative roughness relationship can be used in combination with the equation for shear velocity to calculate mean velocity at the cross-section. Using this friction factor relation for Vermont streams is likely to provide inaccurate results due to the fact that the equation was developed using empirical data from regions other than northern New England.

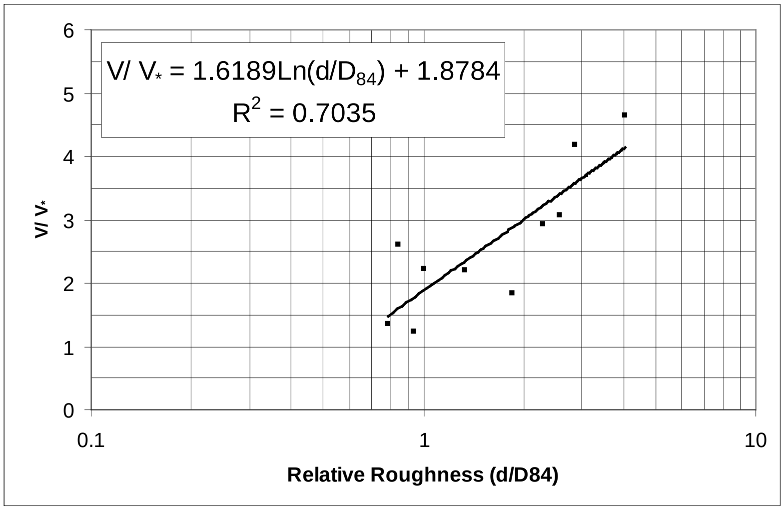
As a test of the Phase 3 velocity calculations velocities were calculated for each stream for every stage at which velocity measurements were made. Table 6 shows a comparison of velocities measured at the study sites during various flow stages and velocities calculated by the Vermont DEC Phase 3 spreadsheet for those same flow stages. Velocities calculated using the Phase 3 spreadsheet differ from measured velocities by an average of 35%.

Table 6. Comparison of measured to calculated velocities.

				d	e
Stream Name	**Measured Velocity (cfs)**	**Calculated Velocity (cfs) (Rosgen, 1998)**	**Percent difference (a and b)**	**Calculated Velocity (cfs) (VT friction factor relation)**	**Percent difference (a and d)**
Battenkill W. Br.	1.45	2.40	40	1.61	10
Battenkill W. Br.	2.75	3.63	24	2.45	-12
Deerfield	1.28	2.08	38	1.36	6
Deerfield	1.12	1.45	23	0.94	-19
Greendale Brook	1.19	1.10	-8	0.73	-63
Greendale Brook	3.53	4.40	20	3.01	-17
Sucker Brook	0.8	1.87	57	1.15	30
Sucker Brook	1.68	4.32	61	2.62	36
Sucker Brook	0.8	1.44	44	0.87	8
Waits River	2.18	3.56	39	2.39	9

A plot showing friction factor versus relative roughness values calculated using data from this study is shown in Figure 4. The relationship of the relative roughness and friction factor data is best described by the equation v/v* = 1.62Ln(d/D84) + 1.88. Velocities for the study sites were recalculated using the revised relationship and are shown in column d of Table 6.

Figure 4. Resistance to flow as a function of relative roughness.



As is expected the velocities calculated for the study streams using the revised friction factor relative roughness relation are much more accurate than velocities calculated using the relationship incorporated into the phase 3 spreadsheet. Velocities calculated using the revised curve vary from measured velocities by an average of 21%. If the value of greatest variance for each set of calculated velocities is considered an outlier and discarded the average variation of the Rosgen based velocities becomes 33% and the average variation of the VT based velocities becomes 16%.

It is to be expected that the relation developed from a particular data set will better predict the related values for that data set than a relation developed on another data set. A true test of the usefulness of the revised relation for predicting friction factor of Vermont streams will require comparison of predicted to measured velocities on other streams in Vermont. It is expected that the accuracy of this curve for calculating friction factor on other Vermont streams will be highly dependent on the stream's similarity to those used in this study. Because of this fact it may become desirable to develop curves for each major stream morphology found in Vermont.

Further Study

Flow measurements will continue at all six sites in order to increase confidence in the stage-discharge rating curves. A stage-discharge relation will be established at the Ranch brook site so that the discharge associated with the identified bankful stage can be determined. When enough stage-discharge data are collected to establish reliable stage-discharge curves the bankfull discharge curve for the complete data set will be added to the regional curve plot.

Flow measurement data collected for the discharge-rating curves will also be added to the relative roughness friction factor plot to increase confidence in the established relative roughness friction factor relationship. Flow measurements will also be made at sites not included in this study to test the accuracy of prediction provided by the relative roughness friction factor relationship when applied to streams outside those included in this study. Exploration into the use of existing data from USGS flow gages for addition to the relative roughness friction factor relationship will also be conducted.

Currently Rosgen E-type channels are not well represented in the Vermont regional curve dataset. E-channels have a much lower width to depth ratio than the C and B-channels that make up a large portion of the Vermont hydraulic geometry dataset (Rosgen, 1998). It is expected that the both the 2001 and 2006 regional curves over-predict the width and under-predict the depth of E-channels. There is interest in adding data from E-channels to document the difference in hydraulic geometry between E and C and B-channels. Identification of appropriate study sites will begin in the 2006 field season.

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Partners and Supporting Agencies

United States Forest Service, Green Mountain National Forest.
United States Geological Survey, New Hampshire/Vermont District.
Vermont Department of Fish and Wildlife.

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