

# Watershed Hydrology Protection and Flood Mitigation Project Phase II - Technical Analysis Stream Geomorphic Assessment

Final Report  
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**VERMONT  
WATERSHED  
HYDROLOGY  
PROTECTION  
&  
FLOOD HAZARD  
MITIGATION  
PROJECT**

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# Vermont Watershed Hydrology Protection and Flood Hazard Mitigation Project

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**Vermont Watershed Hydrology Protection  
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## EXECUTIVE SUMMARY

This report is the second in a multi-phase project being undertaken by the State of Vermont, Agency of Natural Resources (ANR). Phase I of the project involved conducting a literature search and providing discussion and assessment of the impacts of land use change on stream ecology and how levels of change to a stream's hydrology and morphology affect aquatic ecosystems.

To help quantify the relationships between stream geomorphology and land use activities for Vermont conditions and to provide a technical foundation for possible future guidance governing stormwater management runoff control for growing watersheds, ANR commissioned this study under Phase II, *Technical Analysis* of the project. It is anticipated that Phase III of the project will involve the development of a stormwater management guidance manual for the State of Vermont and Phase IV will involve training and education on the implementation of the guidance.

ANR's goal for this phase of the project was to determine, in Vermont, the type and size of watershed hydrologic and geomorphic impact that could result from various watershed land use activities including, watershed development in the natural floodplain, various levels of urbanization, and logging activities.

This report documents multiple lines of evidence used to assess the above goal. The study methodology incorporated several complimentary components to derive relationships between and among the watershed land use activities and stream system health. The study methodology incorporated the following analyses in descending order of significance:

1. Validation of an empirical approach quantifying the relationship between total basin imperviousness and the enlargement of stream channel cross-sectional area.
2. Computation of current stream channel stability using a rapid geomorphic assessment technique.
3. Comparing previously collected stream channel biological monitoring results with total basin imperviousness and the results of the previous two assessments.
4. Comparing stream channel riparian cover as a percent of total channel length.

A total of 8 subwatersheds were investigated as part of the study. Data were collected in the field at 24 separate stream sampling locations (approximately 3 sampling locations per subwatershed). Land use data were provided by the Vermont Center for Geographic Information (VCGI) at the University of Vermont in combination with aerial photography obtained from the Vermont Mapping Program. Biological monitoring data were provided to the project team by the Vermont Agency of Natural Resources, Biomonitoring and Aquatic Studies Section.

### **Background on the Scope of the Study:**

The first component of the study was to validate the empirical relationship of channel enlargement (as measured by cross-sectional area) as a function of total watershed impervious cover. Past investigations have found that channel enlargement is a function of basin imperviousness as well as the corresponding age of that impervious cover. This relationship can be defined by the function:

$$(\text{Re})_{POST} = \left( \frac{(A_{BFL})_{POST}}{(A_{BFL})_{PRE}} \right)$$

where, Re is defined as the channel enlargement ratio, 'A' represents the cross-sectional area of the stream channel and the subscripts BFL, POST, and PRE refer to the bankfull stage, the post-disturbance condition, and pre-disturbance condition, respectively.

The age of the development is also a critical variable in the amount of channel enlargement. In general, the longer a channel is exposed to the forces causing accelerated channel erosion, the larger the channel cross-sectional area. The effect of the age of development is represented by the concept of a "relaxation period." This is defined as the period of time required for a channel to reach an "equilibrium" state in concert with the level of watershed alteration, where the channel erosion processes are in a relative balance with the watershed forces causing erosion.

The results of past investigations for channel enlargement and channel relaxation show strong correlations with basin imperviousness. The equation derived from past investigations for alluvial type (AL-Type) streams for the ultimate channel enlargement ratio is defined as:

$$(\text{Re})_{ULT} = 0.00135(\text{TIMP})^2 + 0.0167(\text{TIMP}) + 1.0$$

$$R^2 = 0.78, (n = 38)$$

where,  $(\text{Re})_{ULT}$  is defined as the channel enlargement ratio once a stream is in equilibrium with its watershed hydrologic parameters, and TIMP is the total basin impervious cover, in percent. Note that the square of the correlation coefficient shows a very strong relationship between basin imperviousness and channel enlargement for the 38 sites investigated.

The hypothesis being tested in this part of the study was to evaluate the cross-sectional area to impervious cover relationship for eight Vermont watersheds and statistically compare the findings with those of previous investigations. If it could be shown that channel enlargement ratios for Vermont streams were drawn from the same population as channel enlargement ratios for non-Vermont streams then the existing relationships could be used to help predict and assess stream morphological impacts associated with different land use modifications.

The second component of the investigation utilized a rapid geomorphic assessment (RGA) technique to define the current stability of stream channels. The technique used a number of visually observed factors to provide a semi-quantitative assessment of a stream's current stability, referred to as the stability index (SI). The primary purpose of the RGA was to corroborate the findings of the more quantitative channel enlargement assessment and to help define past or current modes of channel adjustment (i.e., aggradation, degradation, widening and/or plan form adjustment). The RGA notes whether change in channel form has occurred or is still occurring, however, it does not provide a measure of the rate of change.

The third level of investigation involved the comparison of previously collected biological monitoring data with the corresponding level of impervious cover. The Vermont Agency of Natural Resources, Biomonitoring and Aquatic Studies Section and the Vermont Department of Fish and Wildlife provided the project team with macroinvertebrate and fish biological monitoring data

covering a twelve year period (1986-1998). This analysis was intended to support the more quantitative geomorphological investigation of channel enlargement and channel stability and was not intended as a statistical evaluation of Vermont biological monitoring data.

The final element of the study involved comparing stream channel riparian cover length for each of the selected streams to assess whether or not riparian cover length was a factor in overall physical or biological condition. The methodology utilized aerial photography to estimate the extent of forest buffers in each subwatershed. The extent of the buffer was defined as the length of the forest buffer divided by the total stream length.

## Methodology

The project team employed a ten step methodology to collect and analyze the data. As stated above, data were collected in eight Vermont subwatersheds. Table E.1 presents the basic project methodology.

<b>Table E.1 Basic Project Methodology for the State of Vermont - Watershed Hydrology Protection and Flood Hazard Mitigation Project - Phase II, Technical Analysis</b>	
Step 1:	Select a list of potential candidate subwatersheds representing a range of land use activities
Step 2:	Compile historic data on candidate streams (cross-sectional data, biomonitoring, etc)
Step 3:	Select a "short list" of streams with historical cross-sectional data, past biomonitoring data, and desired range of land use activities; conduct field screening of potential sites
Step 4:	Select the final list of eight subwatersheds for field assessment
Step 5:	Produce base mapping of selected stream reaches (land use/land cover mapping to compute total basin impervious cover (TIMP) and identification of stream location)
Step 6:	Conduct field assessment of selected stream reaches (cross-sectional data and rapid geomorphic assessment at 24 cross-section locations -- 3 in each of the eight selected subwatersheds)
Step 7:	Compile and analyze biomonitoring data for selected streams
Step 8:	Conduct riparian buffer assessment of streams within the urbanized subwatersheds
Step 9:	Conduct data analysis to define channel enlargement relationships, channel stability class, and stream bedload analysis
Step 10:	Evaluate correlations between geomorphic parameters, biomonitoring and land use change as measured by TIMP

The first step was to select an initial candidate list of subwatersheds that met a range of land uses, had past biological monitoring data, and likely had historic stream cross-sectional surveys data (for estimating the pre-disturbance bankfull area,  $(A_{BFI})_{PRE}$ ). Next, a data collection effort was conducted to obtain past biomonitoring information, historic cross-sectional information, and current and past land use information. Candidate sites were then field reviewed to eliminate those where possible conflicts existed. The final selection of subwatersheds and streams involved input from the Project Steering Committee and included reference subwatersheds, subwatersheds with a range of

urban/suburban development densities, a subwatershed where recent logging activity had occurred, and two subwatersheds where upland development was present. Table E.2 lists the final subwatersheds selected for data collection and assessment.

<b>Stream Name</b>	<b>Town</b>	<b>Dominant land use</b>	<b>Impervious Cover<sup>1</sup></b>	<b>Approx. Drainage Area (Sq. Mi.)</b>
Cold River	Clarendon	Reference	<1%	20.7
Dowsville Brook	Duxbury	Logging	6% <sup>2</sup>	6.4
Moon/Tenney Brooks	Rutland	Urban	13 and 6% resp.	5.3 and 4.4
Potash Brook	S. Burlington	Urban	22%	7.4
Roaring Brook	Sherburne	Upland dev.	6% <sup>2</sup>	5.4
Smith	Goshen	Reference	<1%	3.2
Stevens Brook	St. Albans	Urban	13%	6.9
W. Branch Little River	Stowe	Upland dev.	2% <sup>2</sup>	24

<sup>1</sup> subwatershed impervious cover and drainage area at downstream most sampling location

<sup>2</sup> impervious cover estimate includes an "equivalent" impervious value

Subwatershed impervious cover was computed at each of the 24 stream sampling points. Impervious cover was derived using the VCGI's geographic information system and review of aerial photography. An "equivalent" impervious cover value was estimated for those land uses where the hydrologic alteration was not attributed to impervious cover (e.g, logging activities). In these cases, a runoff coefficient approach, based on Natural Resource Conservation Service Methods (NRCS), was used to derive the equivalent impervious value.

Stream geomorphic data were collected in the field at 24 cross-section locations. The types of data collected at each station included, longitudinal channel slope, cross-sectional area, various measurements for channel depth and width, semi-quantitative assessments of channel stability using the RGA approach, stream substrate pebble data, and stream bank soil data. Stream data were analyzed using a series of spreadsheet models to calculate bankfull flowrate ( $Q_{BFL}$ ), current cross-sectional area at bankfull stage, and Manning's roughness coefficient. Next, historical information of channel geometry (from older bridge construction plans, for example) and historical impervious cover estimates (from past aerial photography) were used to estimate the bankfull cross-sectional area for the historic channel [ $(A_{BFL})_{PRE}$ ]. The resulting ratio of current cross-sectional area to historic cross-sectional area ( $Re_i$ ) was used to calculate an ultimate channel enlargement ratio ( $Re_{ULT}$ ). These data were then compared to channel enlargement data from non-Vermont streams using statistical tests. The RGA data were used to compute the stability index for each stream.

Biological monitoring data for macroinvertebrate and fish were assembled and evaluated as a function of subwatershed imperviousness. Biomonitoring data were presented for each stream and each sampling period. Only the overall biological "Community Assessments" for

macroinvertebrates and fish are presented.

## Summary of Results:

### Channel Enlargement Assessment

Table E.3 lists a summary of the resulting data from the channel enlargement assessment for nine Vermont streams (note, Moon Brook and Tenney Brook are within the same subwatershed). The "observed" values were compared to "predicted" values derived from the non-Vermont Enlargement Curve to determine if they were drawn from the same population. Statistical tests for variance and mean were performed for these data and found to be statistically significant at the 95% confidence level.

<b>Table E.3 Summary of Channel Enlargement Assessment</b>											
Basin	Site	Historic Channel Survey Data				Current Channel Survey Data				[(Re) <sub>ULT</sub> ] <sub>OBS</sub>	(A <sub>BFL</sub> ) <sub>PRE</sub> (ft <sup>2</sup> )
		A <sub>BFL</sub> (ft <sup>2</sup> )	t <sub>i</sub> (yrs)	TIMP (%)	(Re) <sub>i</sub>	A <sub>BFL</sub> (ft <sup>2</sup> )	t <sub>i</sub> (yrs)	TIMP (%)	(Re) <sub>i</sub>		
Cold	CLD4					201.2	46.7	2.0			Reference Stream
	CLD5					52.2	80.5	1.0			Reference Stream
Cold (Gould) Dowsville	GLD6					110.3	80.5	1.0			Reference Stream
	DOW1					13.5	46.7	5.8			Reference Stream
	DOW2	60.5	19.5	1.0	1.00	105.5	23.4	5.8	1.04	1.91	60.5
	DOW3	55.2	19.5	1.0	1.00	51.1	23.4	5.8	1.04	1.01	55.2
Moon	MOO1	33.8	19.1	9.3	1.07	41.3	53.7	13.0	1.35	1.39	31.7
	MOO2	51.3	19.8	7.7	1.05	37.4	49.7	13.0	1.32	0.84	48.7
Tenney Potash	TEN1	39.9	4.3	1.0	1.00	57.7	49.6	6.0	1.11	1.50	39.9
	POT1	47.1	14.1	14.4	1.08	75.6	41.5	22.0	1.61	2.18	43.5
	POT2	48.5	14.1	14.4	1.08	63.6	41.5	22.0	1.61	1.78	44.8
	POT3	40.2	13.1	10.6	1.10	59.9	42.7	20.0	1.81	1.76	36.4
Roaring	ROA1	106.9	25.0	1.5	1.01	124.2	30.6	6.0	1.17	1.29	105.9
	ROA2	103.4	25.0	1.5	1.01	165.2	28.0	7.0	1.07	1.78	102.4
	RBT1					28.6	46.7	2.0			Reference Stream
Smith	SMI1					53.6	80.5	1.0			Reference Stream
	SMI2					53.6	80.5	1.0			Reference Stream
	SMI3					51.9	80.5	1.0			Reference Stream
Stevens	STB7	26.8	41.7	8.8	1.15	35.6	48.9	11.0	1.24	1.65	23.3
	STB8	28.6	40.2	8.3	1.13	30.4	48.9	11.0	1.24	1.30	25.3
	STB9	72.7	33.1	12.0	1.18	60.3	52.8	13.0	1.34	1.05	61.5
West Branch	WBL1	303.8	32.0	2.0	1.02	379.0	55.0	2.0	1.03	1.28	299.2
	WBL2	336.5	32.0	2.0	1.02	433.0	55.0	2.0	1.03	1.32	331.4
	WBL3	227.3	43.3	3.0	1.00	216.4	55.0	3.0	1.02	0.99	226.9

A<sub>BFL</sub> = Bankfull channel cross-sectional area; t<sub>i</sub> = area weighted average age of disturbance;  
 TIMP = Total Basin Imperviousness; (Re)<sub>i</sub> = Enlargement Ratio at time t<sub>i</sub> (i.e., current cross-section);  
 [(Re)<sub>ULT</sub>]<sub>OBS</sub> = Ultimate channel Enlargement Ratio, based on observed survey data;  
 (A<sub>BFL</sub>)<sub>PRE</sub> = Pre-disturbance channel bankfull channel cross-sectional area

The original channel enlargement curve for alluvial type streams was revised by integrating the Vermont data into the original database and undertaking a curve fitting process. The following second order polynomial provided the best fit for the data:

*Revised Equation for Channel Enlargement Incorporating Vermont Data*

$$(Re)_{ULT} = 0.0013(TIM P)^2 + 0.0168(TIM P) + 1.0$$

$$(R^2 = 0.83, n = 52)$$

### Channel Stability Assessment

Results of the channel stability assessment are presented in Table E.4. The RGA process was originally developed for application in older urban watersheds that had been under riparian vegetation management programs and, consequently, largely denuded of wooded species. As such, metrics indicative of early geomorphic alteration were not incorporated into the original RGA Protocol. In consideration of the above, a modified RGA protocol was developed for Vermont to include the additional parameters: the number of Large Organic Debris pieces (NLOD) observed within the channel and riparian zone, the number of debris jams (NJAMS) and the number of complete riffle lines (NRIFF). The results are contained within the modified RGA data presented in Table E.4.

<b>Table E.4 Summary of Channel Stability Assessment Using the Modified Rapid Geomorphic Assessment Form</b>								
Basin	Site	RGA FACTOR				Stability Index(1)	Stability Class	Channel Type
		AI	DI	WI	PI			
Cold	CLD4	0.14	0.20	0.14	0.13	0.15	Stable	AL(Ar)
	CLD5	0.14	0.00	0.00	0.38	0.13	Stable	AL(Ar)
Cold (Gould)	GLD6	0.14	0.20	0.29	0.13	0.19	Stable	AL(Ar)
	Dowsville	DOW1	0.67	0.00	0.43	0.13	0.31	Transitional
DOW2		0.14	0.00	0.71	0.38	0.31	Transitional	AL(Ar)
DOW3		n/a	n/a	n/a	n/a	n/a	n/a	AL(Ar)
Moon	MOO1	0.67	0.40	0.88	0.63	0.64	In Adjustment	AL
	MOO2	0.71	0.00	0.86	0.63	0.55	In Adjustment	AL
Tenney	TEN1	0.33	0.17	0.63	0.63	0.44	In Adjustment	AL
	Potash	POT1	0.57	0.20	0.86	0.50	0.53	In Adjustment
POT2		0.33	0.60	0.83	0.43	0.55	In Adjustment	AL(Ar)
POT3		0.60	0.00	1.00	0.60	0.55	In Adjustment	RB
Roaring	ROA1	0.20	0.00	0.83	0.17	0.30	Transitional	RB(Ar)
	ROA2	0.33	0.17	0.57	0.20	0.31	Transitional	AL(Ar)
	RBT1	0.14	0.00	0.71	0.33	0.30	Transitional	AL(Ar)
Smith	SMI1	0.17	0.20	0.29	0.00	0.16	Stable	AL(Ar)
	SMI2	0.00	0.00	0.38	0.00	0.09	Stable	AL(Ar)
	SMI3	0.00	0.20	0.33	0.00	0.13	Stable	AL(Ar)
Stevens	STB7	0.57	0.90	0.70	0.43	0.65	In Adjustment	AL(Ar)
	STB8	0.57	0.17	0.25	0.29	0.32	Transitional	AL
	STB9	0.14	0.17	0.50	0.29	0.27	Transitional	AL(Ar)
West Branch	WBL1	0.71	0.80	0.56	0.75	0.70	In Adjustment	AL
	WBL2	0.43	0.88	0.56	0.75	0.65	In Adjustment	AL
	WBL3	0.43	0.80	0.83	0.88	0.53	In Adjustment	AL(Ar)

(1) SI = Modified Stability Index for Vermont Conditions

AI = Aggradation Factor; DI = Degradation Factor;

WI = Widening Factor; PI = Planimetric Adjustment Factor;

n/a = not available; AL = Alluvial; Ar = Armored; RB = Rock Bed with alluvial banks;

The RGA protocol was applied to 23 sites surveyed in this study, with the exception of Site DOW3,

A simple linear correlation analysis was undertaken relating the Stability Index to Total Basin Imperviousness (TIMP) for 20 of the 23 sites (W. Branch of Little River was excluded from the analysis because of past gravel mining operations) as follows:

$$SI = 0.158(TIMP)^{0.413}, R = 0.75, n = 20$$

The above relation was found to be statistically significant at the 95% confidence level for variance and mean.

### Biological Monitoring Analysis

Table E.5 lists a generalized assessment of the biological monitoring data for the nine Vermont streams evaluated in this. The results suggest that these Vermont streams can be related to their contributing impervious cover and fall into one of two categories. The generally "good" streams, from a biological community assessment perspective, fall into an impervious cover range of 6% and less. The "poor" streams have impervious cover of 12% or greater.

<b>Table E.5 Comparison of Biological Monitoring to Subwatershed Imperviousness</b>			
Stream Name	Subwatershed Current Impervious Cover (%)	Macro-invertebrate Bio-monitoring - Overall Community Assessment*	Fish Bio-monitoring - Overall Community Assessment*
Roaring Brook	6	Fair	Excellent
Stevens Brook	13	Poor	Poor - Fair
Dowsville Brook	6	Good - Excellent	Good
Potash Brook	22	Poor - Fair	Fair - Good
Tenney Brook	6	Fair - Good	Good - Excellent
Moon Brook	13	Poor	Fair
Smith Brook	<1	Excellent	-
Cold River	<1	Good	-
West Branch Little River	2	Good - Fair	Good

\* represents an average of all biomonitoring presented in Table 4.1

### Riparian Cover Analysis

The results of the riparian cover analysis are presented in Table E.6. Forest buffers were identified based on aerial photography for each watershed. A simple methodology was used to estimate the extent of forest buffers in each subwatershed. The extent of the buffer was defined as the length of

the forest buffer divided by the total stream length. The criteria used to determine the length of stream and buffer were:

- The stream length represents the total length of *perennial* streams based on USGS quad sheets.
- A forest buffer is defined as at least a 50' width of forest cover along the stream, with at least 20' of forest cover on each side of the stream.

Based on methodology performed, the results presented in Table E.6 yield no conclusive results to suggest that the extent of riparian cover has an undue influence on biological or physical stream quality. It should be noted that the assessment was conducted for only those streams with measurable development within a fairly modest range of impervious cover (~6 to 22%).

<b>Table E.6 Forest Buffer Length as a Fraction of Total Stream Length</b>		
<b>Stream</b>	<b>Section</b>	<b>Buffer Fraction</b>
Moon Brook	Lower	30%
	Upper	35%
Tenney Brook	--	55%
Stevens Brook	Lower	35%
	Upper	20%
Potash Brook	Lower	20%
	Middle	20%
	Upper	25%

A forest buffer is defined as at least a 50' width of forest cover along the stream, with at least 20' of forest cover on each side of the stream.

### **Conclusions:**

The methodology and data analyses support a suite of conclusions on the findings of this study. The project team identified the following six major conclusions as a result of our work on the geomorphological, and biological assessments:

1. The key hypothesis of this study was to test whether stream geomorphological assessment techniques, that had been developed and tested in regions outside of Vermont, were valid for Vermont conditions. Specifically, two assessment techniques were evaluated: the Rapid Geomorphic Assessment technique that defines stream stability via a stability index value (SI) and the relationship of channel enlargement ratio  $[(Re)_{ULT}]$  to total basin imperviousness. The study results confirmed that both of these techniques could be applied with statistical significance to Vermont conditions.

An Enlargement Ratio equation and curve developed using stream geomorphological data from outside of Vermont was tested for inclusion with data from the Vermont streams investigated in this study and found to be statistically valid for the total population of data-points. This conclusion supports that there is now a statistically valid tool for Vermont conditions to help predict channel enlargement as a function of watershed imperviousness.

2. The channel enlargement ratio  $[(Re)_{ULT}]$  for the nine Vermont streams was found to be somewhat related to total basin imperviousness ( $R^2 = 0.34$ ). The overall channel enlargement equation and curve present a strong correlation between enlargement ratio and total basin imperviousness ( $R^2 = 0.83$ ).
3. The channel stability index (SI) conducted using the Rapid Geomorphic Assessment technique for the nine Vermont streams was also found to be strongly related to total basin imperviousness ( $R^2 = 0.78$ ). The slightly lower correlation coefficient is not surprising given the qualitative nature of the data collection protocol for SI versus the more quantitative nature for  $(Re)_{ULT}$  data collection and analysis.
4. The concept of "equivalent impervious cover," where land uses that alter the hydrologic characteristics of watershed cover without creating impervious cover (e.g., logging and upland development land uses) are equated to an equivalent amount of imperviousness, was found to be a meaningful measure. The resulting channel enlargement and stability index in subwatersheds where this method was employed did not deviate significantly from those subwatersheds where conventional imperviousness was the indicator of hydrologic change.
5. The assessment of biological community health, relying on Vermont biomonitoring data, showed a general relationship of decreasing biological community health with increasing watershed impervious cover. However, since no statistical tests were conducted, the strength of this conclusion should be weighed against the more rigorous statistical tests that were performed for channel enlargement and channel stability class.
6. The methodology used to perform the analysis of the possible benefits of riparian cover on stream biological or physical quality yielded inconclusive results. The possible benefits associated with adjacent wetlands, the level of detail associated with this portion of the study, and/or the comparison between streams with only a modest difference in impervious could have impacted the study findings.

# **SECTION 1**

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# **BACKGROUND**

# SECTION 1: BACKGROUND

## 1.1: STUDY PURPOSE AND BACKGROUND

This is the second in a multi-phase project that is being undertaken by the State of Vermont, Agency of Natural Resources (ANR). The Agency is seeking to assess relationships between flood occurrence and stream resource degradation associated with various land use alteration activities. Phase I of the project involved conducting a literature search and providing discussion and assessment of the impacts of land use change on stream ecology and how levels of change to a stream's hydrology and morphology affect aquatic ecosystems (see Stone Environmental, 1998).

Several other investigators have documented adverse impacts to stream health as a function of increasing land cover alteration (such as urbanization). While the findings of many of these investigations are conclusive, including those presented by Stone Environmental (1998), nearly all work has been conducted outside Vermont, and nearly all outside of New England (see Schueler, 1994).

To help quantify these relationships for Vermont conditions and to provide a technical foundation for possible future guidance governing stormwater management runoff control for growing watersheds, ANR commissioned this study under Phase II, *Technical Analysis* of the project. It is anticipated that Phase III of the project will involve the development of a stormwater management guidance manual for the State of Vermont and Phase IV will involve training and education on the implementation of the guidance.

The ANR developed a list of watershed activities that it believed should be evaluated by this *Technical Analysis*. ANR's stated goal for this phase of the project was to "determine, in Vermont, the type and magnitude of watershed hydrologic and geomorphic reaction, and alterations in sediment distribution, water quality, and the integrity of aquatic ecosystem - that could result from the following activities:"

- Watershed development in the natural flood and migration paths of streams
- Urbanization
  - < Development patterns and cumulative growth in all areas of 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> order watersheds as it relates to flood peaks and stream morphology.
  - < Riparian stream corridor changes.
  - < Land clearing and urbanization taking place in upland areas.
  - < Urbanized areas in the lowlands and middle elevations that have multiple storm water discharges, increased impervious areas, and changes in pervious surface from compaction and grading.
  - < Road building and maintenance.
  - < Channelization including alterations in stream gradient
- Forestry Practices - clear and selective cutting

The following project report documents the multiple lines of evidence used to assess the above stated goals. While not every physical, chemical, or biological impact associated with every activity

listed above is quantified, the study methodology incorporates several complimentary components to derive relationships between and among many of the listed watershed activities and stream system health. The study methodology incorporates the following analyses in descending order of significance to help quantify the above relationships:

1. Validation of an empirical approach quantifying the relationship between total basin imperviousness and the enlargement of stream channel cross-sectional area.
2. Computation of current stream channel stability using a rapid geomorphic assessment technique.
3. Comparing previously collected stream channel biological monitoring results with total basin imperviousness and the results of the previous two assessments.
4. Comparing stream channel riparian cover as a percent of total channel length for those streams within urbanized subwatersheds.

### 1.1.1 Study Objectives

The overall objective of this study is to help quantify the relationships between watershed land use change and the alteration of channel morphology and aquatic ecology in Vermont streams. The principle component of the study design (item 1, above) is based on validation of an empirical approach relating land use change as measured by Total Basin Imperviousness (TIMP) with the enlargement of the cross-sectional area of the "active channel"<sup>1</sup>. The empirical approach expresses channel enlargement as a function of boundary material resistance, the degree of alteration of the sediment-flow regime, and the elapsed time from the occurrence of a disturbance within the watershed and the time required to achieve a new stable channel form. In cases where watershed impervious cover is low and not the principle component of altered land cover, a surrogate value equivalent to TIMP is used.

A secondary objective is to utilize a rapid geomorphic assessment (RGA) technique to quantify current stream channel stability as a function of TIMP. This assessment is intended to support the investigations of channel enlargement relationships to TIMP, as discussed above. Next, data from prior biological monitoring (collected from ANR's Biomonitoring Unit) is used to assess if relationships between total basin impervious cover and biological community health can be correlated with either channel enlargement or channel stability. Finally, the influence of riparian buffer length as a percentage of total channel length is estimated to assess if this watershed factor influences the results of the channel enlargement, channel stability, or biological assessments.

The channel enlargement relationships were developed using case studies on streams representing a variety of physiographic and climatic regions across the United States and Canada. Validation of these empirical relationships to Vermont conditions have the ability to provide decision makers with a useful tool for the assessment and mitigation of morphological impacts associated with land use change.

### 1.1.2 Background on the Channel Enlargement Assessment Methodology

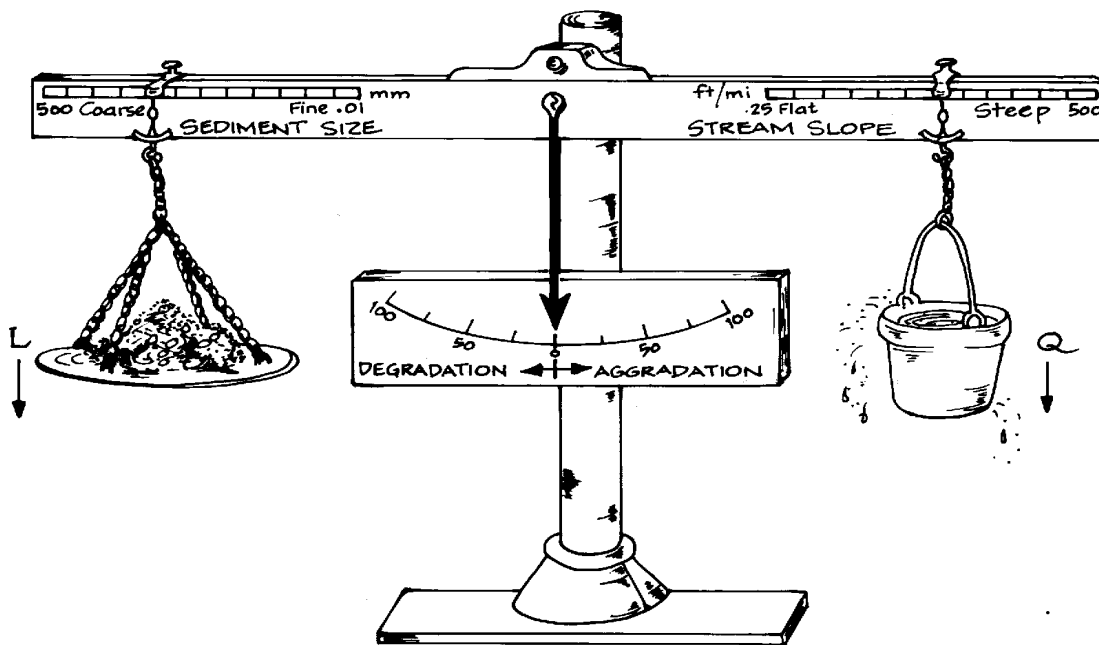
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1 The "active" channel is defined as that conduit conveying flows during dry weather periods and frequent flood flow events.

One possible stable state of a stream channel in erodible materials is one in which the dimensions of the channel forms a balance between the forces tending to erode the channel boundary materials and the resistance of these materials such that the channel is just able to move its sediment load (Leopold et al., 1964). Lane (1955) illustrated this balance using the following proportionality,

$$QS \propto Q_s \phi_i$$

in which Q represents the flow rate, S is the longitudinal channel slope,  $Q_s$  is the sediment influx and  $\phi_i$  is the particle size for which  $i^{\text{th}}$  percent of the material is finer by mass. This proportionality is illustrated using a balance as shown in Figure 1.1.



Sediment Load x Sediment Size %Stream Slope x Stream Discharge

**Figure 1.1: Sediment Load & Size Balanced against Stream Flowrate and Slope**  
 (Source: adapted from Lane, 1955)

A stream is in "equilibrium" or a "stable"<sup>2</sup> state when the proportionality between stream flow rate (Q) and slope (S) are in balance with instream sediment load ( $Q_s$ ) and particle size ( $\phi_i$ ). For example, when flow rate is increased disproportionately to other variables, the bucket representing flow rate and volume becomes heavier and tips the right-hand arm of the scale down causing the indicator to swing to "degradation" (downcutting of the channel bed). The right-hand-side of the proportionality represents stream power (the product of QS). As stream power increases the stream's ability to do work increases. If the bed of the channel is worn into erodible materials then this increase in stream power may result in erosion of the bed materials and enhance channel downcutting.

On the left-hand-side of Lane's (1955) relation, an increase in sediment load ( $Q_s$ ) or the size of the sediment particles (as represented by  $\phi_i$ ) that is disproportionate to the QS may result in "aggradation" (buildup of sediments on the bed). The impact of an increase in  $\phi_i$  is related to stream competence. This is defined as the size of the largest particle the stream can move at a specified flow rate (e.g. the bankfull flow). That portion of the sediment delivered to the channel that exceeds stream competence will build-up within the channel. The impact of  $Q_s$  is related to the capacity of the stream. This is defined as the total mass of sediment the stream can move over a defined time period. Even where a stream may have the competence to move the sediment supply, if the mass of sediment entering the channel exceeds a stream's capacity to move it, the sediments will accumulate within the channel. This aggradation process typically leads to the over development of bar forms, infilling of pools, a loss of channel flow conveyance capacity, increased nuisance flooding, bank erosion, and adjustment of the planimetric form of the channel.

The balance shown in Figure 1.1 is dynamic. The "indicator" in Figure 1.1 swings back and forth between aggradation and degradation in response to variations in the sediment and flow inputs to the channel associated with normal climatic variation. Channel systems, such as those found in Vermont, typically possess a natural ability to absorb these variations within certain limits before a fundamental alteration in channel form may occur. These limits are referred to as thresholds. The terms "dynamic equilibrium" and "metastable equilibrium" have been coined to address adjustments in channel form associated with variations in the "natural"<sup>3</sup> system. A system that is in "metastable equilibrium" is defined as one in which:

- a) the influx of sediment into the subject reach is equal to the mass of sediment leaving the reach (the system is in mass balance); and,
- b) the average dimensions of the channel as represented by hydraulic geometry and plan form parameters are stationary through time.

The last condition does not mean that the channel form is fixed in space. The channel is free to

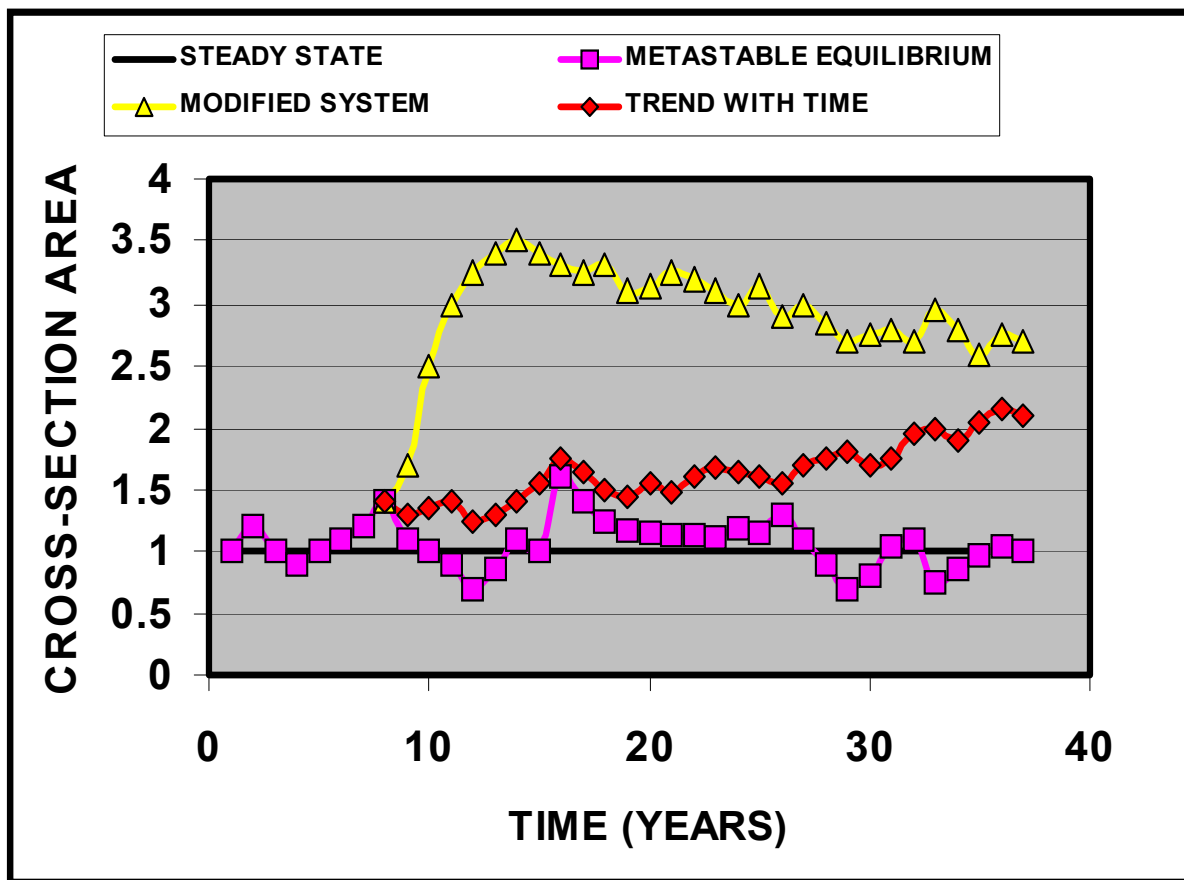
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2 The term "stable" in Lane's (1955) balance refers to a one-dimensional mass balance wherein the influx of sediment to a specified reach is equal to the sediment output. This definition of stability may be best visualized by considering a mobile bed channel with ridge banks. If neither degradation (channel downcutting of the bed) or aggradation (the accumulation of sediment on the bed) is occurring in the reach then the channel is "stable".

3 "Natural" in this discussion refers to a channel system whose morphology is primarily determined by non-anthropogenic factors.

move through space (e.g. meander propagation) as long as the average dimension of its hydraulic geometry and plan form parameters fluctuate about a mean value that remains constant through time. An illustration of a system in "metastable equilibrium" compared with other channel cross sectional area variations is illustrated in Figure 1.2.

Vagaries in rainfall amounts and patterns can result in a disturbance to the factors controlling channel form. These disturbances may either result in temporary or long term morphological adjustment to channel form. The channel may respond to temporary disturbances that exceed thresholds for channel stability by departing from its “stable” form and either returning to its pre-disturbance state following cessation of the disturbance (as in the metastable equilibrium condition illustrated in Figure 1.2), or evolving toward a new equilibrium position. Long term variations in the driving mechanisms triggered by a progressive increase or decrease in climatic factors may result in long term adjustment to the fluvial system as in the trend with time condition illustrated in Figure 1.2. The modified system differs from the trend through time response in the degree and rate of change. However, both types of change can lead to dramatically different channel forms.



**Figure 1.2: Conceptual Illustration of Various States of Equilibrium for Channel Cross Sectional Area Variation as a Function of Time**

The modified response is typical of morphological impacts associated with a catastrophic event or a rapid alteration of the sediment-flow regime caused by forest fires, flow diversion-regulation or other land use alterations. Unlike catastrophic events, that represent short duration high energy episodes, land use impacts through development can lead to small incremental increases in flow energy but with a high frequency of occurrence over a long duration. The thresholds governing channel response to short term (catastrophic) versus long term (urbanization) disturbances may be entirely different. For example, many grasses can withstand flow velocities of 6 fps before their soil binding strength is exceeded. Consequently, they may provide a high level of protection against the erosive power of a rare flood flow event. However, a long term alteration in the flow regime may result in an increase in the frequency of occurrence of flow events that inundate the bank toe. This increase in bank toe inundation may in turn increase the "winnowing"<sup>4</sup> of fine soil materials within the bank despite the root binding provided by the grasses. The slow but progressive winnowing of these materials may eventually expose the roots resulting in plant mortality. The loss of root binding due to plant die off exposes the bank soils to the erosive action of the sediment-flow mixture carried by the stream. A gradual undermining of the bank may lead to bank collapse and ultimately cause adjustment of the channel form.

To summarize the discussion to this point, it has been noted that Lane's (1955) proportionality illustrates that there is a balance between a stream's ability to perform work and the sediment load it carries. Secondly, this balance is not static but fluctuates between aggrading and degrading conditions in response to the normal randomness of the hydrologic system. This randomness may represent disturbances to the factors controlling channel form. Lane's (1955) balance does not explicitly include threshold parameters which implies that channel response is directly proportionate to the magnitude of the disturbance. While the concept of thresholds in geomorphology is well established, Lane's relation is consistent with the argument that different thresholds may apply to "short term" versus "long term" disturbances. Over the "long term" these thresholds may be relatively small implying that stream channels are more sensitive to a disturbance than previously thought.

Lane's (1955) proportionality provides a one dimensional qualitative prediction of the direction of change in channel form. The qualitative nature of the relation arises from our understanding of channel systems and their likely behavior under varying conditions. The one-dimensional approach is an attempt to illustrate in a simple manner a three-dimensional system that consists of complex, inter-related fluvial features covering a continuum of spatial scales. These complex features respond to the cumulative distribution of flow-sediment inputs that act on heterogeneous boundary materials and are modified by complex distributions of biotic forms (riparian vegetation and large organic debris), boulders and other elements contributing to perturbations within the flow field. The result is a system that defies characterization by current quantitative methods.

To better deal with the complex array of fluvial features Lewin (1979) divided them into three distinct categories based on temporal and spatial scales. These categories are:

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4 "Winnowing" refers to the selective removal of fine particles by flowing water.

- A. Macroforms – These forms include features at the scale of the flood plain width such as longitudinal channel slope, meander radius of curvature, pool-riffle spacing, sinuosity, and meander amplitude and wavelength.
- B. Mesoforms – these forms include features at the scale of the width of the active channel. These features include bankfull parameters (channel width, depth and cross-sectional area) and bar forms such as point, medial, and diagonal bars.
- C. Microforms – these forms include features measured at the scale of eddies in the flow field. These features include the spatial distribution of bar form sediments (transverse, longitudinal and vertical axis) and sediment structures such as imbricated sediment forms.

Imhof et al., (1997) in a compilation of other studies noted that the response time required for a feature to adjust to a new equilibrium position or return to its former position is proportional to the spatial scale of the feature. Macroforms require hundreds of years to adjust to a disturbance ( $10^2$ - $10^3$  years), while mesoforms require tens of years ( $10^1$ - $10^2$  years), and microforms may adjust on the time frame of a single flow event or series of events ( $10^{-3}$ - $10^0$  years).

Andrews (1979) observed that channel response to a disturbance can be described using three phases.

- Phase 1: Thalweg realignment and modification of particle roughness due to destruction or reworking of microform features;
- Phase 2: Adjustment of mesoform features (e.g. channel hydraulic geometry as represented by bankfull metrics: width, depth and cross-sectional area); and,
- Phase 3: Macroform feature adjustment (longitudinal profile and plan form features (e.g. meander wavelength, amplitude, etc.).

In this model, microform features are characterized as the most sensitive and first to be altered followed by mesoforms and macroforms in that order. Consequently, the sensitivity of a channel to a disturbance is dependent upon the spatial scale of the feature of interest. It should be noted however, that all features regardless of scales and all phases of the adjustment process are inter-related. Completion of the adjustment process occurs when the balance between the micro and macroform features has been re-established. While macroform adjustment is preceded by mesoform and microform adjustment the reverse is not necessarily true. In other words, microform adjustment, while a prerequisite for mesoform adjustment, does not necessarily mean that mesoform adjustment will occur if microforms are altered.

The temporal and spatial scale of fluvial features presents geomorphologists with problems of observation, measurement and interpretation of the fluvial processes operating on the system. Microforms, because of their sensitivity can be destroyed and reconstructed during a single flow event. They may also undergo progressive alteration during a series of flow events only to be completely reworked during a subsequent event. Superimposed on these responses are site specific influences such as eddies created about a fallen tree, or debris from a failed bank or a large boulder. Microforms are also influenced by upstream and downstream changes in mesoforms and macroforms, such as the passage of a sediment wave or the upstream propagation of a knick point. Given the spatial diversity and temporal scale of change in form, it is difficult to collect data

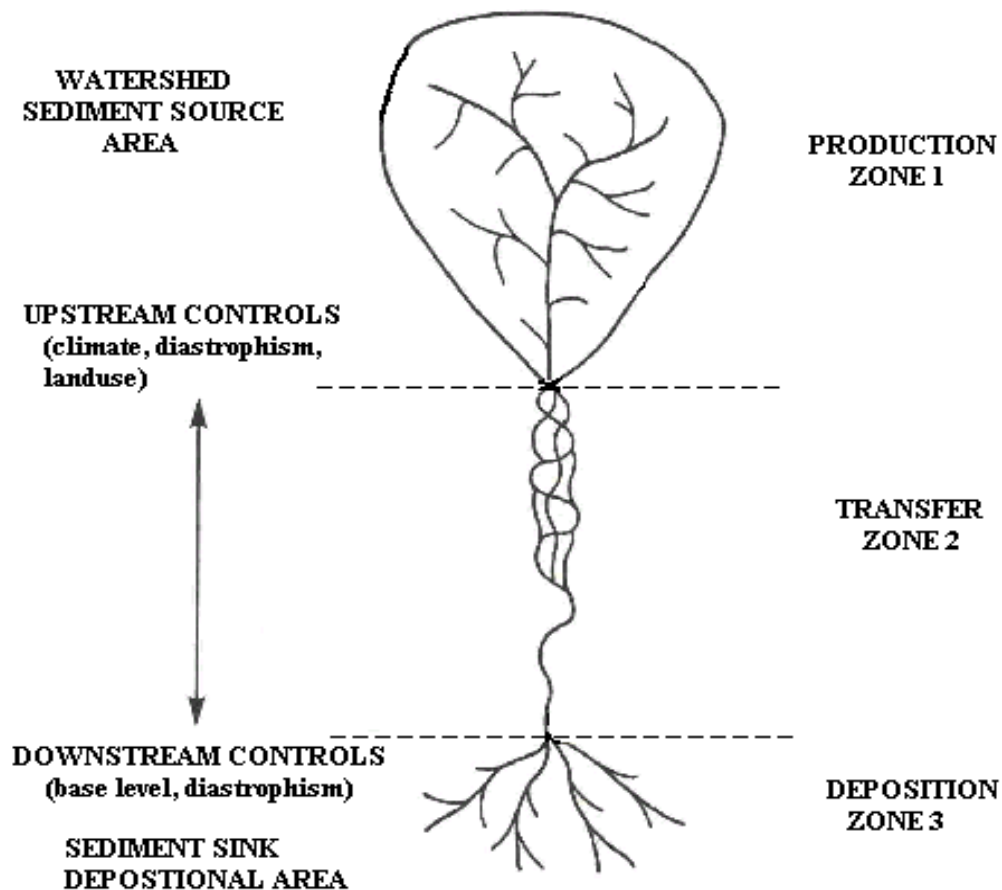
characterizing microform features. Further, microform alteration does not necessarily mean that mesoform and macroform adjustment will occur in all stream types. Consequently, it is difficult to predict channel form adjustment from microform alteration. Given these challenges, microform data have not traditionally been used as an indicator of channel adjustment.

Macroform features represent the other end of the spatial and temporal spectrum. Despite advances in methods of observation, such as large scale photogrammetry, the temporal scale of macroform adjustment presents a unique challenge. The time frame for measurement of change is in hundreds of years and detailed observations of channel form spanning these periods is not generally available. Further, the long adjustment period means that a disturbance that occurred in the past, such as deforestation for agricultural land use, may still be affecting channel planimetric form today. Consequently, the impact of more recent land use disturbances may be superimposed on geomorphic changes related to historic land use alteration. This overlap in the morphological response to a disturbance complicates the interpretation of macroform features. Finally, the response of macroforms to a specific land use alteration may not be observed until mesoforms have completed a significant portion of their adjustment. This means that macroforms may have lag times of tens to hundreds of years before morphological changes to macroform parameters are observed. Given these challenges, macroform parameters are also not typically employed as indicators of channel adjustment.

Mesoforms represent the middle of the spatial and temporal scale for fluvial features. These forms are well suited to standard survey techniques and the temporal scale of adjustment is also more manageable. Further, fluvial features at all spatial scales are inter-related, however, both microforms and macroform parameters are primarily determined by mesoform adjustment. Given the significance of mesoforms and the associated practicalities in observation and response time, it is reasonable that mesoform features should be used to measure and predict channel adjustment to a large scale, long term disturbance in the factors controlling channel form.

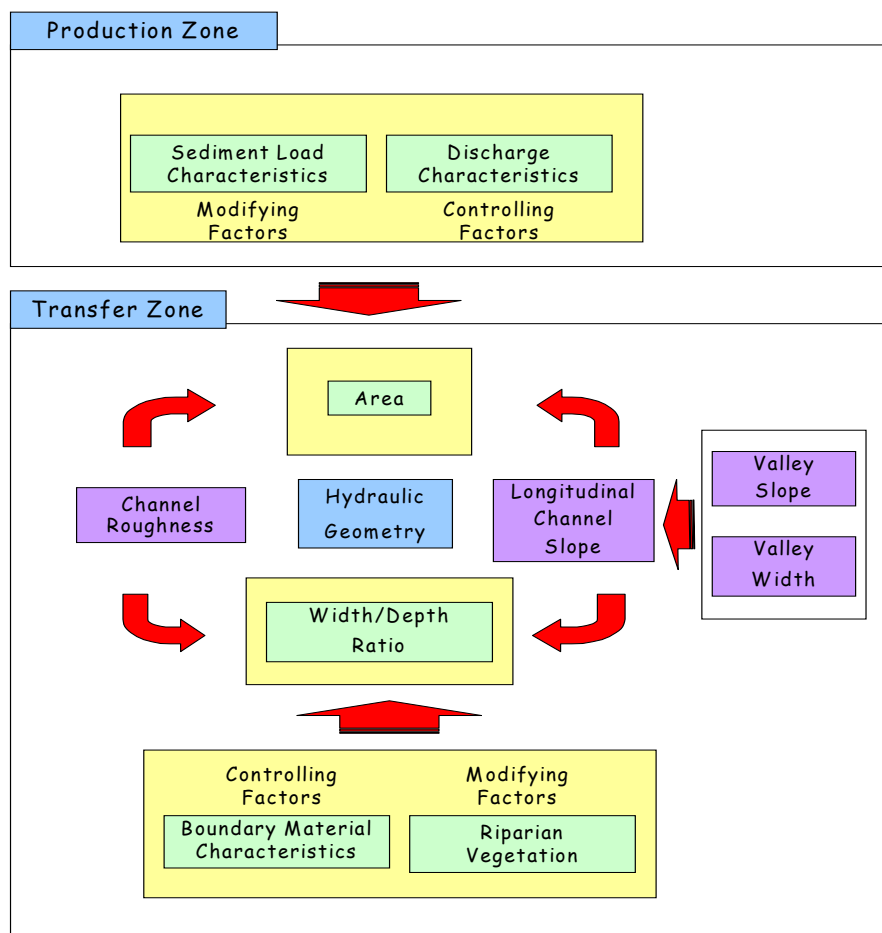
To summarize the above discussions it was noted that Lane's (1955) proportionality is a qualitative, one-dimensional method for the determination of channel response to a disturbance. However, stream channels are complex, three-dimensional systems represented by inter-related features covering a continuum of spatial and temporal scales. To aid our understanding of these complex systems Lewin, (1979) divided this continuum into three distinct groups based on their temporal and spatial scales: macroforms, mesoforms and microforms. Andrews (1979) proposed a three phase model to explain channel response to a disturbance that was consistent with these spatial and temporal scales. It was determined that channel sensitivity to a disturbance is scale dependent with microform features being the most sensitive and responding to a disturbance prior to mesoform and macroform features in that order. However, mesoforms parameters may be the primary determinant of microform and macroform characteristics. This consideration, and practicalities of observation and measurement, means that mesoforms are the best suited features for use in the determination and prediction of channel adjustment to a large-scale, "long term" disturbance in the factors controlling channel form. This means that Lane's (1955) proportionality applies to bankfull flow conditions.

Given that the mesoform features are best suited for the measurement and prediction of channel response to a disturbance, the next step is the definition of the factors affecting mesoform characteristics and dimensions. Schumm (1977) noted that the majority of the sediment ( $Q_s$ ) and flow ( $Q$ ) carried by the channel system originates within the "Production Zone" (see Figure 1.3). This Zone represents those areas that are outside of the flood plain valley as defined by the meander belt width of the active stream channel. The mass of sediment-water generated within the "Production Zone" is temporarily stored in or transported through the "Transfer Zone". The "Transfer Zone" represents the flood plain and active channel system within the meander belt width of an active channel. The sediments transported through the "Transfer Zone" are deposited in the ultimate receiver referred to as the "Deposition Zone." Note, Figure 1.3 is applicable to a wide variety of scales wherein the Production Zone could be a single catchment or as large as a watershed draining a third order tributary.



**Figure 1.3: Illustration of Three Watershed Zones Showing Sediment -- Source, Transportation, and Deposition Areas**

The delicate balance described by Lane (1955) is influenced by a number of watershed and instream factors as illustrated in Figure 1.4 (MacRae, 1991). Basin climate and geology, the only truly independent variables, define the hydrologic and sediment regime characteristics within the "Production Zone" and the valley slope within the "Transfer Zone". The sediment-flow regime within the "Production Zone" represent the factors that control and modify the cross-sectional area (Area) of the active channel. The controlling and modifying factors may be reversed during periods when a sediment influx exceeds stream competence or capacity. This may occur during the active construction phase of urbanization or logging. The shape of the channel, as measured by its width to depth ratio and general cross-section configuration is controlled by the boundary material characteristics as modified by riparian vegetation. The exception to this generality is for channel systems having bank heights of less than 2.5 feet wherein riparian vegetation may become the controlling factor.



**Figure 1.4 Conceptual Model of Stream Channel Morphological Response**

The central portion of Figure 1.4 denotes the balance within the active channel between flow resistance (Channel Roughness), channel cross-sectional area (Area), channel width to depth ratio (Width/Depth), and slope (Longitudinal Channel Slope). This balance may be disrupted by either

land use alteration within the "Production Zone" or through direct modification of the channel, e.g., riparian vegetation management programs, diversions, channelization, gravel mining, and so on within the "Transfer Zone".

Modifications in land use or land use practices typically alter the watershed storage capacity and timing characteristics of runoff from the "Production Zone." Hollis (1975) showed that flow rates for events having recurrence intervals of 6 months and 2 years may increase by 17.5 and 3.5 times the pre-disturbance flow rate, respectively, after a 30% paving of the basin. Marsalek (1993) observed that runoff volume also increases with increasing basin imperviousness such that at 30% imperviousness the direct runoff component of the hydrologic budget increases from about 15% for undeveloped conditions to nearly 35%. MacRae (1996) found that the conversion of an agricultural basin to medium density residential land use increased instream erosion potential by 4.7 times under built out conditions primarily due to the increase in occurrence of mid-bankfull flows.

While flow energy increases with increasing basin imperviousness, Wolman (1960) noted that sediment yield actually decreases. Depending on the predominate soil type, clearing of forests for agricultural use typically results in an increase in sediment yield in the order of 25 times resulting in aggradation within the channel-flood plain system and widening of the active channel (NVPDC, 1980). Sediment yields begin to decline as cultivated fields are reforested or transformed into scrublands or pasture. During the active construction phase of urbanization sediment yields increases in the order of 150 times those rates observed under forested conditions (MWCOCG, 1990). However, as the urban surface is stabilized and paved over, sediment yield declines abruptly to approximately twice the yield observed under forested conditions. The reduction in sediment yield results in a significant decrease in suspended solids producing a "hungry water"<sup>5</sup> phenomena. Referring to Lane's (1955) relation (Figure 1.1), a decline of sediment influx to the channel along with an increase in flow would result in degradation of the channel.

Based on the above assessment of land use alteration, a paving of the land surface results in both an increase in flow energy and decrease in sediment yield. Consequently, basin imperviousness may be considered a surrogate for the direct measurement of parameters characterizing sediment yield (particle size, mass, and timing) and flow regime characteristics (flow rate, volume and timing) from the "Production Zone" (Figures 1.3 and 1.4). Morisawa and Laflure (1979) correlated morphological impacts with basin imperviousness in a study of ten alluvial streams in Pennsylvania and New York States. Morphological impact was expressed in terms of channel enlargement (Re) as defined by the ratio,

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5 Sediment particles in suspension within the water column are carried both downstream by the primary flow velocity and vertically through eddies. The mass of the suspended particles and the collision between particles results in a loss of flow energy through momentum exchange. The result is a dampening effect on flow turbulence. Flow competence requires both drag (the downstream component of flow) and lift (the vertical component of flow) to entrain and transport particles. The dampening effect diminishes as sediment concentration declines within the water column resulting in an increase in stream competence, all other factors being equal.

$$(\text{Re})_{POST} = \left( \frac{(A_{BFL})_{POST}}{(A_{BFL})_{PRE}} \right)$$

in which 'A' represents the cross-sectional area of the active channel and the subscripts BFL, POST and PRE refer to bankfull stage, the post-disturbance channel and the pre-disturbance channel respectively.

Allen and Narramore (1985) also demonstrated that channel enlargement is a function of basin imperviousness in a study of interbedded shale-limestone and chalk streams in north central Texas. However, both the Morisawa and Laflure (1979) and Allen and Narramore (1985) studies included streams that were still undergoing land use modification. Given that some of the streams studied by the above authors may still have been in the process of adjustment, it is possible that they may have underestimated the ultimate channel enlargement.

To address this issue of continued channel enlargement, also defined as channel relaxation, MacRae et al., (1999) collected data from 60 sites in eleven mature urban watersheds in Austin, Texas. These watersheds had been fully developed for between 35 and 65 years. Total Basin Imperviousness (TIMP) was also relatively high ranging from between 35 and 75 percent. The 60 sites were selected based on the availability of historic engineering surveys from which the historic channel cross-sectional area at bankfull stage was determined  $[(A_{BFL})_{HIS}]$ . Each site was then re-surveyed to obtain a current estimate of cross-section area  $[(A_{BFL})_{CUR}]$ . These data indicated that channel enlargement varied with the resistance of the boundary materials. Channels worn into alluvium (AL-Type) reported the highest enlargement ratios followed by channels with rock beds and one or more alluvial banks (RB-Type). The lowest enlargement ratios were recorded for channels with massive rock bed and rock banks. These channel systems were referred to as Rock Controlled (RC-Type). The survey sites were divided into these three categories based on boundary material resistance.

Historic land use data were used to reconstruct the development sequence within the watershed area tributary to each site from a period representing the pre-disturbance condition to the time of the current survey. The pre-disturbance condition was defined as the pre-urbanization period. For approximately 15 of the AL-Type sites, the historic survey closely approximated the pre-disturbance land use condition. In these instances, the historic data were assumed to represent the pre-disturbance channel form  $[(A_{BFL})_{PRE}]$ . A first approximation of the ultimate enlargement ratio was then obtained using the relation,

$$(\text{Re})_{ULT} = a \left( \frac{(A_{BFL})_{CUR}}{(A_{BFL})_{HIS}} \right)^b$$

in which  $(\text{Re})_{ULT}$  represents the ultimate channel enlargement ratio where the mesoform parameters reach an equilibrium state with the altered hydrology of the "Production Zone" and 'a' and 'b' are coefficients.

The above relation was then used to determine the  $[(A_{BFL})_{PRE}]$  for the remaining AL-Type sites using the historic ( $[(A_{BFL})_{PRE}]_{HIS}$ ) and current ( $[(A_{BFL})_{PRE}]_{CUR}$ ) survey data. The two estimates of  $[(A_{BFL})_{PRE}]$  were then correlated and a second approximation of the "Relaxation Curve" for AL-Type streams was derived wherein the correlation coefficient was maximized. The resulting relation was of the following form:

*Relationship of Channel Relaxation as a Function of Age of Development - for AL-Type Streams*

$$\left( \frac{(Re)_i - 1}{(Re)_{ULT} - 1} \right) = 1.032 \left( \frac{(t_i - t_l)}{(t_r - t_l)} \right) - 0.028, R^2 = 0.82, n = 54$$

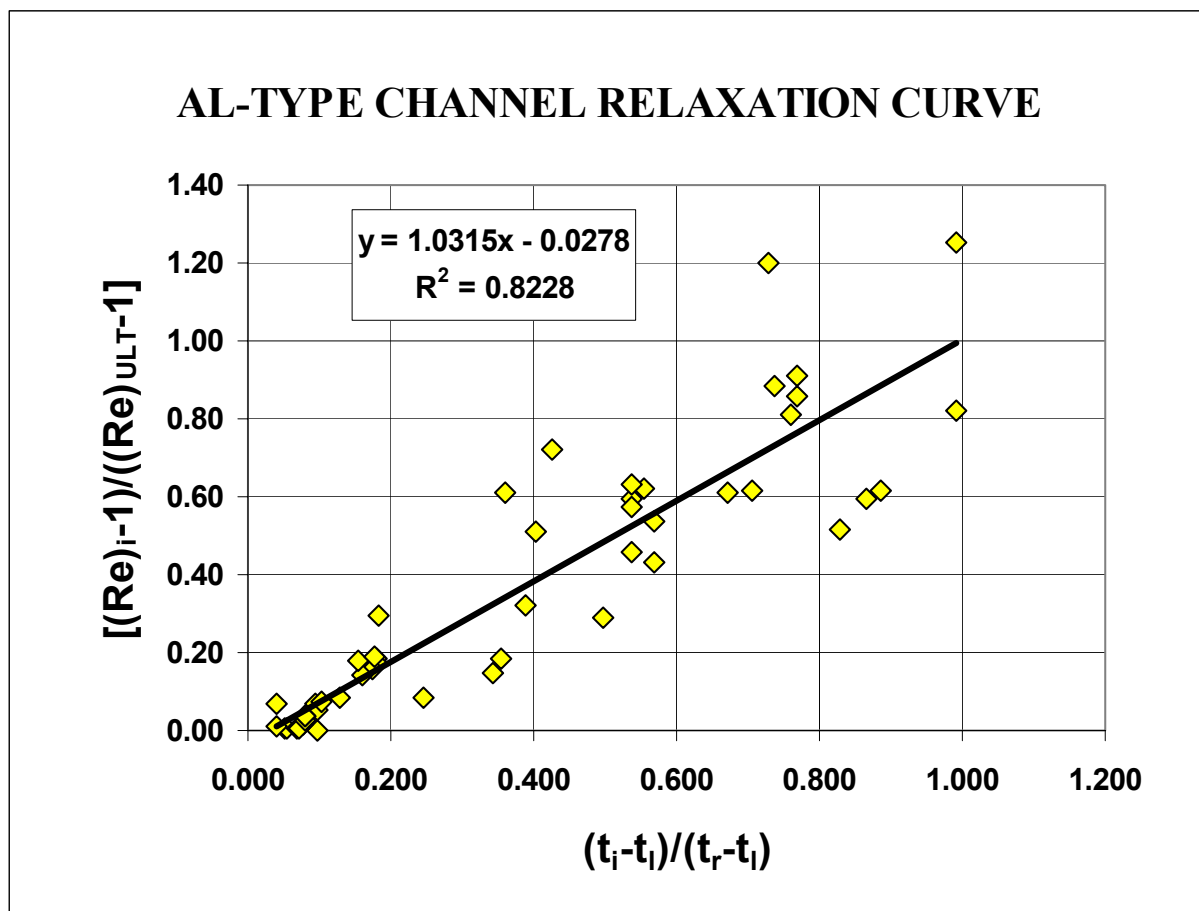
in which  $(Re)_i$  represents the enlargement ratio at the time of the survey,  $t_i$  is the area weighted average age of development,  $t_l$  represents the lag time required before a significant morphological response is observed in the cross sectional area ( $t_l=2.5$ ), and  $t_r$  is total time of the relaxation period ( $t_r=67.0$  years).

The value of  $t_l$  and  $t_r$  in the above relation were determined through curve fitting techniques. The value of  $t_l$  was determined by dividing the time from pre-disturbance to the date of the historic or current survey into time periods corresponding to available land use information (topographic mapping, aerial photography and land use mapping). The beginning and ending date of the time period was noted and the developed drainage area of the basin (DDA) in each time period was measured. These data were entered into the following relation to determine the value of  $t_i$ ,

$$t_i = \frac{\sum_{i=1}^n 0.5DDA_i [(t_n - t_j) + (t_n - t_k)]_i}{\sum_{i=1}^n DDA_i}$$

in which DDA is the developed drainage area of the basin tributary to the survey site that has been urbanized or undergone land use alteration during the  $i^{\text{th}}$  time period,  $t_n$  represents the year of the survey and  $t_j$  and  $t_k$  are the starting and ending years of the  $i^{\text{th}}$  time period respectively.

The Austin Relaxation Curve was then validated using data collected from 42 historic and 35 current cross-sections along a 2,625 ft (800 m) reach of Humber Creek, Toronto, Ontario representing 5 sites (each site consisting of 7 cross-sections on average. The Humber Creek data closely approximated the Austin Relaxation Curve (MacRae and DeAndrea, 1999). The final form of the curve for AL-Type streams is illustrated in Figure 1.5.



**Figure 1.5: Relaxation Curve for Estimating Channel Enlargement at any Given Time Period** (Source: MacRae, et.al, 1999)

The resulting estimates of  $(Re)_{ULT}$  were then used to develop the channel "Enlargement Curve." The adopted form of the channel "Enlargement Curve" was a second order polynomial forced through  $(Re)_{ULT} = 1.0$  at  $TIMP = 1.0$  percent. This form of the relation was adopted because conceptually it can be argued that the channel will not continue to enlarge indefinitely in an exponential manner. The final form of the "Enlargement Curve" for AL-Type streams is,

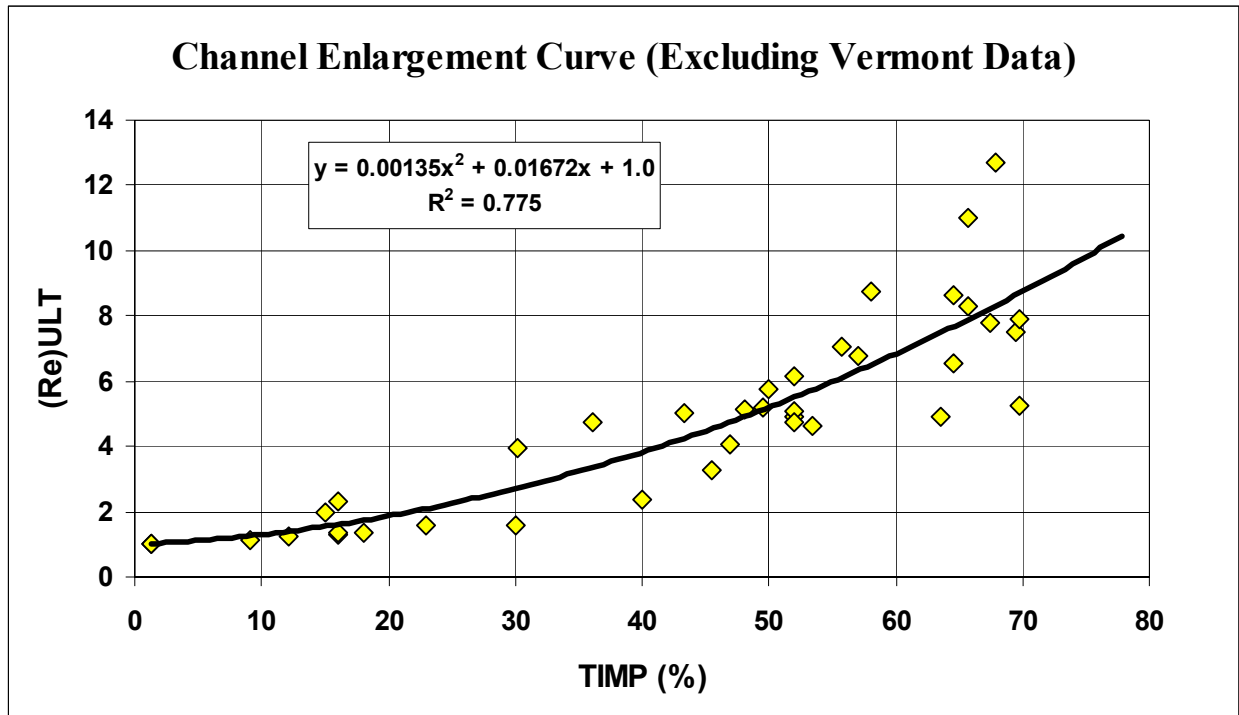
*Original Relationship of Ultimate Channel Enlargement as a Function of Total Impervious Cover*

$$(Re)_{ULT} = 0.00135(TIMP)^2 + 0.0167(TIMP) + 1.0$$

$$R^2 = 0.78, (n = 38)$$

in which  $TIMP$  is the total basin imperviousness and  $(Re)_{ULT}$  is the ultimate enlargement ratio at  $t_i = t_r$ .

Figure 1.6 illustrates the resulting channel "Enlargement Curves" for AL-Type streams incorporating data from Austin, TX. The primary focus of this study is to test these baseline data and the corresponding channel Enlargement Curve by comparing estimates of channel enlargement obtained from the curve to values of channel enlargement obtained for Vermont streams. If it can be shown that the two data sets are drawn from the same population then the existing Enlargement Curve can be used to help predict and assess stream morphological impacts associated with proposed land use modifications. Further, the Enlargement Curve can help in the design of stormwater mitigation strategies in streams already impacted by land use change.



**Figure 1.6: Channel Enlargement Curve for AL-Type and RB-Type Streams** (Enlargement Ratio as a Function of Total Basin Imperviousness (TIMP) for all Channels Excluding Vermont Streams) (Source: MacRae, et al, 1999)

## **SECTION 2**

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# **~~PROJECT~~ METHODOLOGY**

## **SECTION 3**

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# **~~SUMMARY OF~~ FIELD GEOMORPHIC ASSESSMENT DATA**

**SECTION 4**

**BIOLOGICAL  
MONITORING  
ANALYSIS**

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**SECTION 5**  
**DISCUSSION**

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# REFERENCES



# **APPENDIX A**

## **ORIGINAL PROJECT METHODOLOGY**

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# **APPENDIX B**

**LAND USE**

**~~TABLES FOR~~**

**IMPERVIOUS**

**COVER**

**APPENDIX C**

**DIAGNOSTIC**

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**GEOMORPHIC**

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**SURVEY FORM**

*Representative Example for Potash Brook*

**APPENDIX D**

**EXAMPLE**

**OUTPUT**

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**FOR**

**SPREADSHEET**

**MODELS**

# **APPENDIX E**

## **LIST OF**

## **~~CONTACTS FOR~~**

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## **HISTORICAL STREAM**

## **CHANNEL DATA**

# **APPENDIX F**

## **SITE BY SITE SUMMARY OF ~~HISTORICAL~~**

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## **CROSS-SECTION INFORMATION**

**APPENDIX D:  
EXAMPLE  
OUTPUT  
FOR  
SPREADSHEET  
MODELS**

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