Expanded Technical Analysis: Utilizing Hydrologic Targets as Surrogates for TMDL Development in Vermont's Stormwater Impaired Streams

Prepared by the U.S. Environmental Protection Agency
and the
Vermont Department of Environmental Conservation

September, 2006

1. OVERVIEW

The purpose of this expanded technical analysis is to describe logic used to identify indicators and hydrologic targets for TMDL development for waters impaired by stormwater–related stressors in Vermont. This analysis uses Potash Brook as an example case. Potash Brook is on Vermont's §303(d) list as a result of biological impairments. Stressors associated with storm water are the cause of the biological impairment. For this analysis, Potash Brook has been selected as an example because of a greater amount of existing data. However, the underlying logic put forth in this analysis is applicable to all of the "stormwater" impaired streams identified on Vermont's §303(d) list. This analysis builds on the conclusions of the Vermont Water Resources Board's 2004 report titled "Investigation into developing cleanup plans for stormwater-impaired waters". It is intended to supplement the material included in the TMDL documents for these Vermont streams.

An assessment of Potash Brook developed by the Department of Environmental Conservation (DEC) suggests, based on limited data, that enrichment (e.g. nutrients), chemical (e.g. metals, chlorides), and physical characteristics (e.g. temperature, hydrology, sediment) may be contributing to the impairments. Designating a single stressor responsible for the impairment has not been possible with available information. However, the DEC assessment concludes that the multiple factors associated with stormwater runoff (including hydrologic modification, high levels of sediment and silt, cobble embeddedness, and other habitat degradation) are the most significant contributors to observed biological impairments in Potash Brook.

A study conducted on Potash Brook, as part of a watershed restoration plan for the City of South Burlington, incorporated six different types of data collection into the assessment effort *(Pioneer Environmental Associates, 2003).* Monitoring categories included:

- Biomonitoring
- Water quality parameters *(both baseflow and event-based sampling)*
- Substrate sampling
- Geomorphology
- Bank stability evaluation
- Watershed reconnaissance

In addition, the University of Vermont (UVM) has been engaged in sampling Potash Brook, collecting additional data for these same monitoring categories. The South Burlington and UVM work also supports a focus on hydrology and sediment dynamics to address biological impairments in Potash Brook.

2. APPLICABLE WATER QUALITY STANDARDS

Within the State of Vermont, water quality standards are published pursuant to Title 10, Chapter 47 of the Vermont Statutes Annotated (VSA). Authority to adopt rules, regulations, and standards as are necessary and feasible to protect the environment and health of the citizens of the State is vested with the Vermont Water Resources Board. Through adoption of water quality standards developed by the Agency of Natural Resources (ANR), Vermont has identified designated uses to be protected in each of its drainage basins and the criteria necessary to protect these uses [Vermont Water Quality Standards (VWQS)].

In Vermont, numeric biological indices are used to determine the condition of fish and aquatic life uses. Vermont's Water Quality Standards provide the following regulatory basis for these numeric biological indices:

> *"(1) In addition to other applicable provisions of these rules and other appropriate methods of evaluation, the Secretary may establish and apply numeric biological indices to determine whether there is full support of aquatic biota and aquatic habitat uses. These numeric biological indices shall be derived from measures of the biological integrity of the reference condition for different water body types. In establishing numeric biological indices, the Secretary shall establish procedures that employ standard sampling and analytical methods to characterize the biological integrity of the appropriate reference condition. Characteristic measures of biological*

integrity include but are not limited to community level measurements such as: species richness, diversity, relative abundance of tolerant and intolerant species, density, and functional composition.

(2) In addition, the Secretary may determine whether there is full support of aquatic biota and aquatic habitat uses through other appropriate methods of evaluation, including habitat assessments." [VWQS 3-01(D)(1) & (2)].

Vermont's rules also describe management objectives and water quality criteria for Class A(1) Ecological Waters, Class A(2) Public Water Supplies, and Class B Waters. For example, management objectives for aquatic biota and wildlife in Class B waters shall be *"sustained by high quality aquatic habitat with additional protection in those waters where these uses are sustainable at a higher level based on Water Management Type designation"*. The VWQS identify specific biological criteria for each Water Management Type.

3. Potential Stressors

Bioassessment Concerns

Potash Brook contains a mix of pools, runs, and riffles that were targeted for biological assessment. Macroinvertebrate community data provide the most significant basis for designating non support of aquatic life uses in Potash Brook. Impairment of the macroinvertebrate community is due to loss of sensitive taxa and compositional shift toward more tolerant generalist taxa. The end result is a very simplified community structure and altered functional resiliency. Fish community evaluations were also conducted for Potash Brook, with scores consistently in the good range.

Potential Contributors

Habitat and Sedimentation: Physical observations and chemical water quality data provide strong evidence that storm water is a significant source of multiple stressors to biological communities in Potash Brook. Physical habitat data collected at the time of biological sampling indicate high levels of sediment, silt, and embeddedness are evident at all mainstem sites. The percent sand observed within the riffle habitat ranges up to 20 – 40 percent. An observational silt rating (0-5) assigned to each site after macroinvertebrate collection is often in the 3-5 range, indicating significant plumes of silt cloud the water during kick net sampling.

The restoration plan assessment for Potash Brook also confirmed overall urban development as a primary factor responsible for stressors directly or indirectly linked to biological impairments. Major findings identified in the restoration plan assessment report include:

- Moderate embeddedness was noted at four locations in the Potash Brook channel, as well as at one tributary location. A second tributary sample location indicated a high level of embeddedness with a strong bimodal distribution of sediment grain sizes.

- A channel / bank stability assessment was conducted at four locations in Potash Brook, as well as at two tributary locations using the Pfankuch evaluation procedure. Channel adjustment was evident at all monitoring stations, with aggradation as the primary process. Channel adjustment noted included: increases in width / depth ratio, sediment storage, bank erosion rates, and a decrease in pool quality / habitat diversity.

Nutrients: A high percentage of algae cover the lower reaches of Potash Brook. These observations, coupled with chemical sampling, provide some evidence of elevated nutrients. Periphyton algae observations indicate the substrate (cobble) is often 50-80 percent covered by either filamentous or blue green algae. Nutrient sampling at base flow over the past several years show dissolved phosphorus to be slightly elevated at 20-30 ug/L on mainstem sites. *[Note: The Lake Champlain TMDL addresses nutrients in tributaries, which includes Potash Brook].*

Toxics: Water quality monitoring data show Potash Brook to be high in conductivity, chloride, and sodium. Elevated conductivity caused by high chloride and sodium generally implicates storm water from impervious surfaces as exerting a major influence in the watershed. Iron and manganese are also elevated, but to a lesser degree. None of these substances was found at levels exceeding any pollutant specific criterion in Vermont's water quality standards.

Weight of Evidence

Overall, data suggests that degraded habitat and increased sedimentation are the highest concerns relative to biological impairments in Potash Brook. Table 3-1 summarizes likely and possible sources. Major problems appear to be associated with macroinvertebrate communities, which are more sensitive to habitat alterations and changes in substrate composition from siltation. Problems with nutrients and toxics would also have an adverse effect on fish communities. However, fish assessment scores are consistently in the good range, indicating that these substances do not appear to be significantly contributing to the biological impairment.

Table 3-1. Potential Stressors Contributing to Biological Impairments

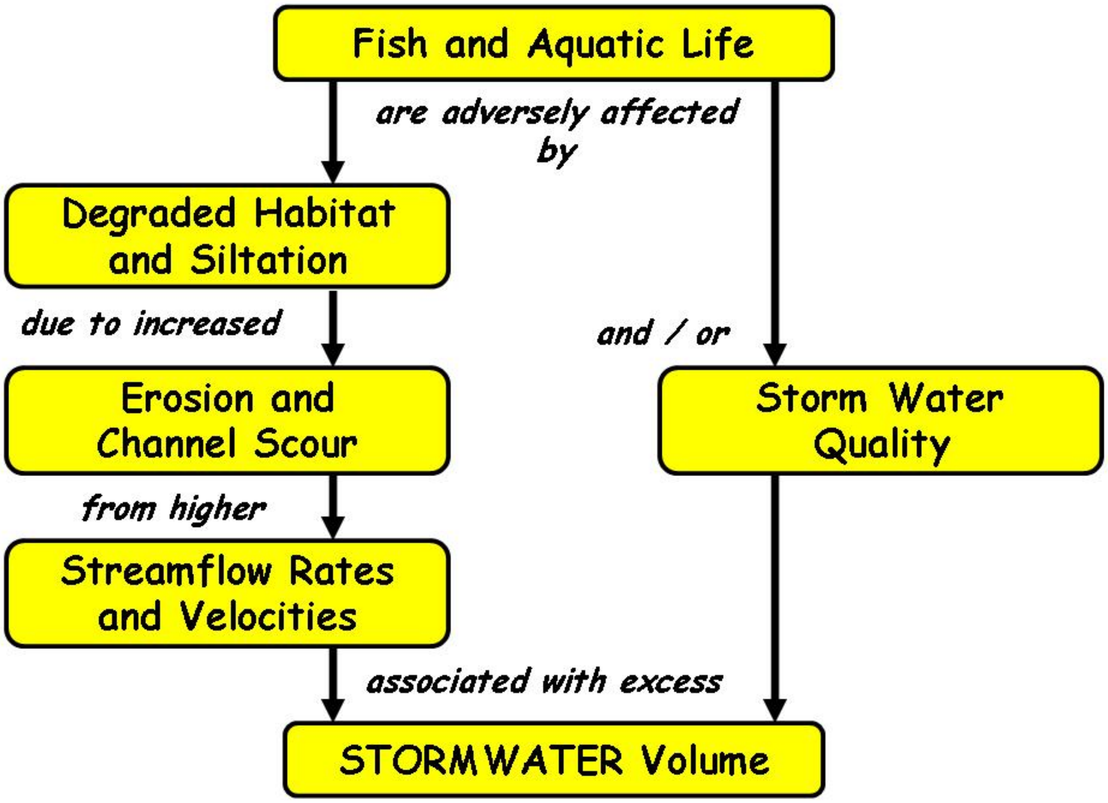
Stressor	**Importance**	**Sources**	
		Likely	**Possible**
Impaired Instream Habitat	**High**	Altered hydrology	Channelization
		Reduced pool : riffle ratio	Reduced sinuosity
		Reduced pool volume	Increased width : depth ratio
Increased Sedimentation	**High**	Increased stormwater volume	Decreased median particle size (d_{50})
		Gully erosion	
		Erosion from land use activities	
		Channel degradation & aggradation	
Nutrients & Toxics at Low Flow	Medium	Low base flow	
		Decreased Infiltration	
Nutrients [1]	Low-Medium	Stormwater runoff from multiple sources	
Toxics	Low-Medium	Winter road de-icers	
		Runoff from area roads & parking lots	
Note: [1] Addressed by Lake Champlain Phosphorus TMDL			

4. SURROGATE MEASURES

Potash Brook is on Vermont's §303(d) list as a result of bioassessment data. Existing information suggests that the impairment is most likely caused by water flow and sediment dynamics being out of balance. Physical habitat in the channel no longer supports healthy macroinvertebrate communities, as measured using biological criteria developed by DEC pursuant to the Vermont's Water Quality Standards.

Hydrology is a major driver for both upland and stream channel erosion. Consequently, control of high water flows will also achieve reductions in delivery and transport of sediment in Potash Brook *(Figure 4-1)*. Best professional judgment suggests that a storm water management plan targeted toward restoring an appropriate balance of water flow and sediment loading has the greatest potential for success.

Figure 4-1. Relationship of Biological Impairment to Surrogate Measures



Note: Boxes depict measured or calculated key indicators

Regulatory Basis

Common ways to address biological impairments through TMDLs often focus on sediment. A loading capacity for sediment can be estimated using available data and basic principles of sediment transport. However, sediment targets may be of limited value in guiding management activities needed to solve identified water quality problems.

Instead, this TMDL uses *"other appropriate measures"* (or surrogates) as provided under EPA regulations [40 CFR §130.2(i)] to augment analysis of habitat degradation and the role of sediment. For the Potash Brook TMDL, hydrologic targets are used as a surrogate measure to address the biological impairment.

The *"Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program"* (FACA Report, July 1998) offers some guidance on the use of surrogate measures in TMDL development. The FACA Report indicates:

> *"When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional "pollutant," the state should try to identify another (surrogate) environmental indicator that can be used to develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not. The criterion must be designed to meet water quality standards, including the waterbody's designated uses. The use of BPJ does not imply lack of rigor; it should make use of the "best" scientific information available, and should be conducted by "professionals." When BPJ is used, care should be taken to document all assumptions, and BPJ-based decisions should be clearly explained to the public at the earliest possible stage.*
>
> *If they are used, surrogate environmental indicators should be clearly related to the water quality standard that the TMDL is designed to achieve. Use of a surrogate environmental parameter should require additional post-implementation verification that attainment of the surrogate parameter results in elimination of the impairment. If not, a procedure should be in place to modify the surrogate parameter or to select a different or additional surrogate parameter and to impose additional remedial measures to eliminate the impairment."*

5. INDICATORS AND RELATIONSHIPS

Biological communities are subjected to many stressors associated with storm water runoff. These stressors relate, either directly or indirectly, to runoff volumes. Adverse effects occur through increased watershed loads (e.g. surface and gully erosion), from increased in-stream loads (e.g. bank erosion), habitat degradation (e.g. siltation, scour, over-widening of stream channel), washout of biota, and loss of habitat due to reductions in stream base flow.

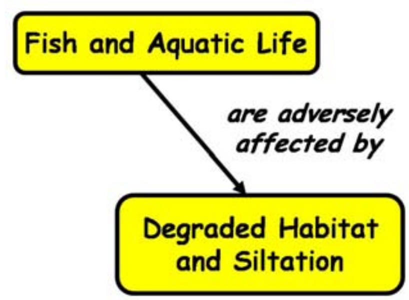
These stressors may act individually or cumulatively to degrade the overall biological community in a stream. Degradation may reach a point, as in Potash Brook, where aquatic life uses are not fully supported and the stream does not attain Vermont's water quality standards. Consequently, this TMDL utilizes storm water runoff volume as a surrogate measure, in place of the traditional *"pollutant of concern"* approach.

A combination of stress factors is represented by storm water runoff volume as a surrogate TMDL measure. Use of this measure addresses sediment delivered through erosion processes. The measure also addresses physical effects on the stream channel caused by storm water runoff, such as sediment release from channel erosion and scour from increased flows. Physical alterations to the stream are substantial contributors to aquatic life impairments.

Reductions in storm water runoff volume will also help restore diminished base flow (e.g. increased groundwater recharge), another aquatic life stressor. Lastly, this surrogate measure is appropriate because the amount of other potential pollutants (e.g. nutrients, toxics) delivered to Potash Brook is a function of the amount of storm water runoff generated within the watershed.

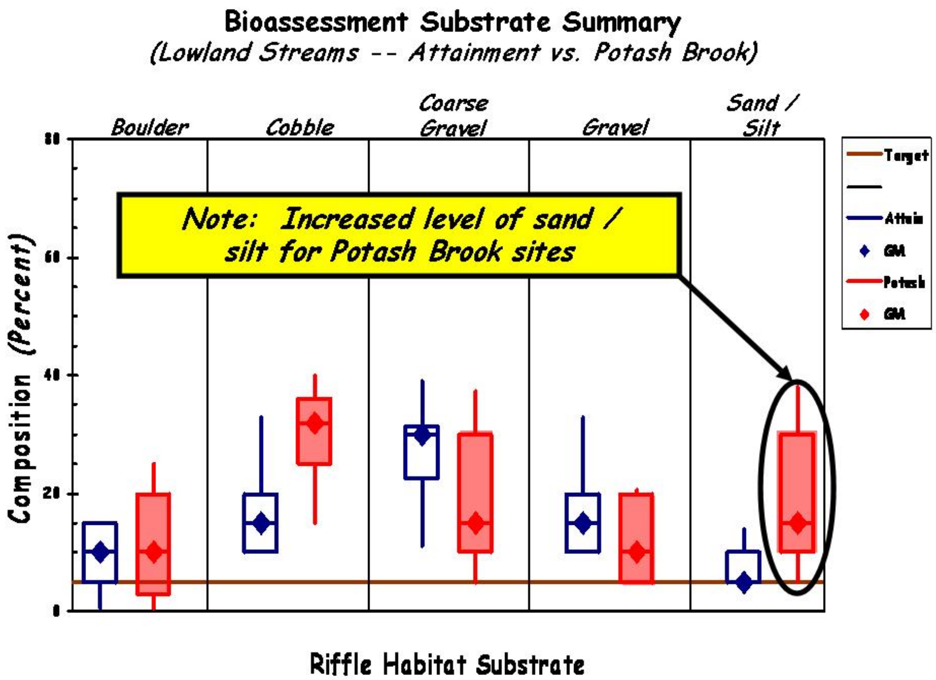
Degraded Habitat and Siltation

Decisions about storm water impairment are ultimately based on the biological criteria. Positive changes in physical habitat conditions within the stream indicate progress towards attaining Vermont's Water Quality Standards. The adverse effects of degraded habitat and siltation on macroinvertebrate communities have been well documented.



Filling of cobble / gravel substrate with fine grained material (e.g. sand / silt) often results in the loss of pollution intolerant taxa. An overall decrease in average substrate particle size results in a shift toward more tolerant macroinvertebrate species. This, in turn, reduces biological assessment scores towards impaired conditions. Figure 5-1 displays physical habitat information collected at the time of biological sampling to illustrate this concern, using data both for lowland Champlain Valley attainment streams in Vermont and for Potash Brook.

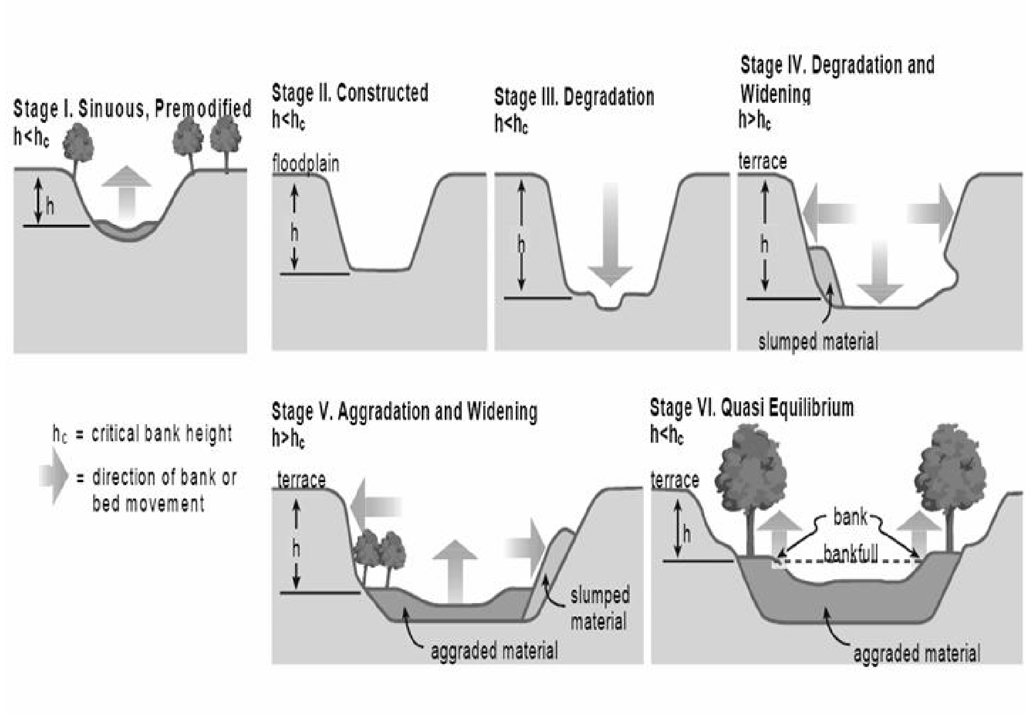
Figure 5-1. Substrate Composition -- Attainment Streams vs. Potash Brook



<u>*Channel Processes and Instability*</u>*:* A TMDL developed for Shades Creek near Birmingham, Alabama provides some logic that supports the approach taken for Potash Brook. Biological assessments and habitat studies concluded that increased water volumes and velocities within the channel adversely affected biological communities. Increased flows were attributable to nonpoint source runoff from existing development in the watershed. The role of channel processes and the effect of instability on physical habitat was a key part of the Shades Creek TMDL.

A conceptual model of channel evolution was used to characterize varying stages of channel modification through time, as illustrated in Figure 5-2 *(Simon and Hupp, 1986).* Stage I, undisturbed conditions, is followed by the construction phase *(Stage II)* where vegetation is removed and / or the channel is modified significantly (through altered hydrology, for example). Degradation *(Stage III)* follows and is characterized by channel incision.

***Figure 5-2*.** Channel Evolution Model



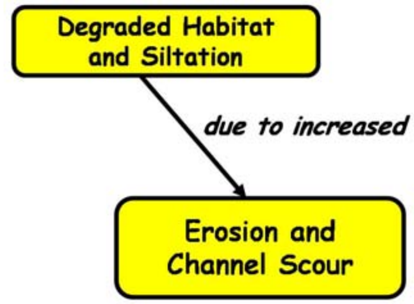
(from Simon & Hupp, 1986)

Channel degradation leads to an increase in bank heights and angles, until critical conditions of the bank material are exceeded. Eventually, stream banks fail by mass wasting processes *(Stage IV)*. Sediments eroded from upstream degrading reaches and tributary streams are deposited along low gradient downstream segments. This process is termed aggradation and begins in Stage V.

Aggradation continues until stability is achieved through a reduction in bank heights and bank angles. Stage VI (restabilization) is characterized by the relative migration of bank stability upslope, point-bar development, and incipient meandering. Stages I and VI represent two true *"reference"* or attainment conditions.

The physical habitat of Potash Brook has been degraded with many reaches showing signs of channel instability. Increased levels sand / silt *(Figure 5-1)* reflect channel evolution model stages IV and V *(Figure 5-2)*. Activities intended to address these degraded habitat conditions should consider erosion processes that contribute to increased levels of measured sediment, as well as channel scour that transports it through the Potash Brook system. Efforts to address degraded habitat in Potash Brook should also consider the role that increased storm water runoff volumes and altered hydrology contribute to the problem.

Erosion and Channel Scour



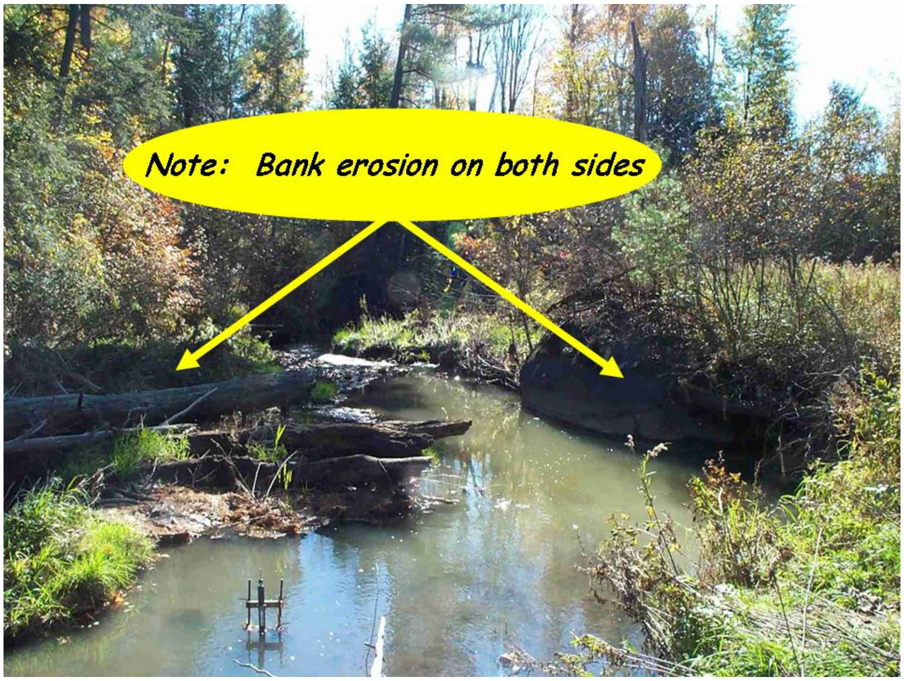
Most of the sediment supply that enters streams affected by storm water, such as Potash Brook, is generated by erosion processes including:

- Bank erosion
- Surface erosion
- Gully erosion

Bank erosion is driven by channel stability, discharge volumes, and stream velocities, while surface and gully erosion result from excess water runoff. Because erosion and hydrology are connected, the timing of delivery and transport mechanisms is an extremely important consideration. The following sections briefly discuss each of the major erosion processes that affect Potash Brook, as well as a framework for identifying potential measures to address water quality concerns.

Bank Erosion & Channel Movement: Confronted by more frequent and severe floods, stream channels must respond. They typically increase their cross-sectional area to accommodate the higher flows. As described in Figure 5-2, this is done either through widening of the stream banks, down cutting of the stream bed, or frequently both. This phase of channel instability, in turn, triggers a cycle of stream bank erosion and habitat degradation, as seen in Potash Brook *(Figure 5-3)*.

Figure 5-3. Bank Erosion in Lower Potash Brook



Discharge flow rate is a major factor that affects sediment transport in stream systems. Higher discharge volumes lead to increased flow velocities, thus raising shear stress and stream power exerted on the channel bed and banks. This effect, combined with channel stability, determines the amount of sediment that is mobilized, which in turn influences habitat and aquatic biota.

Surface Erosion: Excessive water runoff across a watershed can lead to detachment of soil particles. If the runoff volume is high enough and soils are exposed, surface erosion occurs. Surface erosion rates are affected by several factors including:

- soil type
- hill slope
- vegetative condition
- rainfall intensity

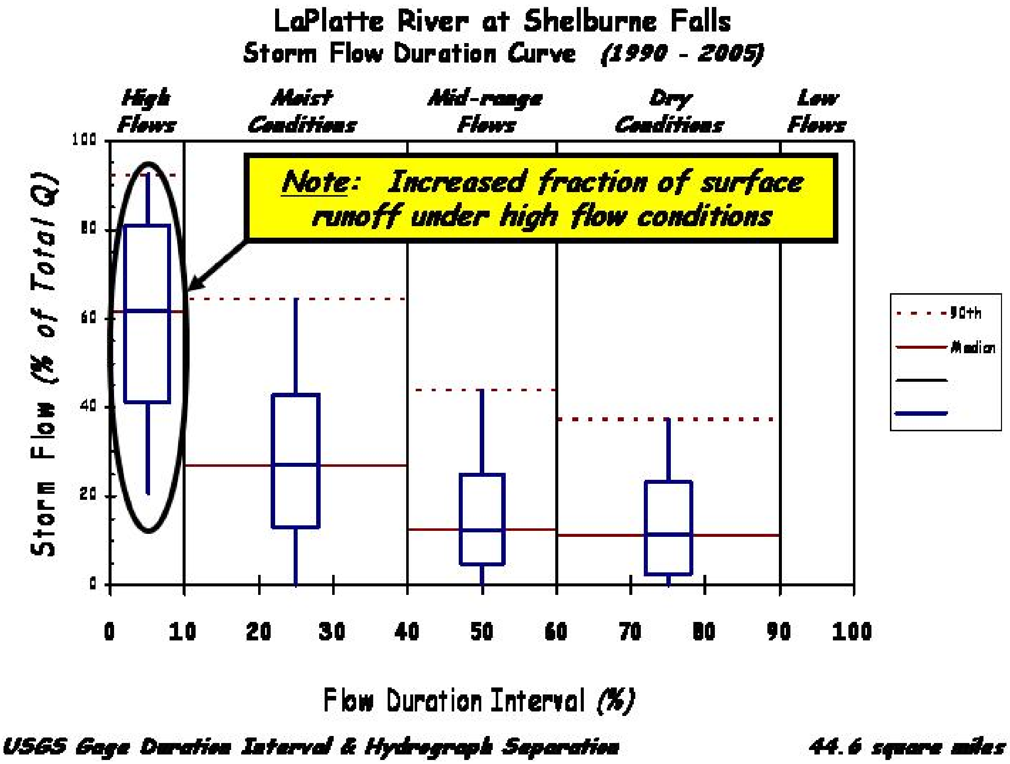
Runoff following rain events can be one of the most significant transport mechanisms of sediment and other nonpoint source pollutants. Precipitation is obviously the driving mechanism responsible for storm flows and associated surface runoff. Rainfall / runoff models, such as HSPF, SWAT, or SWMM, are generally used to provide detailed estimates of the timing and magnitude of storm flows. However, these can also be very rigorous and time-consuming approaches.

Over the past several years, basic hydrology in the form of flow duration curves has been used to support the development of TMDLs. Flow duration curve analysis identifies intervals, which can be used as a general indicator of hydrologic condition (i.e. wet versus dry and to what degree). Duration curves help refine assessments by expanding the characterization of water quality concerns, linking concerns to key watershed processes, prioritizing source evaluation efforts, and identifying potential solutions.

Development of duration curves requires the analysis of hydrologic information. For this reason, an alternative method can use the stream flow data to examine general watershed runoff patterns. Hydrograph analysis has proven to be a useful technique for a variety of water-resource investigations. Streamflow hydrographs can be separated into base-flow and surface-runoff components *(Sloto and Crouse, 1996)*. The base-flow component is traditionally associated with groundwater discharge and the surface-runoff component with precipitation that enters the stream as overland flow.

Information from hydrograph separation can be displayed as a fraction analysis using duration curve intervals to examine the percentage (or fraction) of total flow that consists of base flow and storm flow. Figure 5-4 illustrates the potential effect that storm flows may exert across the range of flow conditions, grouped by duration curve zone using data for the LaPlatte River (located south of Burlington and Potash Brook). In the case of Figure 5-4, surface runoff has its greatest effect on the LaPlatte River during high flow conditions (median value of 61 percent). Correspondingly, sediment delivered to stream systems as a result of surface erosion will also be greatest during high flows.

Figure 5-4. Fraction Analysis of Storm Flow Relative to Total Streamflow



Gully Erosion: Gullies are relatively steep-sided watercourses, which experience ephemeral flows during heavy or extended rainfall. Gully erosion is caused when runoff concentrates and flows at a velocity sufficient to detach and transport soil particles. Widening of gully sides subsequently occurs by slumping and mass movement. Runoff may also enter a gully from the sides, causing secondary gullies or branching. Like surface erosion, sediment from gullied areas is delivered to stream systems during high flow conditions. Gully formation may be triggered by land use changes, such as vegetation removal or by construction of new commercial / residential areas.

Gully development associated with concentrated flow is evident in the Burlington area, including the Potash Brook watershed. Figure 5-5 shows a gully that leads to Potash Brook caused by concentrated runoff from impervious surfaces (noted in the air photo corresponding to location of picture). Figure 5-6 shows another gully in the Centennial Brook watershed (adjacent to Potash), which resulted from concentrated parking lot runoff. Figures 5-5 and 5-6 highlight the importance of water and sediment delivered from gullies with respect to addressing aquatic life impairments in Potash Brook and other Burlington area streams.

Figure 5-5. Gully Erosion -- Potash Brook Watershed

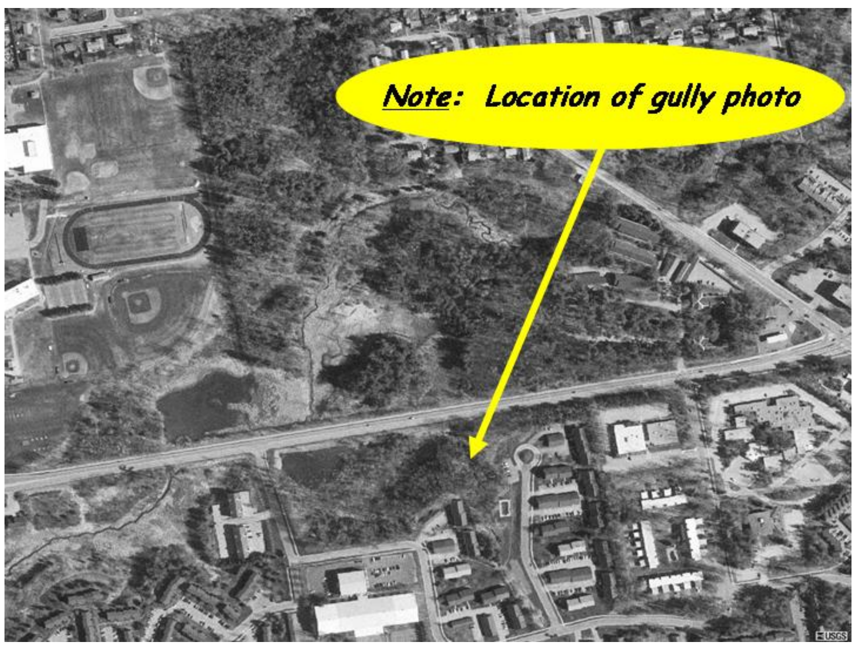
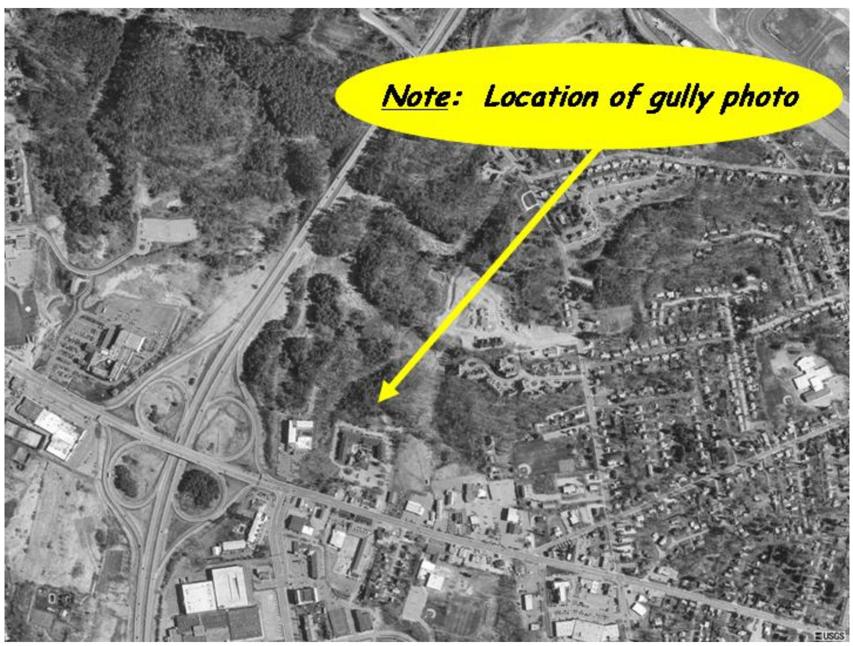


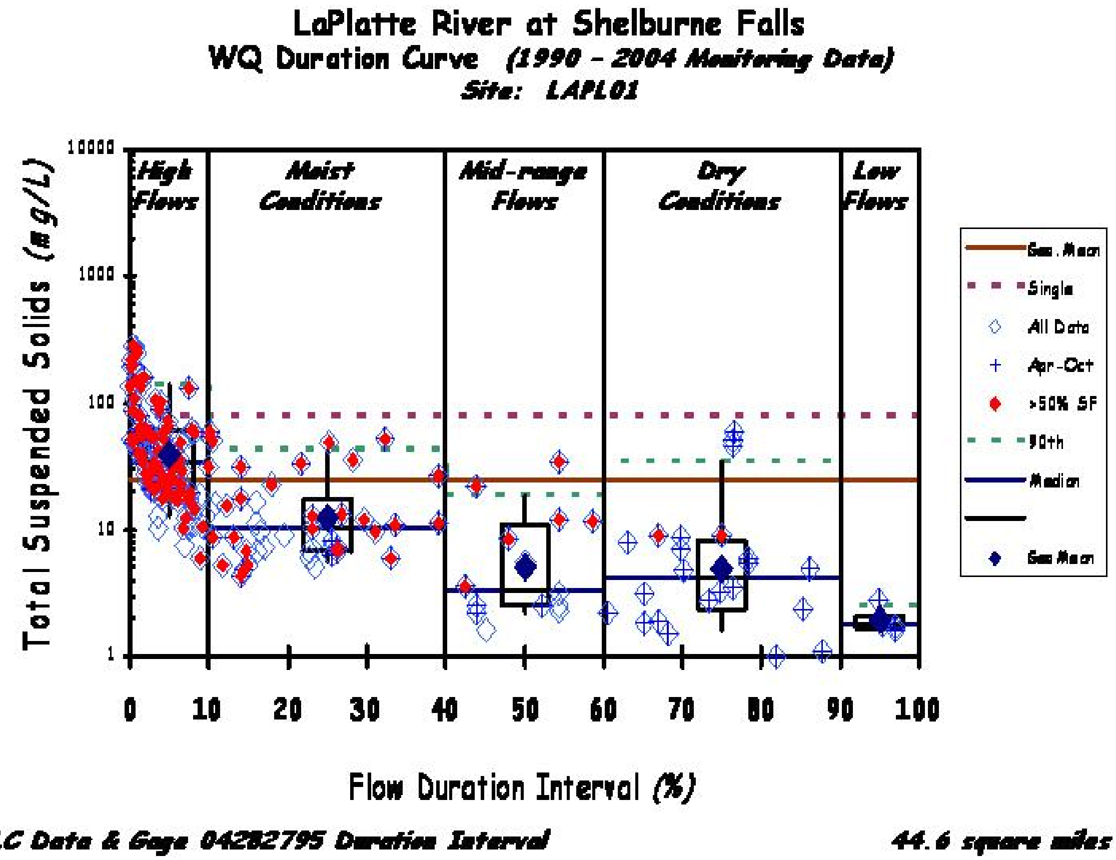
Figure 5-6. Gully Erosion -- Centennial Brook Watershed



Timing: An important aspect in development of a framework to address control of sediment sources is the timing of delivery and transport mechanisms. Duration curve analysis is a useful way to look at storm water and its effects on water quality. The analysis provides a hydrology-based context for examining and interpreting water quality data, allowing consideration of the full range of flows. Duration curves offer a technique for presenting water quality data, which characterizes concerns and describes patterns associated with impairments.

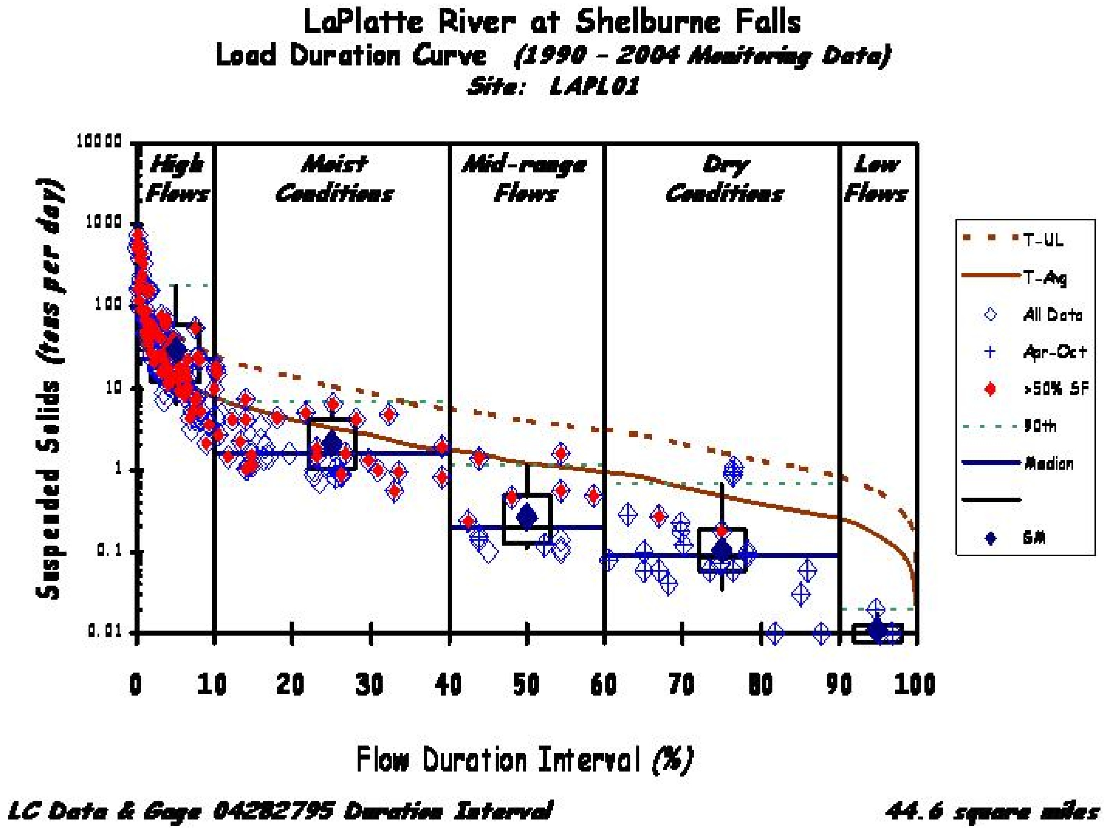
A duration curve analysis *(Figure 5-7)* was developed using data from efforts to monitor the water quality of major tributaries to Lake Champlain (in this case, the LaPlatte River south of Burlington). The intent is to look at patterns between total suspended solids (TSS, an indicator of in-stream sediment) and flow conditions.

Figure 5-7. Water Quality Duration Curve Analysis -- LaPlatte River



As indicated in Figure 5-7, TSS concentrations increase significantly in the high flow zone (i.e. the upper ten percent of all daily average flows). When looking at the water quality monitoring data in terms of loads, the increase of sediment is even more dramatic in the high flow zone *(Figure 5-8)*. This is consistent with the discussion on sediment supply, i.e. erosion processes exert the greatest effect on these waters under high flow conditions. Thus, the relationship between stream flow and sediment for Champlain Valley streams is significant. Efforts to reduce peak flows will decrease sediment loads, in turn improving macroinvertebrate scores.

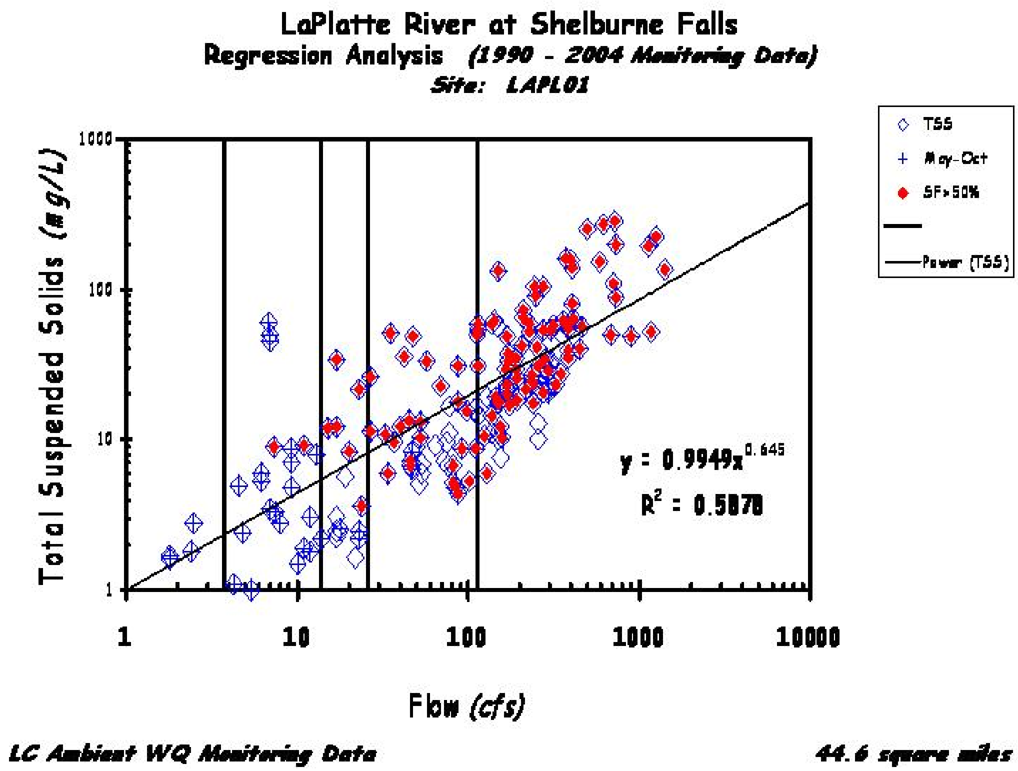
Figure 5-8. Load Duration Curve Analysis -- LaPlatte River



Relationships Between Flow & Sediment: The *"Protocol for Developing Sediment TMDLs"* (EPA, 1999) indicates the appropriateness of using empirical relationships between stream flow and sediment, known as rating curves. The Shades Creek, Alabama sediment TMDL used this type of approach, plotting discharge against concentration in log-log space to obtain a power function by regression (Simon, et. al, 2004).

Figure 5-9 illustrates development of a rating curve based on LaPlatte River total suspended solids data. As indicated, there is a direct correlation between flow and TSS concentration. A similar relationship was observed with Lake Champlain tributary data collected for the Little Otter Creek. This relationship supports use of stream flow as a surrogate measure for sediment in addressing biological impairments.

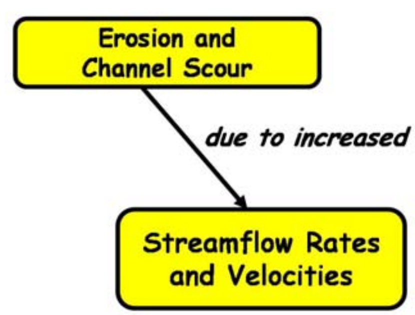
Figure 5-9. TSS Rating Curve -- LaPlatte River



In addition to documenting the relationship between flow and sediment, rating curves can be used to estimate the annual TSS yield from the watershed. The Shades Creek TMDL, for instance, used mean daily flow data and suspended sediment transport relations to estimate annual suspended sediment yields. A similar approach with mean daily LaPlatte River flows and the relationship in Figure 5-9 results in an estimate of 80 tons / square mile per year total suspended solids, as an example. Following a discussion of stream flow rates, this method can be used to demonstrate the relative effect of altered hydrology on sediment loads.

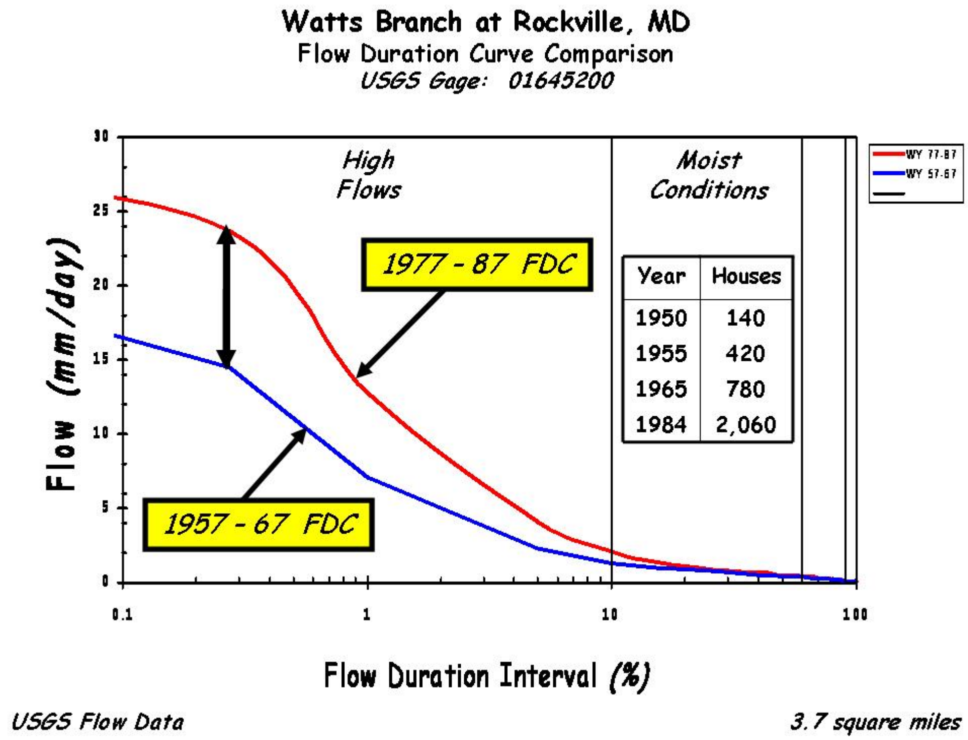
Streamflow Rates and Velocities

The effect of urbanization on stream hydrology has been studied for years. In particular, urbanization tends to result in more impermeable area. Higher amounts of impervious cover, in turn, increase the volume of surface runoff to local streams. Flow duration curves can be used to illustrate this effect.



Leopold (1994) described a small watershed in the Washington, DC area, Watts Branch, which experienced a tremendous growth in housing and accompanying infrastructure *(from 140 houses in 1950 to 2,060 in 1984).* Figure 5-10 depicts the change in the flow duration curve for this watershed. For instance, at a flow duration interval of 0.27%, roughly equal to the 1-year (or 1/365) return period, there was more than a 60% increase in flow.

Figure 5-10. Change in Flow Duration Curve of Small Urbanized Stream

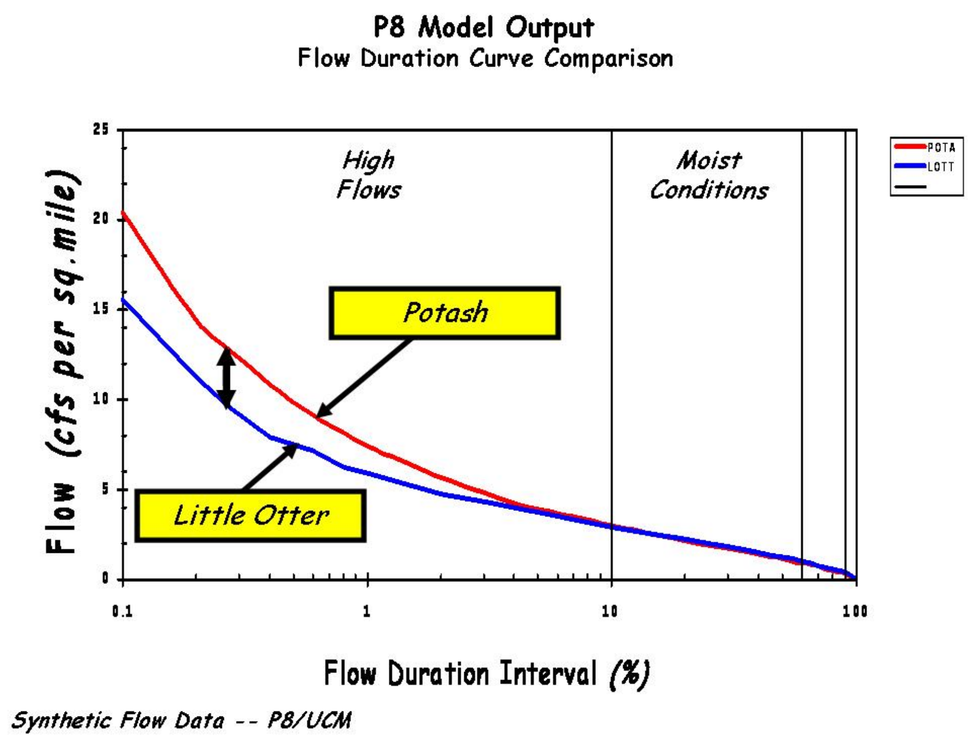


Flow Duration Curves: Because of the need to address the full spectrum of flows, duration curves are a useful technique for describing the hydrologic condition of rivers and streams. A hydrology-based framework using flow duration curves offers an opportunity for enhanced targeting, both in TMDL development and in water quality restoration efforts. Flow duration curves, when combined with other basic elements of watershed planning, can help point problem solution discussions towards relevant watershed processes, important contributing areas, and key delivery mechanisms.

Duration curves provide a quantitative method in which to develop targets for the Potash Brook TMDL. In particular, a comparison of flow duration curves between attainment and impaired streams can reveal obvious patterns. A duration curve on a storm water impaired stream, for example, will typically show significantly greater discharge rates for high flow events when compared to the curve for an attainment stream, similar to the pattern in Figure 5-10. As discussed earlier, the increased predominance of high flow events in impaired watersheds creates the potential for increased storm water pollutant loads from the watershed, increased scouring and stream bank erosion, as well as possible displacement of biota.

Limited flow data exists for both impaired and attainment streams in Vermont. Consequently, synthetic flow duration curves have been developed *(Figure 5-11)* using a calibrated rainfall/runoff model based on land use and cover (TetraTech. 2005). The P8 - Urban Catchment Model *(P8-UCM, Walker, 1990)* was used to develop these curves. Inputs to P8-UCM included climatological data, percent watershed imperviousness, pervious curve number, and time of concentration.

Figure 5-11. Synthetic Flow Duration Curves Used in Potash Brook TMDL



The relative difference between curves is used to quantify target flow conditions needed to restore the hydrology of impaired streams. Hydrologic targets are focused on a 1-year return period (or flow duration interval of approximately 0.3% referenced earlier). A statistical approach developed by UVM researchers cooperatively with DEC allowed selection of the most appropriate attainment streams for comparison with each storm water impaired stream *(Foley, 2005).* Table 5-1 summarizes attainment streams best matched with Potash Brook.

Table 5-1. Attainment Streams Matched with Potash Brook

Stream Name	Status	Flow at 0.3% FDI *(cfs/mi^2)*
Potash Brook	Impaired	12.24
LaPlatte River	Attainment	11.52
Little Otter Creek	Attainment	9.02
Mean Flow -- Attainment Streams		10.27
Difference between Potash & Mean Attainment Flow = 16%		

Shear Stress, Velocity, & Stream Power: Vermont has developed a set of "Protocol Handbooks" for conducting stream geomorphic assessments, which includes a section addressing particle entrainment and sediment transport *(VT ANR, Appendix O, 2004)*. The manual provides a discussion on empirically derived equations for estimating conditions necessary to entrain sediment particles. Shear stress is one parameter often used as a measure of a stream's ability to mobilize and transport sediment.

Shear stress is the force exerted on bed material caused by the shearing of the fluid. Shear stress varies with depth and increases linearly to a maximum at the bed. Based upon physical properties, the following equation for estimating shear stress has been developed:

$$\tau_0 = \gamma_w \, R \, s \quad \textit{(lb / sq. ft.)}$$

where:

τ_0 is the shear stress of the water
γ_w is the specific gravity of water *(62.4 lb / ft^3)*
R is the hydraulic radius *(approximately the mean depth)*
s is the channel slope

The flow velocity in a river also expends energy on the channel. Some of the energy is used to perform work in transporting the sediment load. Leopold (1994) has characterized rivers as transport machines, comparable to any machine such as a locomotive. Power utilization results in work done, i.e. power is the rate of doing work. Using the machine analogy, Leopold further describes stream power as the product of mean velocity times shear stress, or:

$$\omega = u \, \tau_0 \quad \textit{(lb / ft – sec)}$$

where:

ω is the stream power
u is the mean stream velocity *(ft/sec)*

Mean velocity of the stream can be estimated using Manning's equation:

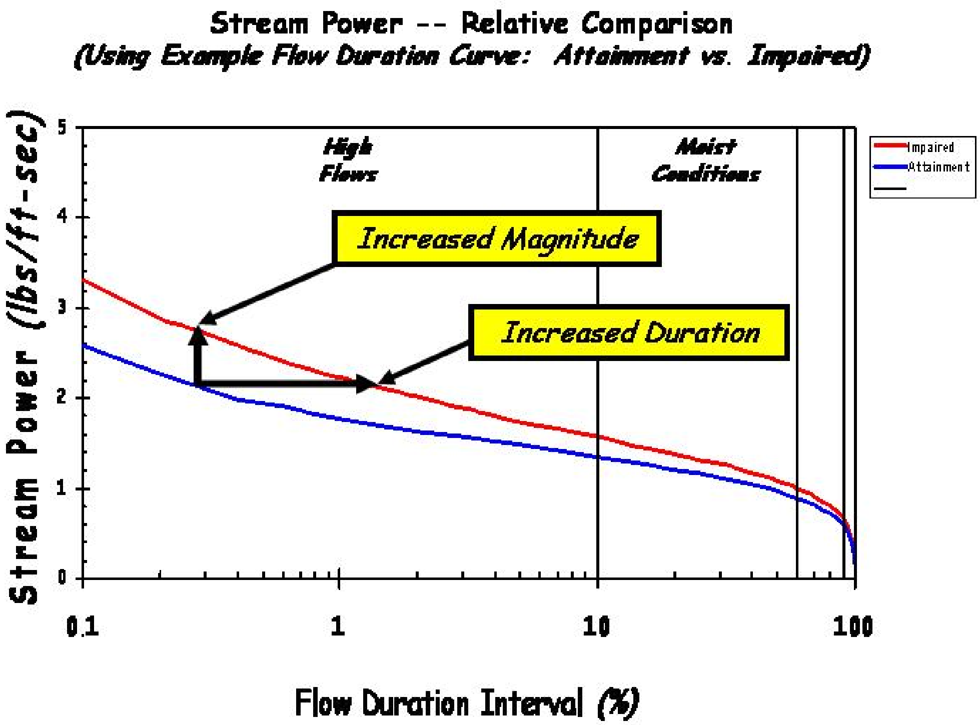
$$u = (1.49 / n) \; R^{(2/3)} \; s^{(1/2)}$$

where:

n is Manning's roughness coefficient

Leopold (1994) indicates there is a logical connection between sediment transport and stream power. Channel degradation and gullying can also be associated with greater stream power. Figure 5-12 offers another way to view the effect of increased flows on stream power that may result from land use changes. This general analysis uses regional hydraulic geometry relationships from Vermont's Stream Geomorphic Assessment "Protocol Handbooks" *(Appendix J).*

Figure 5-12. Relative Effect of Increased Flow on Stream Power

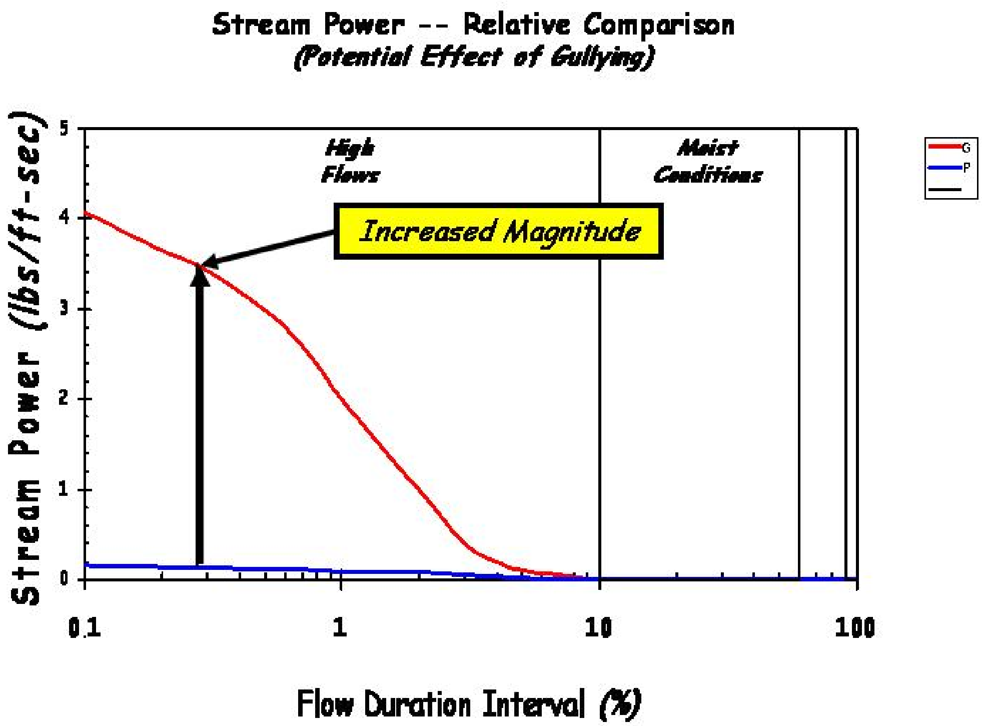


Note: ***Analysis based on regional relationships for illustrative purposes***

These relationships can be combined with unit area flow duration curves derived from P8-UCM to provide a comparative estimate of the relative effect of increased flow rates on stream power, as shown in Figure 5-12. The intent of Figure 5-12 is to highlight both the increase in magnitude and duration in stream power associated with increased flows. The stream is subjected to greater forces at high flows that can degrade channel material. Furthermore, these increased forces occur over a longer period of time.

The effect of increased stream power at higher flows is even more pronounced in the transport and delivery of sediment associated with gullies. As discussed earlier, concentrated runoff from impervious surfaces triggers gully formation. Precipitation that would normally infiltrate into pervious grass or forest land becomes subjected to the same type of forces that degrade stream channels. In addition, stream power is often greater in gullies due to increased slopes (i.e. gullies often create abrupt drops with accelerated flow velocities). Figure 5-13 illustrates these concepts.

Figure 5-13. Relative Effect of Increased Flow on Stream Power in Gullies



***Note:* Analysis for illustrative purposes**

Critical Stress and Particle Movement: A given particle will move only when the shear stress acting on it is greater than the resistance to particle movement. The magnitude of shear stress required to move a given particle is known as the critical shear stress (τ_{cr}). When shear stress equals critical shear stress, the channel will likely be in equilibrium. Where shear stress is excessively greater than critical shear stress, channel degradation will likely result. Thus, describing relationships between hydrology, shear stress, critical stress, and sediment movement is an important part of understanding channel adjustments that affect stream habitat. Particle size is a major factor affecting critical shear stress, largely due to the influence of weight.

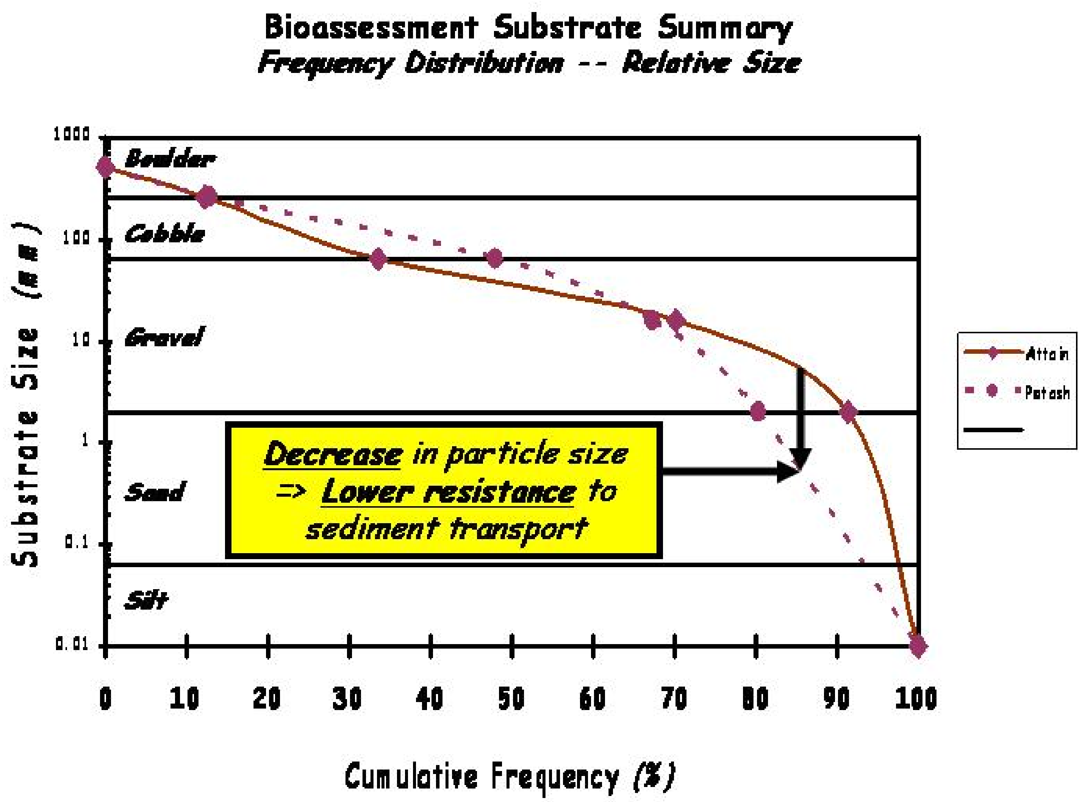
Vermont's stream geomorphic assessment protocol *(Appendix O)* includes a table that illustrates the potential effect of particle size on critical shear stress. Table 5-2 provides a summary, which includes a relative comparison of shear velocities needed to mobilize each size class. This information is intended simply to highlight the importance of particle size, shear stress, and shear velocity (u_{*0}) in mobilizing and transporting channel sediment. Table 5-2 is a practical tool for estimating what size material in the channel might move under specified conditions of flow, and should only be used as a first approximation (Leopold, 1994).

Table 5-2. General Relationships -- Particle Size and Critical Shear Stress

Class Name	**Particle Size** *(mm)*	*(in)*	**Critical Shear Stress** *(τ_{cr} : lbs / sq.ft.)*	**Critical Shear Velocity** *(u_{*0} : ft/sec)*
Boulder				
Very Large	2048 - 4096	> 80	37.4	4.36
Large	1024 - 2048	> 40	18.7	3.08
Medium	512 - 1024	> 20	9.3	2.20
Small	256 - 512	> 10	4.7	1.54
Cobble				
Large	128 – 256	> 5	2.3	1.08
Small	64 - 128	> 2.5	1.1	0.75
Gravel				
Very Coarse	32 – 64	> 1.3	0.54	0.52
Coarse	16 – 32	> 0.6	0.25	0.36
Medium	8 – 16	> 0.3	0.12	0.24
Fine	4 – 8	> 0.16	0.06	0.17
Very Fine	2 – 4	> 0.08	0.03	0.12
Sands				
Very Coarse	1 – 2	> 0.04	0.01	0.070
Coarse	0.5 – 1	> 0.02	0.006	0.055
Medium	0.25 – 0.5	> 0.01	0.004	0.045
Fine	0.125 – 0.25	> 0.005	0.003	0.040
Very Fine	0.062 – 0.125	> 0.003	0.002	0.035
Silts				
Coarse	0.03 – 0.062	> 0.002	0.001	0.030
Medium	< 0.03	> 0.001	0.001	0.025

Another way to view the relationship between critical shear stress, shear velocity, stream power, and flow is using the substrate composition information presented in Figure 5-1. A general cumulative frequency distribution can be estimated using size class information for the attainment streams and Potash Brook, similar to a pebble count analysis *(Figure 5-14)*. At the right side of the graph (above the 70th percentile), the increased sand / silt fraction is very noticeable. This corresponding decrease in particle size means the channel has a lower resistance to sediment transport.

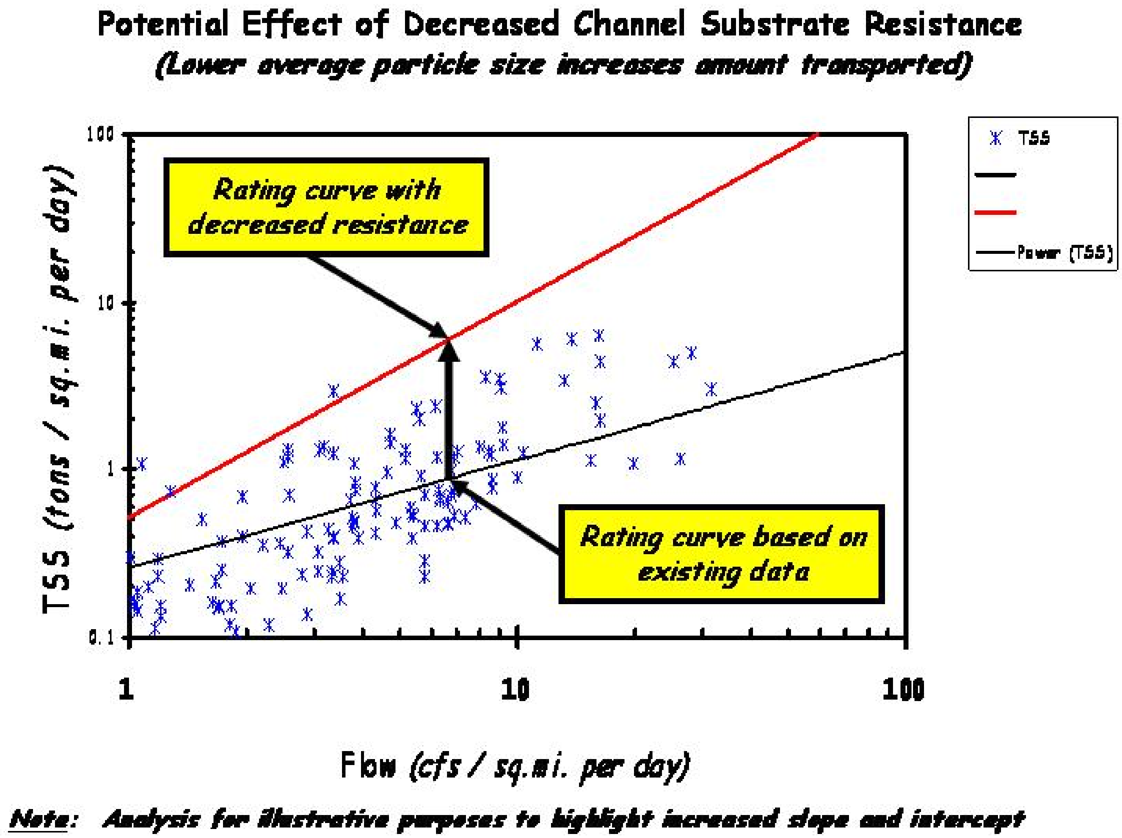
Figure 5-14. Size Class Frequency Distribution



Note: *Analysis for illustrative purposes only*

The use of hydrologic targets for Potash Brook is further supported based on relationships between flow, velocity, shear stress, and stream power. Increased sediment transport occurs from elevated velocities associated with higher stream flow. Impaired streams, such as Potash Brook, will mobilize more sediment even if flows are held constant, due to decreased resistance associated with the greater sand / silt fraction in the channel substrate. This is illustrated with the sediment rating curve shown in Figure 5-15. The net effect of a decrease in average particle size and lower resistance to sediment transport is an increase in both the slope and intercept of the sediment rating curve.

Figure 5-15. Cumulative Effect on TSS Rating Curve

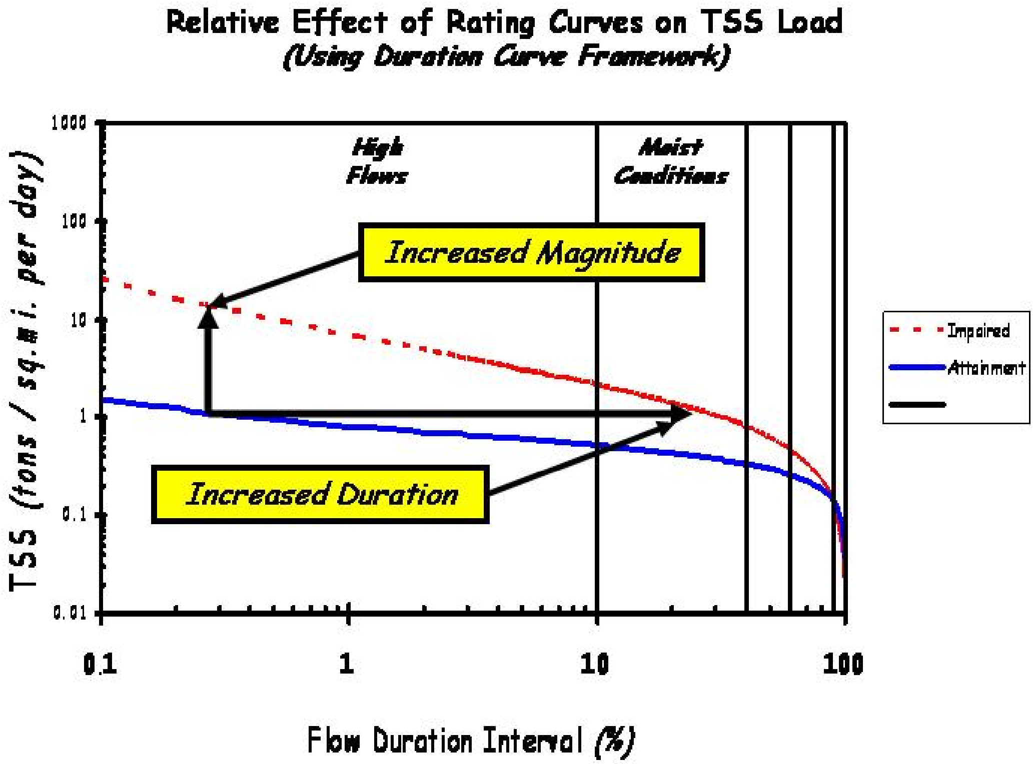


Relative Effect of Flow on Sediment Yield: As discussed earlier, a rating curve is commonly used to estimate sediment load on days when no measurements are available (Linsley, et. al, 1982). Although such relationships are approximate, rating curves can be used to illustrate the relative effect of altered hydrology on annual sediment yield. The sediment rating curve approach, for instance, has been used to estimate flow related changes in sediment supply / transport from hydrograph changes due to timber harvest (USEPA, 1980). The change in stream flow calculations also relate to similar processes in urban watershed development (Rosgen 1996).

In addition to increased channel sediment supply, water delivered through gullied areas also contributes soil based on erosive action associated with greater stream power. Rosgen (1996) has described the effect of increased sediment supply in relation to stream discharge and sediment rating curves. Degraded channels, for instance, are typically associated with a high sediment supply. As discharge increases, one would expect not only higher sediment transport rates, but also an exponential increase in sediment transport per unit discharge.

The potential combined effect of altered hydrology and channel substrate on sediment load can be illustrated using a duration curve framework. Figure 5-16 shows a relative comparison of TSS loads using unit area flow duration curves developed for attainment and impaired streams in Vermont *(Figure 5-11)*. Changes in channel substrate (and the decreased resistance to sediment transport) are reflected using a rating curve with an increased slope and intercept *(Figure 5-15)*.

Figure 5-16. Potential Effect of Altered Hydrology and Substrate on TSS Load

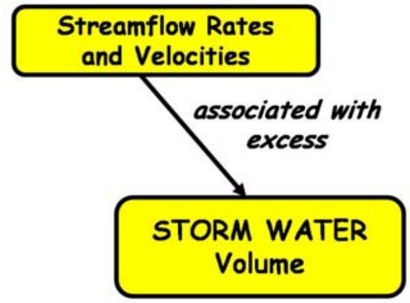


Note: ***Analysis for illustrative purposes only***

The intent of Figure 5-16 is to emphasize that the relationship between flow and sediment is complex, and is definitely not linear (i.e. in Figure 5-16, a 25% decrease in the 1-day flow results in nearly a 70% reduction in annual sediment load, which should improve macroinvertebrate scores).

A high level of uncertainty exists in identifying where specific sources of sediment originate (e.g. knowledge regarding in-channel sources versus gully erosion and wash off). However, in spite of this uncertainty, there is a common thread in how sediment is delivered and transported within the watershed -- that common thread is storm water volume, which makes it a very appropriate indicator for addressing biological impairments in Potash Brook.

Storm Water Volume



Weight of evidence from data associated with bioassessments indicates that degraded habitat and sedimentation are the highest concerns relative to biological impairments in Potash Brook. There are considerable scientific uncertainties regarding the role of water and sediment and their effect on biological communities (especially where streams are highly unstable).

It is possible to develop a TMDL for storm water impaired streams using water (i.e. discharge) as a surrogate measure, based on its relationship to erosion processes, sediment, and channel stability. Existing water quality information from streams in the Lake Champlain Valley, combined with basic hydrology/sediment dynamics principles, demonstrate the appropriateness of stream flow as a surrogate measure to address biological impairments. In an approach using surrogate measures, stream flow and sediment characteristics of watersheds that are in compliance with the VT WQS provide estimates of *"assimilative capacity"*. Appropriate levels of discharge and sediment loading become the storm water management targets.

The Vermont Water Resources Board's "Investigation into developing cleanup plans for stormwater impaired waters (2004) suggested that either water flow or sediment targets could be used to guide the development of the storm water management plan. However, analysis of sediment dynamics in any watershed can be an extremely complex endeavor. It often involves construction of a sediment budget, describing erosion processes that contribute to the overall sediment load. This includes addressing upland sources of sediment, as well as accounting for in-channel processes.

The mechanisms controlling erosion (both upland and stream bank) and sediment transport are extremely complex. This makes any quantitative analysis of sediment very difficult to conduct with accuracy. Order of magnitude estimates are often the best one can hope to achieve. Many complex modeling approaches have been suggested in the literature, most of which require extensive field data collection and calibration. The time and labor-intensive nature of such models generally makes their use infeasible.

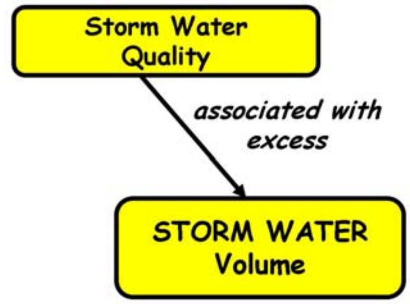
The Vermont Water Resources Board report noted that there is significantly less uncertainty about stream hydrology than there is about stream sediment dynamics. Consequently, the Board concluded that flow targets should be the primary indicators driving TMDL allocations and development of specific management strategies. The rationale behind use of flow targets is presented throughout this expanded technical analysis and is summarized in Table 5-3.

Table 5-3. Summary of Rationale for Use of Flow Targets

Connection	Key Points	
Biology to Sediment	• Potash Brook is *impaired based on macroinvertebrate scores*, and degraded habitat and increased sedimentation are the highest concerns	*[Section 3] [Table 3-1]*
	• Substrate composition data indicates that the *sand / silt fraction* in Potash Brook is *significantly greater* than lowland attainment streams	*[Figure 5-1]*
	• Filling of cobble / gravel substrate with *fine grained material* often results in the *loss of pollution tolerant taxa* (reducing biological assessment scores towards impaired conditions)	*[Section 5]*
Sediment to Storm Water Volume	• Hydrology is a major driver for both upland and stream channel erosion. *Sediment delivery* to Potash Brook from major erosion processes (bank, gully, surface) occurs under *high flow conditions*, as evidenced through duration curve analysis of TSS data	*[Figures 5-7 and 5-8]*
	• Analysis of TSS rating curves shows a *positive correlation between flow and total suspended solids* (a reduction in higher flows results in a reduction in TSS)	*[Figure 5-9]*
	• Examination of physical processes behind sediment delivery and transport (shear stress, velocity, stream power, particle size) indicate that a *reduction in high flows will lead to a reduction in sediment*	*[Figures 5-12 and 5-14]*
	• As *discharge decreases*, the corresponding *decrease in sediment is likely to be exponential* because multiple sources of sediment are linked to storm water volume (bank erosion, gully erosion, surface erosion, lower resistance of channel substrate to sediment transport)	*[Figures 5-15 and 5-16]*

In summary, hydrology is a major driver for erosion processes, both from the watershed and from the channel -- control of high water flows will also achieve reductions in channel sediment movement. If sediment does not respond as desired over time, sediment loading might be revisited. This strategy is based on the assumption that there is a relationship between healthy in-stream geomorphology/habitats and storm water management. The precise nature of this relationship is uncertain. It is reasonable, however, to expect that as hydrology and sediment dynamics are restored, habitats will improve, and the macroinvertebrate community will recover.

Storm Water Quality



Storm water runoff from developed areas typically contains many pollutants. Pollutants accumulate on impervious surfaces and are washed off during rain events and snow melt. Paved surfaces and piped drainage systems efficiently transport these pollutants from the watershed to the stream. Some pollutants directly affect aquatic life while others degrade the quality of aquatic habitat.

Assessments of Potash Brook (VT DEC, 2005; Pioneer Environmental Associates, 2003) found that sediment is the pollutant, which is likely having the greatest adverse impact on aquatic life in Potash. The impact is to the habitat -- sediment deposition creates conditions less conducive to healthy aquatic life. Storm water runoff reductions established by the Potash TMDL are expected to result in sediment reductions sufficient to address these habitat impacts, as described previously.

Other pollutants found to be somewhat elevated in Potash Brook, and potentially contributing to the aquatic life impairment, include phosphorous, chloride and sodium. In Table 3-1, these pollutants are given medium importance during low flow conditions and low-medium importance overall. The Potash TMDL is addressing these pollutants in two different ways. First, storm water runoff reductions are expected to increase infiltration which will lead to increases in base flow. The increased base flow will lower the concentrations and impacts of these pollutants during low flow conditions. Second, phosphorous loading will be decreased both by the reductions in runoff volume (which will directly address the dissolved phosphorous component) and the resulting sediment reductions (which will address the particulate phosphorous component associated with sediment). Chloride and sodium levels are difficult to control with BMPs, but as long as some portion of the storm water volume reduction is accomplished via infiltration, these chemical loadings will be reduced.

In addition, a separate phosphorous TMDL has been completed that covers all tributaries to Lake Champlain, including Potash Brook. The Lake Champlain TMDL and accompanying implementation plan address specific phosphorous reduction measures needed in the Lake Champlain basin. Given that the current phosphorous levels in Potash are actually close to nationally recommended levels (and Vermont has not yet adopted numeric P criteria for streams), any reductions needed are likely more modest than those needed for Lake Champlain.

6. ADAPTIVE MANAGEMENT

Establishing TMDLs employs a variety of analytical techniques. Some analytical techniques are widely used and applied in evaluation of source loading and determination of the impacts on waterbodies. For certain pollutants, such as sediment, methods used are newer or in development. The selection of analysis techniques is based on scientific rationale coupled with interpretation of observed data. Concerns regarding the appropriateness and scientific integrity of the analysis have been defined and the approach for verifying the analysis through monitoring and implementation addressed.

"Adaptive management" is often defined as the reliance on scientific methods to test the results of actions taken so that the management and related policy can be changed promptly and appropriately. The FACA report indicated that *"adaptive management involves setting goals and developing implementation plans based on existing data, providing for additional data gathering and monitoring of results achieved, and revising goals and implementation plans as appropriate in light of the subsequent data and monitoring"*.

The TMDL process accommodates the ability to track and ultimately refine assumptions within the TMDL implementation planning component. The Potash Brook TMDL is intended to be adaptive in management implementation. This plan allows for future changes in loading capacities and surrogate measures (allocations) in the event that scientifically valid reasons support alterations. It is important to recognize the continual study and progression of understanding of water quality parameters addressed in this TMDL (e.g. bioassessments, habitat, channel conditions, sediment, hydrology). The Potash Brook TMDL contemplates the availability of new information as monitoring plans are implemented. In the event that data show that changes are warranted in the Potash Brook TMDL, these changes will be made.

However, there could come a time in the future management of Potash Brook (or other stormwater impaired streams) that even after the hydrology is treated, there may be ongoing hill slope failures associated with channels moving from the degraded stage in the channel evolution model to later widening and floodplain redevelopment stages. These failures may continue even under a hydrologic attainment scenario as there will be flows (energy) and groundwater processes to initiate and push these slope failure processes (that were originally started as a result of the stormwater stressor). As these failures will continue for some time, both in the channel, and in some of the more active gullies, the adaptive management approach may need to be tempered with respect to when and where better substrates and corresponding biological response is observed.

7. References

Booth, D. and L. Reinelt. 1993. *Consequences of Urbanization on Aquatic Systems – Measured Effects, Degradation Thresholds, and Corrective Strategies*. pp 545-550. In: Proceedings Watershed '93 A National Conference on Watershed Management. March 21-24, 1993. Alexandria, VA.

Cleland, B.R. November 2003. *TMDL Development From the "Bottom Up" -- Part III: Duration Curves and Wet-Weather Assessments*. National TMDL Science and Policy 2003 -- WEF Specialty Conference. Chicago, IL.

Fitzgerald, E. April 2006. University of Vermont Geomorphic Assessment Project. Prepared for Vermont Agency of Natural Resources. Burlington, VT.

Foley, J. and B. Bowden. October 2005. *University of Vermont Stormwater Project -- Statistical Analysis of Watershed Variables*. Prepared for Vermont Agency of Natural Resources. Burlington, VT.

Leopold, L.B. 1994. *A View of the River*. Harvard University Press. Cambridge, MA.

Linsley, R.K., M.A. Kohler, and J.L. Paulus. 1982. *Hydrology for Engineers (3rd ed.)*. McGraw-Hill. New York, NY.

Pioneer Environmental Associates. January 2003. *Potash Brook Watershed Restoration Plan -- Final Report*. Prepared for the City of South Burlington, VT. Middlebury, VT.

Rosgen, D.L. 1996. *Applied River Morphology*. Wildland Hydrology. Pagosa Springs, CO.

Schueler, T. 1994. *The Stream Protection Approach: Guidance for Developing Effective Nonpoint Source Control Programs*. USEPA. Center for Watershed Protection. Silver Spring, MD. 68 p.

Simon, A and C.R. Hupp. March 1986. *Channel Evolution in Modified Tennessee Channels*. Proceedings of Fourth Interagency Sedimentation Conference. V.2, Section 5, pp. 5-71 to 5-82. Las Vegas, NV.

Simon, A., E. Langendoen, R. Bingner, R. Wells, Y. Yuan, and C. Alonso. 2004. *Suspended-Sediment Transport and Bed-Material Characteristics of Shades Creek, Alabama and Ecoregion 67: Developing Water Quality Criteria for Sediment*. USDA -- Agricultural Research Service, National Sedimentation Laboratory. Oxford, MS.

Sloto, R.A. and M.Y. Crouse. 1996. *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis*. U.S. Geological Survey Water Resources Investigations Report 96-4040. Lemoyne, PA. 46 p.

TetraTech. 2005. *Stormwater Modeling for Flow Duration Curve Development in Vermont*. TetraTech, Inc. Fairfax, VA.

Vermont Agency of Natural Resources. April 2004. *Stream Geomorphic Assessment -- Protocol Handbooks*. Vermont Department of Environmental Conservation. Waterbury, VT.

Vermont Water Resources Board. 2004. *Final Report -- Investigation into Developing Cleanup Plans for Stormwater Impaired Waters*. Docket No. INV-03-01. Montpelier, VT.

U.S. Environmental Protection Agency. 1997. *Urbanization and Streams: Studies of Hydrologic Impacts*. Office of Water. EPA 841-R-97-009. Washington, D.C.

U.S. Environmental Protection Agency. 1999. *Protocol for Developing Sediment TMDLs*. Office of Water. EPA 841-B-99-007. Washington, D.C.

U.S. Environmental Protection Agency. 2004. *Total Maximum Daily Load (TMDL) for Siltation, Turbidity, and Habitat Alteration in Shades Creek -- Jefferson County, Alabama*. USEPA Region 4. Atlanta, GA.

Walker, W. 1990. *P8 Urban Catchment Program Documentation -- Version 1.1*. Prepared for IEP, Inc. Northborough, MA and Narragansett Bay Project. Providence, RI.