

STREAM TURBIDITY SIGNATURES
WITHIN THE HAYWARD BROOK WATERSHED STUDY

By

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BScF

A THESIS SUBMITTED IN PARTIAL FUFILMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science in Forestry

Faculty of

Forestry and Environmental Management

This thesis is accepted.

.....

Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

December 2002

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ABSTRACT

This thesis is about studying the turbidity signatures of 5 forest streams that are part of the Hayward Brook Watershed Study in southern New Brunswick, Canada. These signatures were derived over a period of 6 years, using special turbidity probes located at specific locations within each of 5 second-order streams. It was found that each stream had its own turbidity signature, and that this signature was affected by

- watershed size,
- watershed topography,
- weather and season,
- stream channel stability,
- location of turbidity measurement probe
- land-use pattern within watershed.

In this, land-use pattern refers to

- roads that intersect the watershed,
- road configurations and substrates,
- forest operations and road traffic (frequency, timing and, type).

Forest streams with the least traffic and operations within their catchment areas had mildly active turbidity signatures, with short and well spaced turbidity events. Forest watersheds with much traffic or containing a severely eroded road had very active turbidity signatures involving many large overlapping peaks. Forest streams within watersheds with road maintenance and harvest operations returned to pre-harvest turbidity signatures by the end of the second post-harvest year.

The continuous turbidity measurements were converted to suspended sediment concentrations, to determine total annual sediment yields per watershed. The resulting yields were placed into the context of expected soil losses as calculated by way of the Universal Soil Loss Equation. This equation generated numbers in good agreement with the field-derived values.

A stochastic model (Random Turbidity Pulse Model) was developed to simulate the high-event component of the stream turbidity signature and the related sediment yields. This model was parameterized by extracting 3 land-use generalizable parameters from the observed frequency distributions for peak duration, peak height, and time interval between peaks for each of the 5 streams. The resulting model was calibrated to conform with the field-observed sediment yields for each of the 5 streams.

Keywords: forest streams, watersheds, turbidity signatures, suspended sediment yields, soil loss, stream turbidity model.

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ACKNOWLEDGEMENTS

After three years my thesis is complete, and I owe a great deal of thanks to those who gave me support during this time. The people who certainly deserve the most credit are Dr. Paul Arp, my wife Carole, and my family. I thank Dr. Arp for the opportunity to study under his direction and for his patience and enthusiasm as he guided me through the interpretation and writing of this Thesis. His ability to ‘look outside the box’ continuously provided me with a multitude of ideas that eventually were incorporated into the document. His interest gave me the drive that allows me to continuously work at 100 percent on this project. I thank Dr. Arp for periodically asking “Joe, are you having fun”, and for his introduction into stochastic modeling which for me was one of the most interesting chapters in this thesis.

A millions thanks to Carole, Laura, and Gregory for allowing me to hide away and work on studies during many late nights, long weekends, and several weeks of our summer holidays. I thank Carole for her understanding, and her management of our family, work and study time. I hope Laura and Gregory will look back and realize that to achieve your goals requires hard work and a continuous drive. Others who have given their time and expertise are my advisory committee; Drs. F-R. Meng and A. Diamond. I thank these gentlemen for their guidance and ideas, and the time they gave to review my document.

I must also acknowledge the support given by the management team of the Environmental Conservation Branch of Environment Canada. In particular I thank Dr. Alex Bielak and Geoff Howell. They saw this as a development opportunity for me, and through their support and lobbying, obtained approval from the department which allowed me to undertake the part time studies while keeping a much need income.

In closing I would like to thank my parents, Myrna and Doug Pomeroy. They, unlike other parents I knew, spent much of their hard funds to ensure each of their seven children could obtain an education in any profession. Little did they or I realize that their support will always be ongoing, and would allow me to attain a university degree at a Master level, 20 years later.

CHAPTER 1

TURBIDITY SIGNATURES

INTRODUCTION

Water quality has become an important land use management issue. In particular, water turbidity in surface waters is not only unsightly, but interferes with the general functioning and well being of many aquatic ecosystems and organisms habitat (Patric 1976, Anderson and Potts 1987, Chow *et al.* 1990). Forest streams produce clear water most of the time. However, there are many processes within the forested landscape that cause forest stream water to run turbid from time to time. This thesis provides a case study for examining daily turbidity in five second-order forest streams, all located within the Hayward Watershed Study Project, in New Brunswick, over a period of six years. This case study deals with acquiring long-term hour-by-hour turbidity signatures of each of the 5 streams, and by making a concerted attempt to characterize these signatures in terms of:

- watershed size,
- watershed topography,
- weather and season,
- stream channel stability.
- land-use activities, road and stream junctions within watershed

In this, within-watershed land-use activities (frequency, timing and, type), refers to cutting operations within watershed, including stream buffer zones. Road-stream junctions make special reference to road type, and traffic condition.

A turbidity signature for each stream is a time-series record of suspended particle concentrations for that stream. Each signature is unique to any one particular stream, by reflecting all those processes that specifically deal with soil particle loss from the watershed. In this, the commercial use of the forest within a watershed is a major concern: there is a need to know how much that use enhances within watershed erosion, and therefore, stream turbidity. In principle, removal of the forest canopy would enhance soil exposure, reduce evapotranspiration and infiltration, and increase runoff (Lull and Reinhart 1972, Patric 1976, Wenger 1985, Martin 1988, Fahey and Coker 1992, Martin and Hornbeck 1994, Stanley and Arp 1998, Brady and Weil 1999, Kreuzweiser and Capell 2001). The specific objectives of the case study of this thesis are: To acquire, document and analyze the turbidity signatures from the five forest streams:

- To relate the turbidity signatures to
 - ◊ within-watershed processes,
 - ◊ general watershed attributes (slope-length, slope, soil erodibility, vegetation cover),
 - ◊ season and weather.
- To quantify sediment yield for each of the five forest streams based on each turbidity signature.
- To compare the resulting sediment yields with estimates from the Universal Soil Loss Equation.
- To characterize peak height, duration, and time between high turbidity events in terms of the watershed attributes of these streams.

- To develop a model that simulates the turbidity signatures based on three essential characteristics of each turbidity signature, i.e. turbidity peak height, peak duration, and time duration between peaks.

The collation of this information should, in principle, be useful for assessing impacts of forest management activities on stream turbidity and sedimentation yields in areas similar to this case study (Granillo *et al.* 1985, Lawler 1991, Hindall 1991). The value of obtaining detailed long-term turbidity signatures for understanding relationships between land, land-use and stream and within stream and lake sediment loads has already been recognized elsewhere, e.g., Gray 1970, Inland Waters 1979, Fattorelli *et al.* 1988, and Gomez and Church 1989.

The following chapters deal with:

- an overview of the current New Brunswick forest stream policy, regulations and guidelines, and reviews the relevance of the policies in a scientific context (Chapter 2);
- a presentation of the Hayward Brook Watershed case study area, including physiographic description, and details about the case study design (Chapter 3);
- a overview of the turbidity instrumentation used in the case study, turbidity sampling, and data quality control procedures (Chapter 4);
- a display and general characterization of each turbidity signature in relation to within-basin activities, and road-stream configurations (Chapter 5);
- the conversion of each stream turbidity signature to suspended sediment concentrations, and to basin-specific sediment yields (Chapter 6);

- a comparison of the five basin-specific sediment yields with sediment yields expectations from the Universal Soil Loss Equation (Chapter 7);
- the parameterization of turbidity peak height, duration, and time between individual peaks for each high-turbidity event within the five turbidity signatures (Chapter 8);
- the development of a stochastic model (Random Pulse Turbidity Model) to simulate within-stream turbidity, and subsequent sediment yields based on the general forest watershed attributes of each of the five streams (Chapter 9);
- a summary of main findings, claims of original work, and recommendations for further research (Chapter 10).

Included in the appendices are:

- detailed procedures describing data quality control (Appendix 1);
- listing of model components of the random pulse turbidity model (Appendix 2);
- dataset of stream turbidity and suspended sediment concentrations collected at Freshwater Creek Watershed (Appendix 3).

CHAPTER 2

STREAM TURBIDITY: STREAM REGULATIONS AND PHYSIOLOGICAL RATIONALE

INTRODUCTION

In order to keep forest streams clean and maintain a high degree of water quality, governments have set in place various policies, acts and guidelines to regulate type and extent of allowable and non-allowable land-use activities in and near streams and lakes (Anderson 1998, Forman 1995). A considerable portion of these policies, acts and guidelines deals with avoiding episodes of high stream turbidity, as potentially caused by deliberate or non-deliberate soil disturbance activities within streams, near streams, and within watersheds. This chapter is used

- to review current forest management policies and regulations for forest streams in New Brunswick in reference to stream turbidity, and stream sedimentation in general,
- to underscore the scientific need for these regulations.

For instance:

- in New Brunswick, suspended sediment concentrations normally range between 0 to 50 mg l⁻¹, with extremes reaching 200 to 250 mg l⁻¹ (Inland Waters 1982).
- Lower concentrations are generally found in Newfoundland and Nova Scotia (Inland Waters 1982).

- But concentrations as high as 800 mg l⁻¹ have been recorded in selected rivers of Nova Scotia and Prince Edward Island (Inland Waters 1982).
- In Atlantic Canada, the percent fines in stream-beds range between 5 to 45 %. Recent streambed increases in fine textured materials have been related to upland soil erosion (Caissie and Arseneau 1999).
- A decrease in fish egg survival has been noted within increasing streambed fines ranging between 3 to 20 % (Caissie and Arseneau 1999).

FOREST MANAGEMENT REGULATIONS

Forest management regulations that are, in part designed to deal with stream water turbidity and sedimentation in New Brunswick are governed by several Acts, guidelines and best management guidelines or BMP's (Wood River 1999, NBNRE 1996, Jewett 1996). The dominant legislation is the Crownlands and Forest Act. It requires a forest management plan to be developed that includes actions to "try and preserve the quality of water". In addition, the Clean Water Act and the Forest Management Manual for Crown Lands, Watercourse Buffer Zone and BMPs are also part of the operational constraints for planning and executing forest management actions (Jewett 1996, NBNRE 1996). Information on individual attributes of these policies and regulations can be viewed at the following internet web site;

- <http://www.unb.ca/web/forestry/centers/cwru/water.htm> (Forbes 1997);
- <http://www.gnb.ca> (New Brunswick government).

The most important factors to be considered in relating land-use impacts on forest stream turbidity and sediment loading are: stream environment (stream order, buffer zones, topography, channel physiography, flow accumulation patterns leading toward stream), and watershed-specific spatial configurations between streams, and other line and area-specific landscape structures such as forest roads, buffer zones, and clear-cut land surfaces.

STREAM ORDER AND BUFFER ZONES

Streams differ continuously along their length from headwaters to mouth (Forman 1995). In headwaters, first-order streams generally emerge from springs and seepage areas. First order streams are generally narrow, shallow, and have clear, cool and fairly fast flowing water. The amount of water that flows increases along the stream as more and more ephemeral streams and groundwater channels join the main flow channel, by way of topographically definable flow accumulation patterns. Further downslope, some of the first-order streams may flow into depressions, ponds, lakes, marshes, or active and non-active beaver ponds. All these areas act like sponges regulating floods and curtailing turbidity and sediment loads in the higher order streams (Forman 1995). First-order streams tend to have rocky stream-beds, and are interspersed with gravel, silt, and organic muck beds, depending on local flow conditions. Flow conditions generally alternate between riffles and pools. Stream banks are generally shallow, and stream meandering is mostly absent, except where the land flattens out.

For second-order to fourth-order streams, there is a need to maintain cool, clear and clean cobble-gravel stream-bed, to protect valuable nesting habitat for cool freshwater fish such

as salmon and trout. Hence, management practices that disallow entry of soil sediments into first order streams naturally protect all the higher order streams below from high turbidity events and high rates of stream sedimentation. In addition, the higher order streams also need to be buffered against nearby up-slope activities, especially those that could add to stream warming and further sedimentation. For that reason, stream regulations tend to increase the width of stream buffer zones, from about 15 m on either side of first order streams which are at least 0.5 m wide, to 30 m or more of either side of higher order stream, and lakes. Slope is another factor determining buffer width regulations: the steeper the slope towards the stream, the wider the buffer zones need to be.

Since there are many mapped and unmapped first order streams, there is much area covered by 15 m stream buffers, and this would considerably reduce the overall area available for forest harvesting. Therefore, forests along low order streams less than 0.5 m wide can be selectively harvested up to a 3 m distance from the stream (NBNRE 1996, Jewett 1996). Machine traffic and cutting within the 3 m zone is, however, a severe violation against these regulations: such activities could destabilize stream-banks, and often open up easy flow channels (ruts and gullies) from up-slope areas towards the stream.

Additional protection for forest streams against high turbidity and sedimentation can be obtained by replacing straight buffers with curvilinear buffers. Doing this should reduce overall tree blow down. Avoiding tree blow-downs is important for several reasons, e.g. reduced chances for generating sediment sources within the buffer zone itself due to tree uprooting, and related exposure of the mineral soil below. Other reasons relate to the conservation and protection of wildlife habitat (NBNRE 1996, Wood River 1999).

In some cases, stream channels by themselves are the source for much in-stream sedimentation. This occurs where stream banks are deep, and are being undercut by natural stream meandering. Past practices of diverting streams from their original bed are now being discouraged, and special permits are required for any activity that requires an alteration of the stream channel e.g. New Brunswick Stream Alteration Permit.

ROADS INTERSECTING WATERSHEDS AND STREAMS

Several assessments of stream quality in forest managed areas have found that road construction and the annual maintenance of these roads to be a major cause of soil erosion and stream sedimentation (Martin and Hornbeck 1994, Forman 1995, Rummer *et al.* 1997, Clarke *et al.* 1996). To reduce the disruption of soils associated with roads, regulations are being reviewed continuously to develop better guidelines for road-bed stabilization, ditch placement, ditch diversions, placement of proper sediment pools along ditches, cross drainage requirements underneath roads on long slopes, culvert selection and placement, bridge construction, location, use of geo-textiles, etc. (NBNRE 1996, Jewett 1996). Added to these regulations should be season and weather-dependent road-use regulations. This is to avoid road-damaging traffic when road beds are soft and susceptible to rutting, and when traffic on the road would splash considerable amounts of road silt into nearby ditches, and streams. Once roads start to rut, road repairs add further to the overall sediment release from roads. Grading of roads should also be timed with weather and season: special rules need to be in place for not shoving road gravel onto bridges.

Stream sedimentation problems are also associated with abandoned roads (PALCO 2002). In many cases, lack of maintenance further exacerbates the problem often causing major road wash-out over roads which – in turn – may encourage gully formation towards the washout, or from the washout. At present, there are few to no regulations dealing with road decommissioning, including follow-up thereafter.

CLEAR-CUTS WITHIN WATERSHEDS

Area-based structures have been found to be major factors influencing turbidity and sedimentation in streams. These include clear cut blocks, slopes within watersheds, and exposed mineral soils (erodibility) (Kirby and Mehuys 1987, Chow *et al.* 1990, Salehi *et al.* 1990, Renard *et al.* 1991, Coote *et al.* 1992, Krause 1998 and, Wang *et al.* 2000).

Larger block size generally has more off-road transportation and structures such as: extraction trails, access roads, and landing sites. These often result in greater amounts of rutting, soil compaction, and soil exposure. In many instances, rutting may run up and down slopes. Krause (1998) found that an average harvested block may have up to 36 % of its area affected by medium induced soil surface disturbances.

Matters became worst in areas with high and long slopes causing fast overland flow. The amount of soil that erodes from any road surface also differs by soil type. Compacted soils, and soils with a high composition of silts and clay have poor water infiltration, and therefore, have high surface runoff and erosion.

Forest cover type also influences stream turbidity and sedimentation. As the amount of forest and ground cover decreases, the greater is the chance of increased soil erosion.

TURBIDITY IMPACTS ON AQUATIC LIFE

Elevated concentrations of turbidity and sedimentation cause significant impacts to the aquatic communities, habitat, behavior, and physiology. When one trophic level is affected by a change in its environment, others trophic levels respond. In the aquatic environment, drifting or movement down-stream appears to be a dominant behavioral response to turbidity stress. Studies show that alterations in behavior of a population occur when suspended sediment concentration range between 40 to 120 mg l⁻¹(Anderson 1998).

Behavioral responses are often a short-term defense to even minor turbidity change. Long term physiological responses occur when enhanced levels of turbidity persist, i.e., sedimentation concentrations greater than 80 mg l⁻¹. These events are generally long-lasting and can cause death at various species-specific levels. The following studies illustrate some of the dynamics between increased stream turbidity and biological response.

One of the first responses of a number of aquatic species to stream turbidity is an avoidance: avoidance behavior was found in juvenile Coho Salmon when suspended sediment concentrations exceeded 88 mg l⁻¹ (Anderson 1998). Although the response was quick and was reversed as conditions improved, the change may have caused a reduction in feeding, and a disruption in territory positioning (Anderson 1998).

Avoiding turbidity forces many aquatic organisms to select territories they normally would not choose: studies have shown that elevated turbidity increases in the downstream 'drift' of fish and benthic invertebrates (Anderson 1998, Vogel and Beauchamp 1999). Increased invertebrate drift has been noted in 23 mg l⁻¹ of suspended sediment (Anderson 1998). In response, fish species also increase drifting. Doing so leads to a loss of territory, and a decrease in protection against other predators. Salmonids change territories when suspended sediment concentration increased above 30 mg l⁻¹. Meanwhile, macro-invertebrate density decreases by 25-60 % when concentrations reach 40 to 120 mg l⁻¹ (Murphy 1962, Guildford *et al.* 1987, Holopainen and Huttunen 1992, Anderson 1998).

Brook Trout generally feeds fairly passively by capturing drifting food at locations of reduced water flow, i.e., pools and eddies. As turbidity increases to (10-20 NTU), Brook Trout leave these areas, and start to feed in other areas of higher water flow rate, where food is less easily caught. As a result, Brook Trout expends more energy, and growth rates decline. At 30-40 NTU, the challenge of food retrieval increases further.

A reduction in feeding is, in part, simply related to reduced visibility. In general, fish use binocular vision when foraging, because binocular vision provides a greater search volume, and a more precise orientation visualization of the position of the prey (Vogel and Beauchamp 1999). Elevated turbidity also increases the back-scattering of light: this reduces the contrast between prey and its background, thereby reducing the overall effective reaction distance. For example, reaction distances of Lake Trout declined by 80 % by increasing the turbidity level from 0 to 5 NTU (Vogel and Beauchamp 1999).

Increased turbidity reduces primary production which results in change in the macro-invertebrate communities. Concentrations above 115 mg l^{-1} reduce the light penetration that is essential to algae and other periphyton communities (Holopainen and Huttunen 1992, Anderson 1998,). Also, high populations of shredder invertebrates are replaced by grazers, collectors and gatherers (Anderson 1998).

Physiological responses of fish to elevated suspended sediment include a reduction in growth, alterations in blood chemistry, and hormones and death. Changes occur when gills are traumatized and damaged by sediment abrasion (Caissie and Arseneau 1999). The degree of damage depends on particle size and angularity and, exposure time. Gill damage leads to particle adsorption and infection by protozoans. This weakens the fish through lowering their resistance to future infection and environmental stresses. Gill damage was observed in Rainbow Trout exposed to 270 mg l^{-1} of sediment, and in juvenile Rainbow Trout exposed to 4900 mg l^{-1} for 16 days (Anderson 1998).

Increased turbidity impacts the stream-bed composition by altering the physical structure of the stream-bed, and by decreasing the stream's carrying capacity for biological organisms. For example, increased suspended sediment causes reductions in pool depth and riffle areas, leads to decrease feeding, cover, laying of eggs, and rearing of young (Anderson 1998, Caissie and Arseneau 1999). A reduction in egg survival is linked to an accumulation of fine sand in the interstitial spaces of gravel beds. This clogging causes a disruption of egg-gas and metabolic waste exchange with the stream water (Anderson 1998). As a result, egg survival in Rainbow Trout decreases when fines in gravel beds increases by 3 %. A 40 to 80 %

reduction in egg survival was noted in Coho Salmon. For Cutthroat Trout the percentage of fines ranged between 20-50 % (Anderson 1998).

In PEI's Morell River, 36 % fines have caused a significant reduction of emergence success of salmonid fry although differences in mortality may be linked to turbidity, event duration, and time of year. The degree of accumulation of fine sediments appears to be more important for species survival than concentration of suspended sediments within the water column (Anderson 1998).

During low winter flows, sediments entering streams tend to deposit in areas that are critical for fish survival. In winter months, fish have reduced energy reserves and must overwinter in pools or behind in-stream cover to reduce energy expenditure (Anderson 1998). Exclusion from preferred habitat increases their energy expenditure and stress. Death generally occurs when concentration, duration and timing of turbidity events produce extreme conditions.

The greater the turbidity, the greater is the possibility of abrasion of, e.g., gill damage, enhanced infection, egg mortality and reduced embryo survival (Caissie and Arseneau 1999). Aquatic studies show that turbidity as low as 5 NTU can be sufficient enough to hinder the ability of fish to recognize prey causing a switch in feeding methods (Anderson 1998). With increasing turbidity, depth of light penetration into surface water is decreased, thereby affecting overall biological productivity within streams and lakes by way of reduced primary biomass production. Suspended particles gradually settle in lakes and streams as sediments during periods of low flow, thereby potentially choking biologically active stream and lake bottoms over time (Dughrow and Everhart 1971, Granillo *et al.* 1985). During period of high flow, sediments tends to get relocated further downstream, all the way to estuaries, thereby exporting

problems that are essentially generated inland to marine ecosystems as well. Attached to suspended particles are in many cases, nutrients, and – in some cases – chemicals from overland spray operations (Forman 1995).

CHAPTER 3

THE HAYWARD BROOK WATERSHED STUDY CASE STUDY

INTRODUCTION

The objectives of this chapter are to:

- provide an overview of the biophysical features of the case study area including,
- forest soil units, climate, forest cover, soils, topography,
- overview of land-use activities.

In 1994 a multi-partner stakeholder group was established in southern New Brunswick with the objective of developing a management plan for a generally forested area known as the Fundy Model Forest (Fig. 3.1). One of the main projects within the Fundy Model Forest was a multi-component study known as the Hayward Brook Watershed Study. This study included several studies to assess change to aquatic and terrestrial ecosystems as the landscape was altered by road construction, and forest harvesting (Parker 1997). One component of the Hayward Brook Watershed Study was the monitoring of stream water quality and quantity.

BIOPHYSICAL FEATURES

The HBWS area includes 30 km² of 80 year old north-temperate mixed Acadian forest. The area is located within the Continental Lowland Ecoregion, Anagance Ridge Ecodistrict 29; latitude 45 53 'N, and longitude 65 11' W (Sims 1995, Roberts 1997). Elevation of the area ranges from 252 m in the headwaters to 26 m at the confluence with the Anagance River (Fig. 3.2).

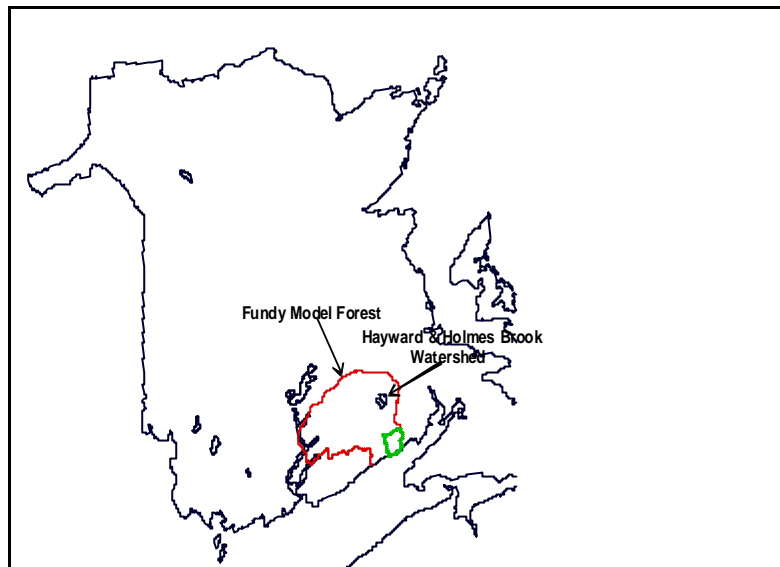


Fig. 3.1. The Hayward Brook Watershed Case Study Area
New Brunswick, Canada.

The bedrock of the area lies within the old Appalachian geological province. The Appalachian uplands consist of southwest-northeast synclines and anticlines that were periodically eroded and flooded by seawater. The continuous deposition, folding and faulting characterizes the Mississippian age, and underlies the rolling to hilly upland of the area. Wide spread deposition characterizes the later Pennsylvanian period. The Petitcodiac group and the Boss Point geomorphic formations of the Pennsylvanian age are found in the HBWS (Aalund and Wicklund 1950). The Petitcodiac or Pcu3 district (PET3 Geomorphological District) is composed of reddish or grey soils of fine to medium grained sandstone, grey, green, and red mudstone, and a minor portion of grey and red granule to cobble conglomerate and coal. The BOSS Geomorphological District

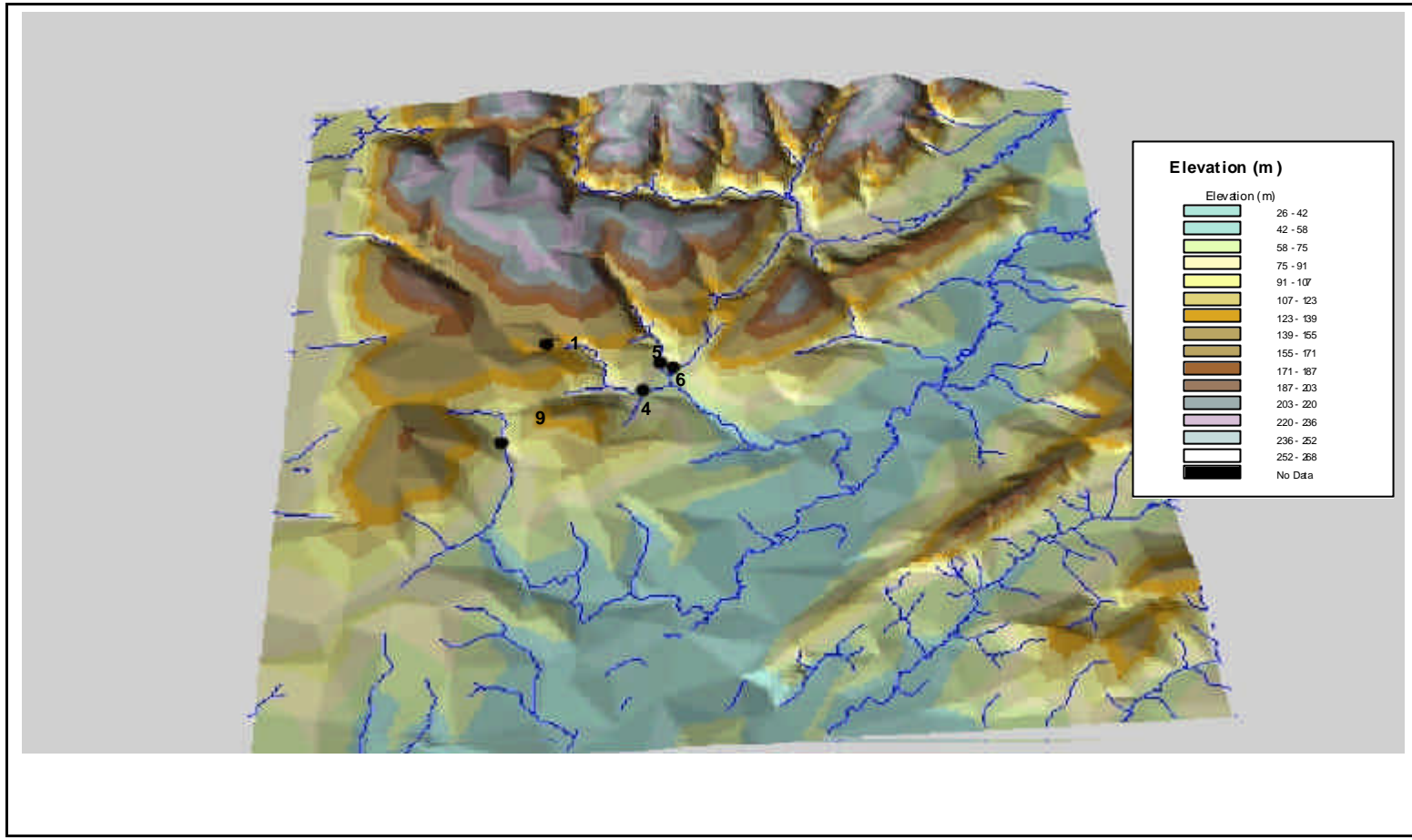


Fig. 3.2. Elevation (m) and location of monitoring stations in Hayward Brook Watershed Study.

lithologies are predominantly grey to greyish-green, grey mudstone and rarely red mudstone, infrequent red sandstone, carbonaceous mudstone, butuminous limestone, quartz pebble conglomerates, quartz sandstones, and impure coal (Sims 1995, Hovey 1996) (Fig 3.3).

The parent materials from which the soils of the area developed are glacial tills. Aalund and Wicklund (1950) listed the Parry, Salisbury, and Sunbury soils as the three main soil associations within the area. Fahmy and Colpitts (1995) redefined the soil map using a naturally occurring regoliths characterized by overlying parent material and solum as mapping units (Fig. 3.4). The Salisbury and Parry soils are derived from non to slightly-calcareous red mudstones, feldspathic to lithic sandstones and polymictic conglomerates. These soils are well to imperfectly drained lodgement tills (Fig. 3.5). The Salisbury unit is derived from red mudstone, and has a loam to sandy-clay loam consistency. The Parry forest soil units are derived from coarse textured red conglomerates and sandstones with gravel and stones mixed within. It has a loam to sandy-loam structure. The Sunbury soils are derived from coarse textured, non-compacted till deposits, and have a yellowish brown, friable, rapidly permeable sand loam to loamy-sand consistency (Fahmy and Colpitts 1995).

CLIMATE

Climate is characterized as the inland Harvey-Harcourt site region with annual degree day sum of 5°C (Fahmy and Colpitts 1995). Average annual precipitation is approximately 1400-1600 mm. About 16 % of this falls as snow. The late fall and early

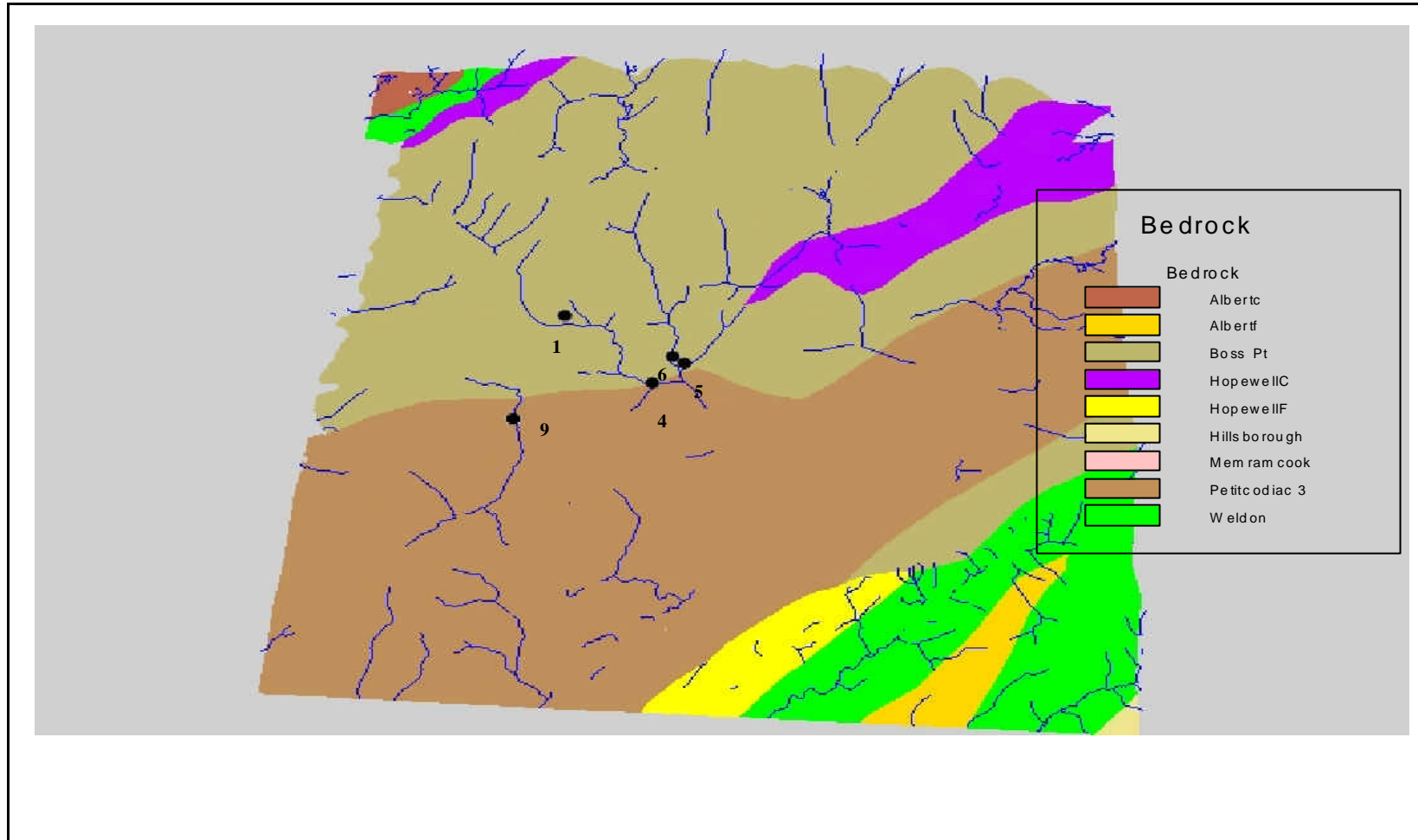


Fig. 3.3. Bedrock geology and location of monitoring stations in the Hayward Brook Watershed Study Area.

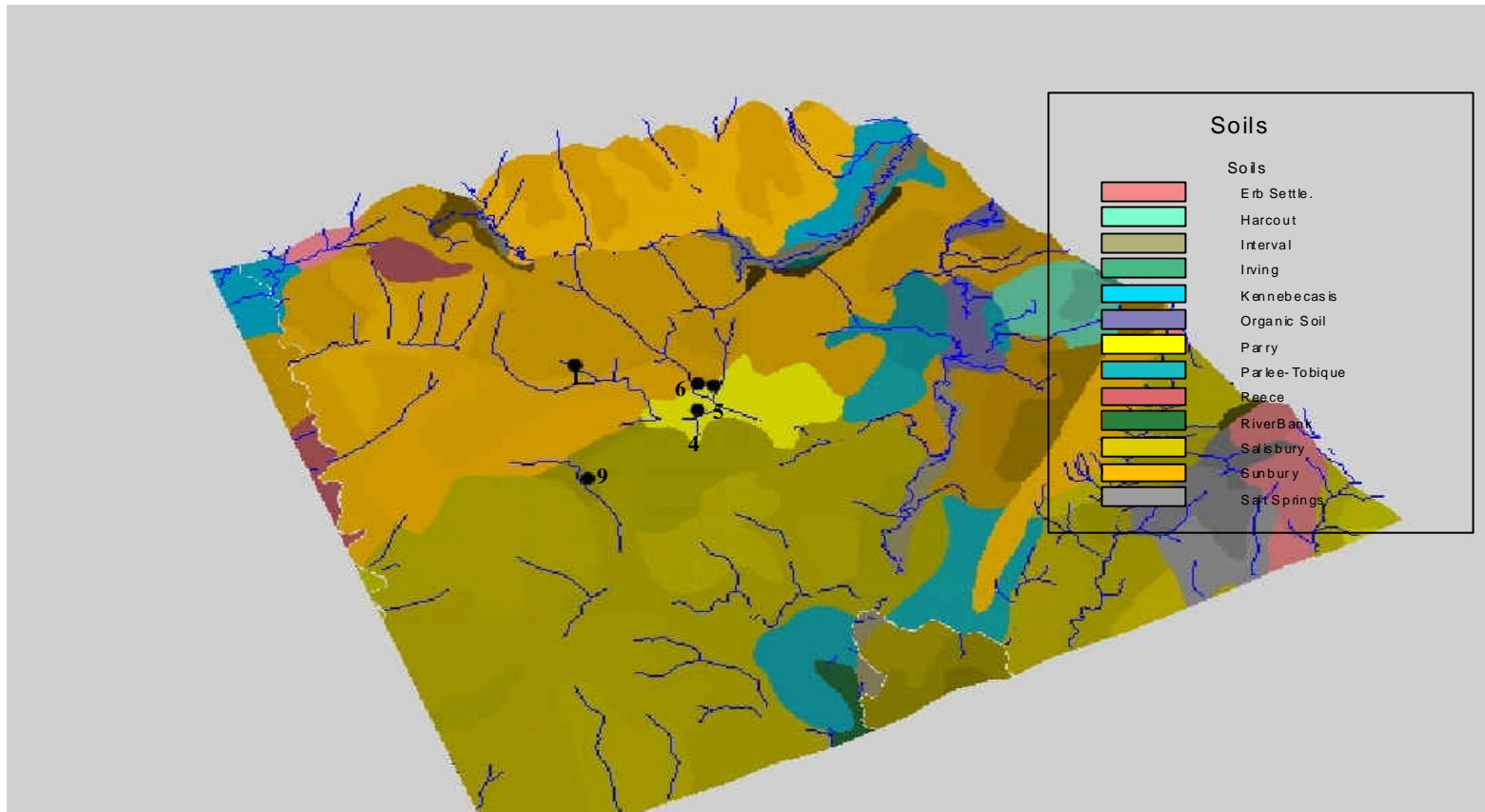


Fig. 3.4. Forest soil units and location of monitoring stations in the Hayward Brook Watershed Study Area.

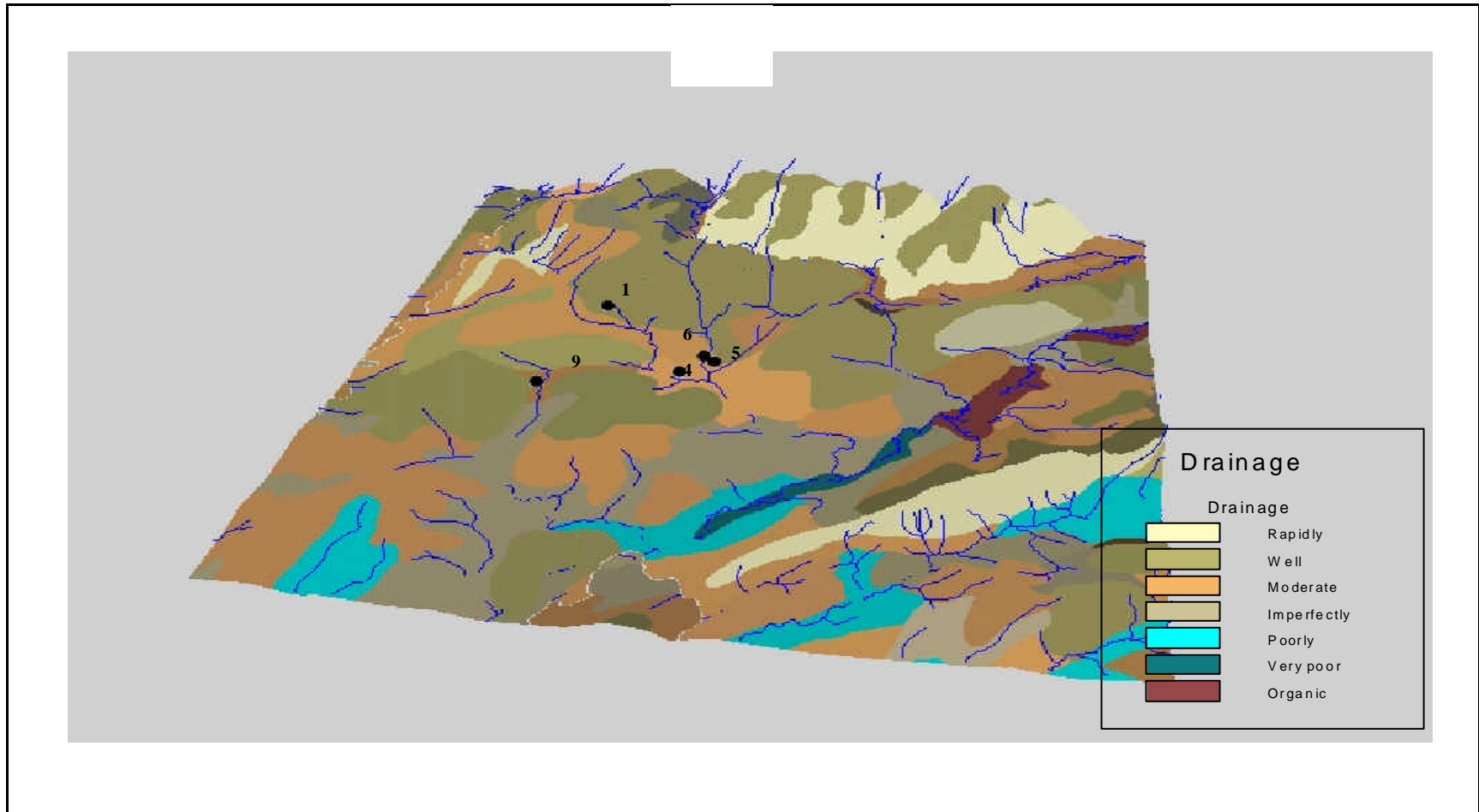


Fig. 3.5. Drainage classes and location of monitoring stations in the Hayward Brook Watershed Study Area.

spring seasons are generally wet and, the late spring to early summer the driest seasons (Sims 1995).

FOREST COVER

The forest is a multi-layered community with a dominant and subdominant canopy, and a shrub and herbaceous stratum (Sims 1995) (Fig. 3.6). The canopy consist of eight stand types (Roberts 1997). Tree species evenness is low with 80% of species being found on less than 20% of the area and, species richness averaging 15 species / 5m² plot (Roberts 1997). The general forest cover consist of deciduous trees on the ridges, conifer and a minor deciduous component on the mid-slopes and, conifer near the streams Tree species found within the Anagance Ridge Ecodistrict are:

Ridge tops:

White Birch (*Betula papyrifera* Marshall),

Red Maple (*Acer rubrum* L.),

Trembling Aspen (*Populus tremuloides* Michx.),

Large-tooth Aspen (*Populus grandidentata* Michx.).

Mid-slopes:

Red Spruce (*Picea rubens* Sarg.),

White Spruce (*Picea glauca* (Moench) Voss),

Black Spruce (*Picea mariana* (Miller) BSP),

Red Maple (*Acer rubrum* L.),

Balsam fir (*Abies balsamea* (L.) Miller),

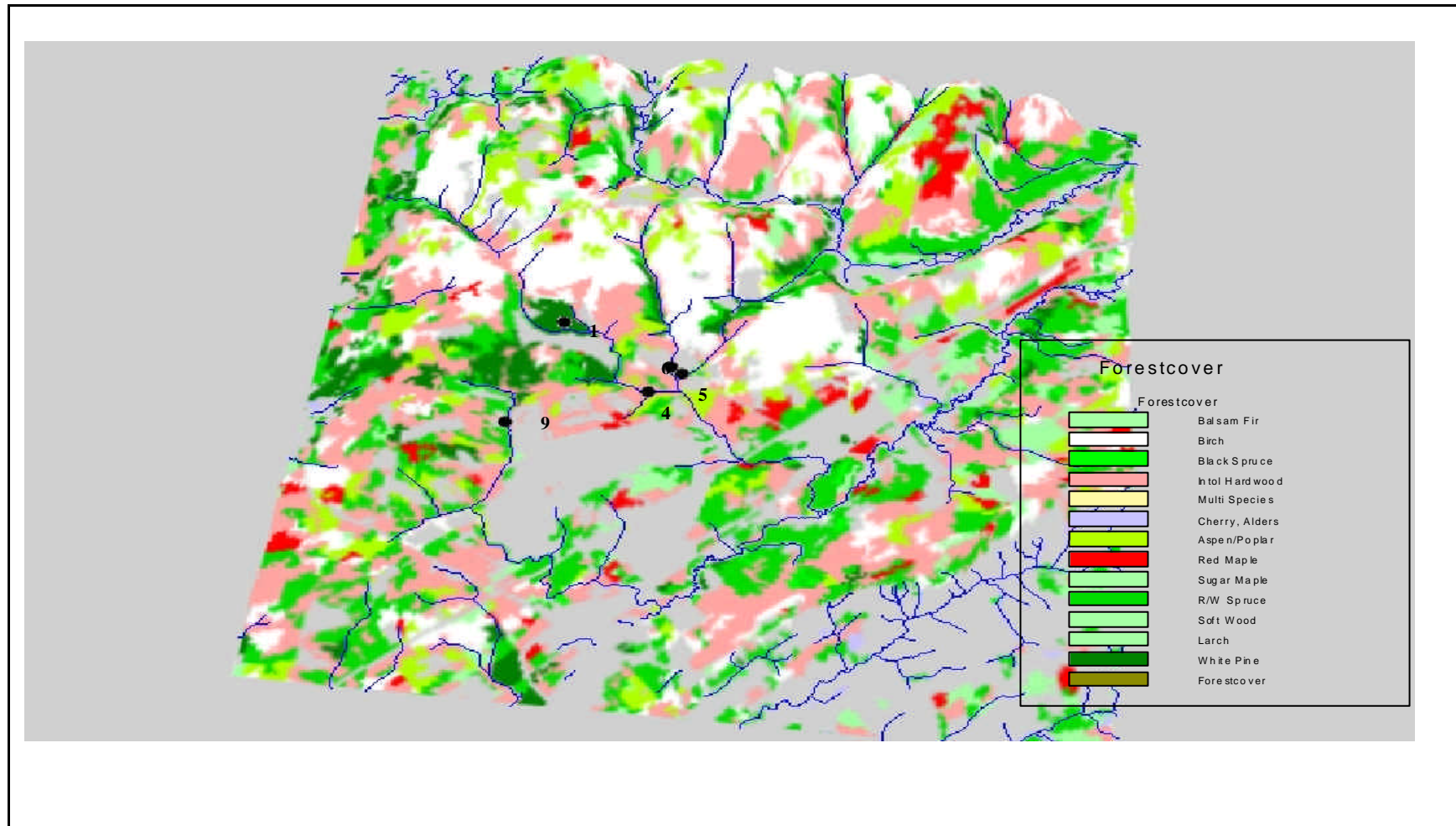


Fig. 3.6. Forest cover type and location of monitoring stations in the Hayward Brook Watershed Study Area.
(grey areas represent non-forested land)

Bottom Slopes:

Black Spruce (*Picea mariana* (Miller) BSP),

Red Spruce (*Picea rubens* Sarg.),

Red Maple (*Acer rubrum* L.),

Balsam fir (*Abies balsamea* (L.) Miller),

Ironwood (*Carpinus caroliniana*),

White Ash (*Fraxinus americana*),

Yellow Birch (*Betula Lutea*).

Scattered throughout the entire area are stands of:

White Pine (*Pinus strobus* L.),

Red pine (*Pine resinosa* Aiton),

Jack Pine (*Pinus banksiana* Lambert).

The herbaceous understory which includes tree species less than 1 metre tall consist of 106 species which represent perennial angiosperms, ferns, *Sphagnum spp.*, mosses, and liverworts (Sims 1995, Roberts 1997).

STREAMS

The physical habitat of selected streams were classified by Chiasson (1997). The classification characterizes the number of pools, runs and riffles counted within a specified distance (Table 3.1).

Table 3.1: Number of pools, runs and riffles in each study stream as recorded in 1994.

Stream	Distance (m)	Number of pools	Number of runs	Number of riffles
4	200	20	23	29
5	300	20	25	26
6	250	21	26	29
9	250	28	26	20

*(Chiasson 1997)

Stream substrate was classified according to the frequency of small and large cobble, gravel, sand, vegetation, and woody debris found within 25 cm² of 1.0 m² area

(Chiasson 1994, Chiasson 1997). Large cobble was the most common substrate in Stream 9 - Holmes Brook, followed by Streams 6,5 and 4 (Fig. 3.2). Sand was the next most common substrate with the highest amounts found in Stream 4. Fifty % less was present in Stream 9, and 75 % less in Streams 5 and 6. Gravel was the least found substrate with similar amounts in each stream. Small cobble content was minor with Stream 9 having the highest and an absence in Stream 5.

Aquatic vegetation was found growing in those streams with lower amounts of sand in the stream bed composition. Large amount of growth are found in Streams 5 and 6 whereas; in Stream 4 vegetation growth was minimal because of the high sand component in the streambed. The concentration of woody debris was high in Stream 5 and, low in Streams 4, 6 and 9.

TOPOGRAPHY

Slope within the watersheds range between 2 to 25 % (Fig. 3.7, 3.8, 3.9). Larger slopes are located in the northern section. Slope decreases to zero as the watersheds approach the Anagance lowlands. At the watershed scale slope ranges between 0 to 16

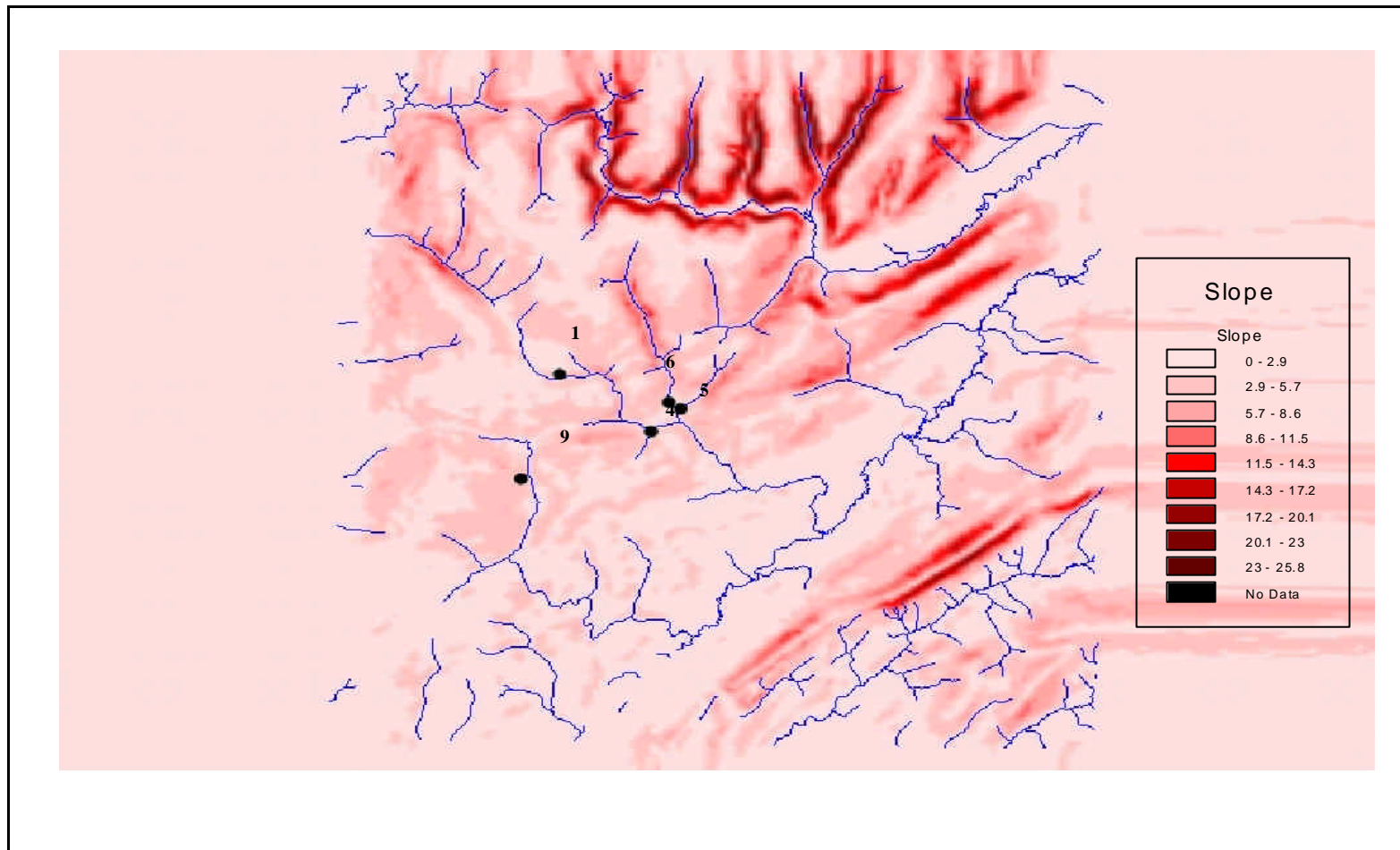


Fig. 3.7. Slope (%) and location of monitoring stations in the Hayward Brook Watershed Study

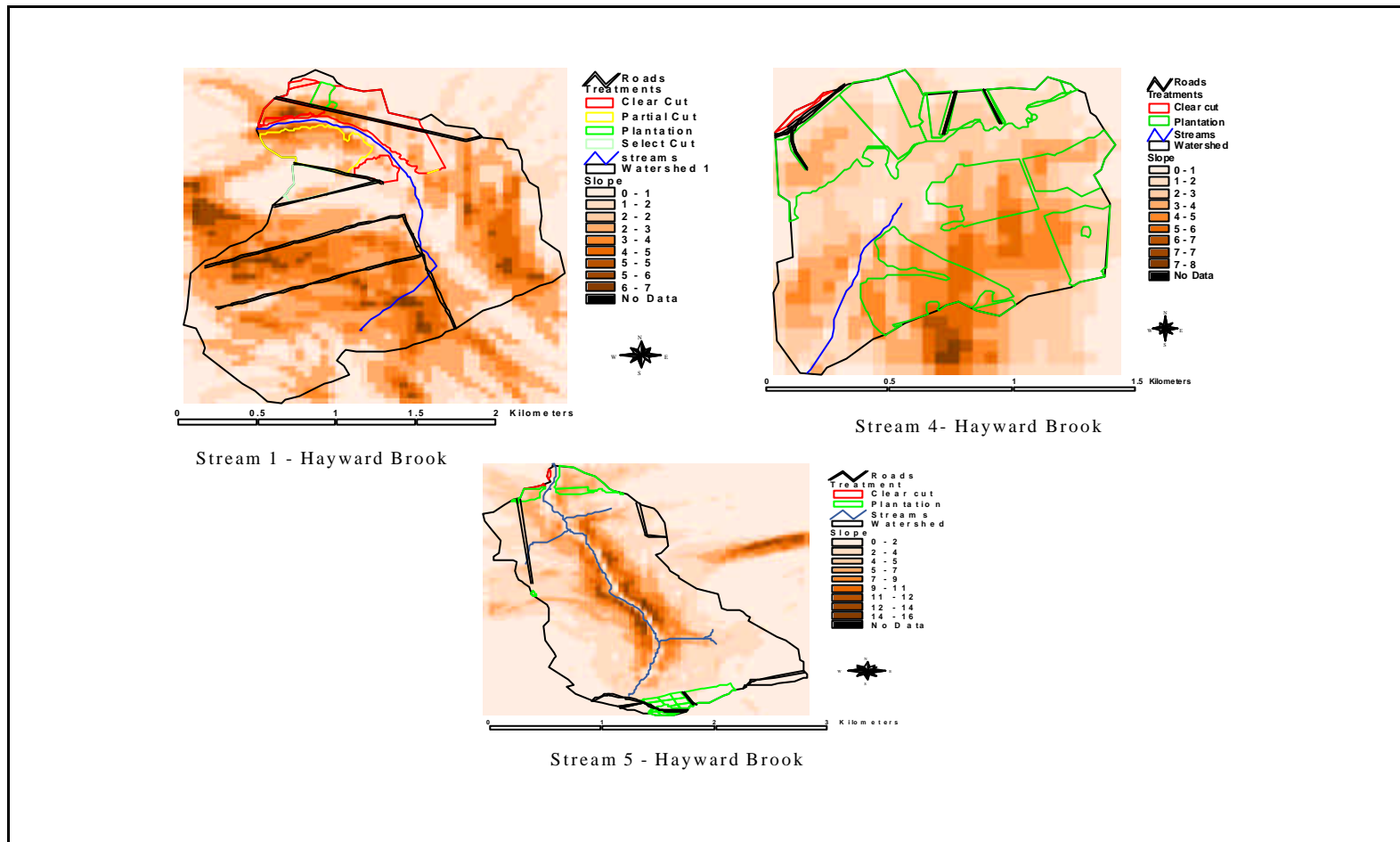
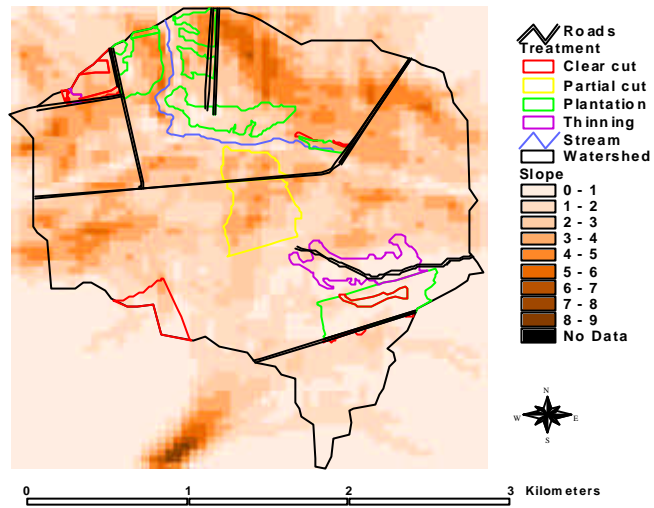
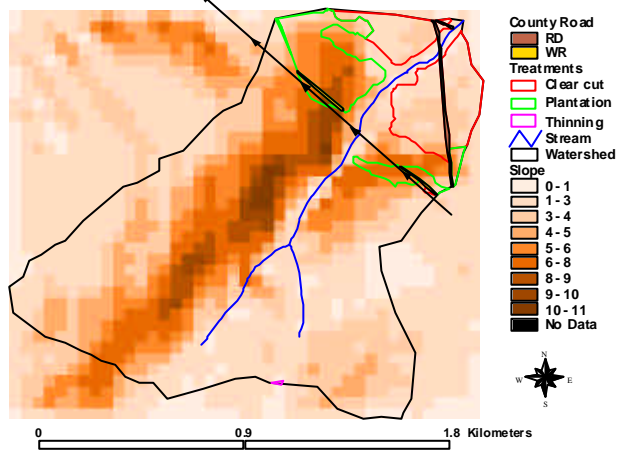


Fig. 3.8. Slope (%) and land transformations with Streams 1,4 and 5 of Hayward Brook Watershed Study Area.



Stream 9 - Holmes Brook



Stream 6 - Hayward Brook

Fig. 3.9. Slope (%) and land transformations with Streams 6 and 9 of Hayward Brook Watershed Study Area.

%). In watershed 1 harvest roads were built in the higher sloped areas to the west (Fig. 3.8). Watershed 4 is relatively flat with a small area to the south having higher slopes (Fig. 3.8). The headwater area of watershed 5 has the steepest slope within the HBWS (Fig. 3.8). Watershed 6 also has significant slope on the north side adjacent to the stream (3.9). This slope combines with a road to become a significant source of erosion. Watershed 9 has high slopes to the north and east of the stream (Fig. 3.9). One of the treated blocks in a north-west region has been identified as an area of soil erosion.

LAND-USE ACTIVITIES AND PATTERNS

The land-use within the HBWS watersheds was minor up until 1994 (Fig. 3.10). In March 1994 four water monitoring stations were installed on the tributaries of the Hayward Brook; Streams 1,4,5,6 (Fig. 3.2). A fifth station on Stream 9 was installed in April 1995 in the adjacent Holmes Brook. Main roads were built in April-May 1995 and forest harvesting began in May 1995 (Fig. 3.11). In 1997 further harvesting occurred in the watershed 4.

Land-use within selected basins included clear cut harvesting adjacent to 30, and 60 m wood stream buffer and, adjacent to a selectively cut stream buffer (Table 3.2).

Harvesting was done using a tracked feller buncher. This machine uses a hydraulic claw to secure and cut several whole trees at one time. Trees are then piled

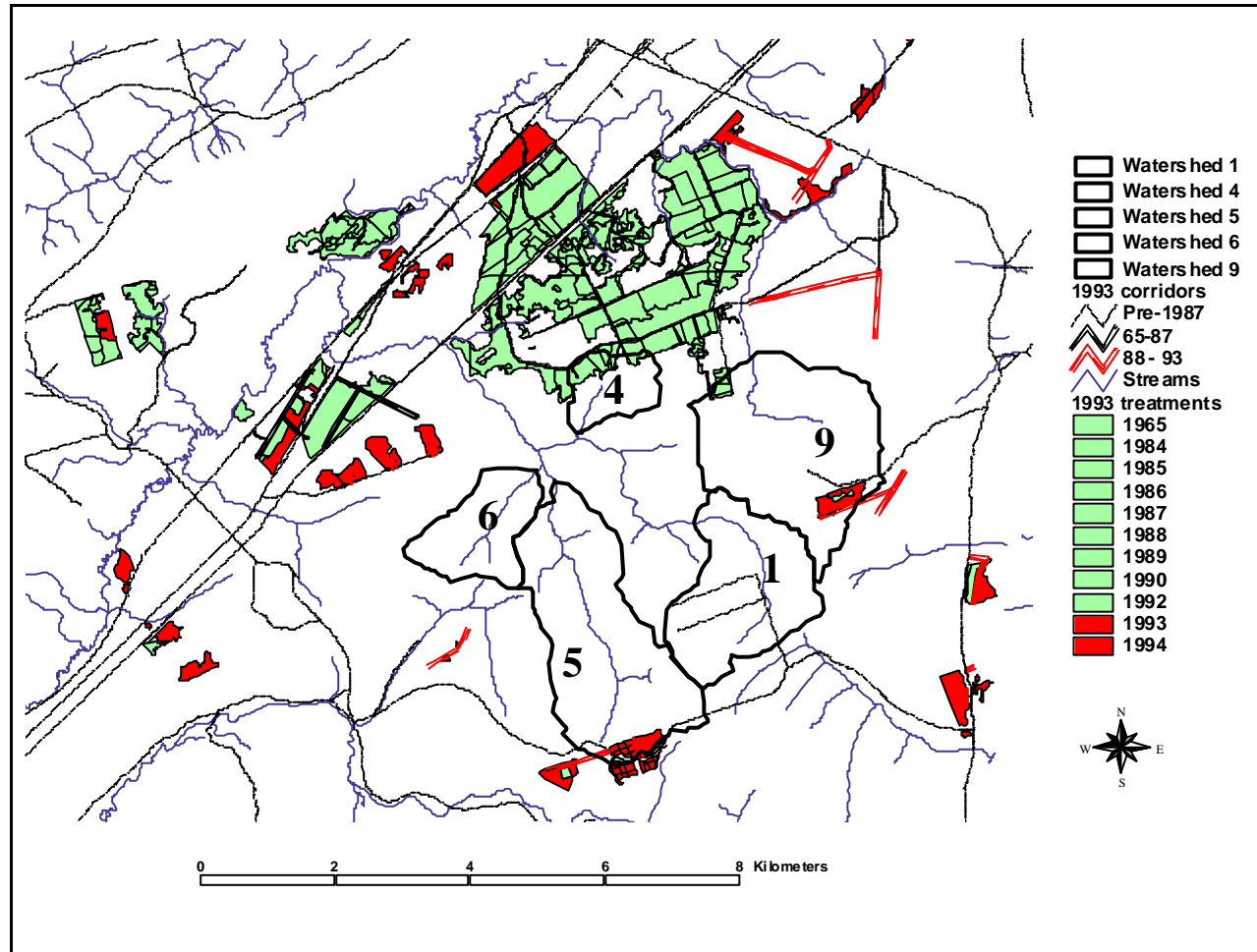


Fig. 3.10. Landscape transformations up to 1994 within the Hayward Brook Watershed Study Area.

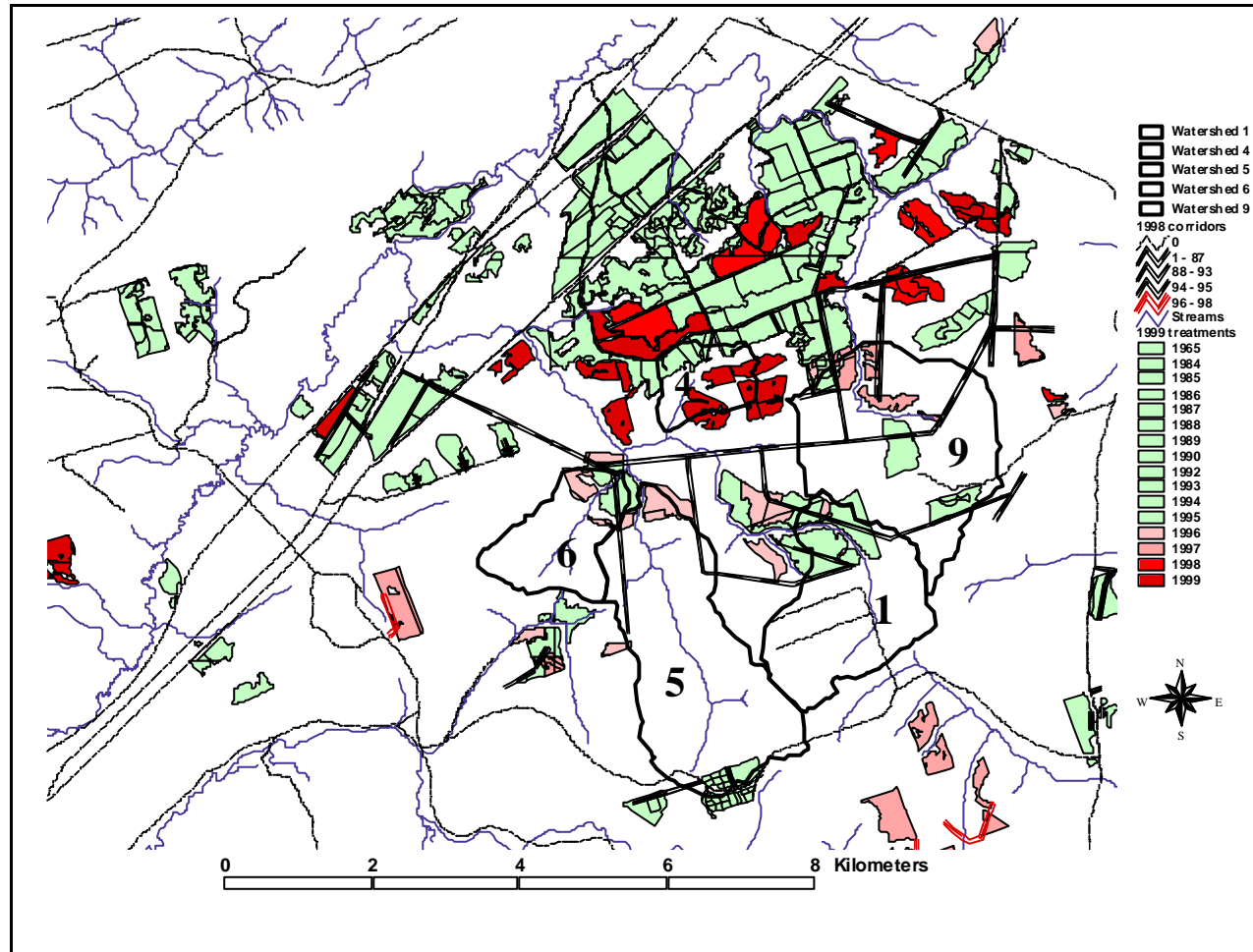


Fig. 3.11. Landscape transformations in the Hayward Brook Watershed Study as of 1999.

Table 3.2: Land change dates for each watershed within the Hayward Brook Watershed Study Area.

Watershed	Start Date	Finish Date	Land-use Change
1	06/1995	09/1995	clear cut harvest adjacent to a selective harvested stream buffer, roads and a culvert
4	-----	-----	no-land-use change
5	05/1995	09/ 1995	clear cut harvest adjacent to a 30 m buffer commercial roads and culverts
6	07/1995	09/1995	clear cut harvest adjacent to a 30 m buffer recreational roads, commercial roads and culvert
9	06/1995	12/1995	clear cut harvest adjacent to a 60 m buffer commercial/recreational roads and culverts

along side the cutting trail. A tracked processor then removes the limbs and cuts the tree to appropriate length. Slash (limbs) is used for a road bed for the machinery. Logs were transported to landing using a wheeled porter. Selective harvesting was done using a chainsaw and skidder (Krause 1998). The percentage of harvested area in each watershed ranged from 7 to 17 % (Table 3.3).

Table 3.3: Percent area of land-use within the Hayward Brook Watershed Case Study Area in 1996.

Water-shed	Area Ha	clear cut	roads	Select cut
1	480	2.3	0.8	16.0
4	160	----	1.6	-----
5	720	7.0	0.4	-----
6	230	17.0	0.4	-----
9	600	12.0	1.0	5.7

ROAD CONDITION REFLECTS SOIL TYPE

The driving condition of roads within the HBWS can be used as a quick indication of the stream turbidity that can occur in adjacent streams. Roads that quickly became greasy during periods of rain were generally adjacent to streams with higher turbidity (yellow area – Fig. 3.12). Roads that remained relatively dry during periods of rain were normally adjacent to streams with lower turbidity (red areas).

Low turbidity in Stream 1 was associated with the dry, sandy road conditions found in the southern Sunbury forest soil unit. These soils have a high permeability and low surface runoff. This allows soils to remain firm and dry during rain events. Rutting of the roads in this area was rare. Slightly differing conditions were found in the northern part of the study area, adjacent to Stream 4.

Soils in this area have a greater sandy-cobble composition, causing roads to become water saturated, but not greasy. Rutting in this area can be severe during wet periods. Turbidity in the adjacent stream was high as a result of soil erosion from stream banks.

Roads in the western and eastern sections of the study area became greasy and rutted during rain, and dusty during dry periods. These conditions result from the combination of the Parry and Salisbury forest soil units that have a loamy to sandy-loam consistency, low permeability, and high surface run-off. This results in high erosion during wet periods, and clouds of dust during summer months. The high turbidity in Streams 6 and 9 reflect the susceptibility of these watersheds to erosion and runoff.

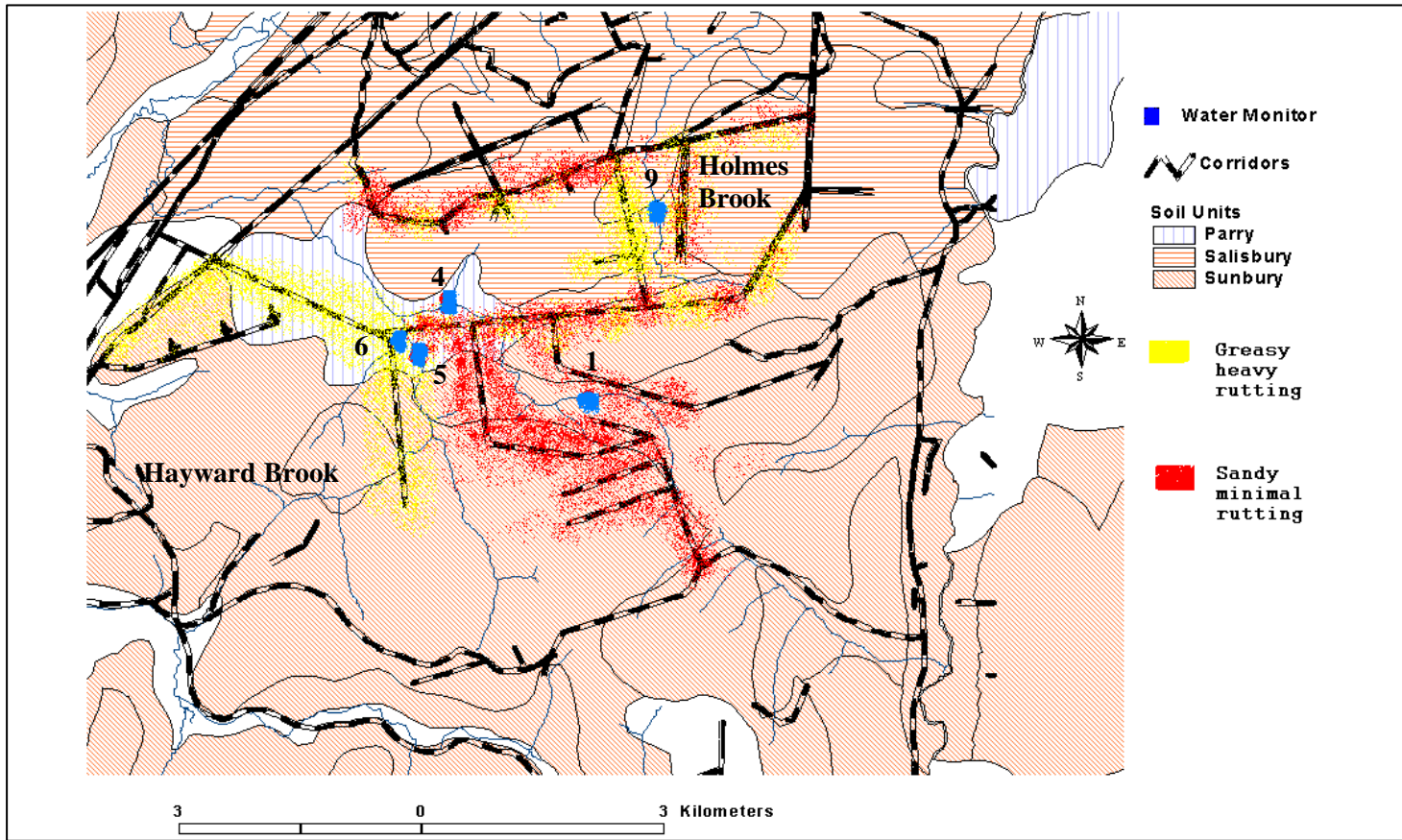


Fig. 3.12. Association between soil characteristics and road conditions.

CHAPTER 4

INSTRUMENTATION

This Chapter presents details regarding:

- concepts, principles, and definitions relevant to turbidity measurements,
- case study details about automated and year-round stream turbidity instrumentation and other measurements (stream discharge, suspended sediment concentrations), including site selection and instrument installation and maintenance,
- matters dealing with data quality and data quality control.

CONCEPT, PRINCIPLES, AND DEFINITIONS RELEVANT TO TURBIDITY MEASUREMENTS

Historically, first attempts to determine matters of suspended sediments in stream water dealt with direct measurement of suspended material of grab samples, in mg/l, through filtering of water, and subsequent drying and weighing of filtrate. Such attempts, although simple in concept, are often quite limited in accuracy and precision because absolute amounts of suspended sediments in sample filtrates are often below 1 mg, and two measurements are required of each filter paper, before and after filtration. Subsequently, the extent of water turbidity was analyzed through light measurements, by either measuring amount of light retained by the sample, or amount of light scattered by the sample. These measurements were based on the assumptions that amount of light retained or scattered per sample is directly proportional to

amount of suspended sediments per unit volume of water. Of these two measurements, the former is not as reliable as the latter, because light is not only retained by suspended particles, but also by dissolved constituents of the water, such as dissolved organic matter, and dissolved heavy metals such as Fe and Mn. In general, measurement of scattered light improves the accuracy of the turbidity measurements, from clear to coloured water samples (Dughrow and Everhart 1971).

Most of the early turbidity measurements were performed in the laboratory. For this purpose, grab samples would be obtained from streams or lakes according to predetermined sampling protocols, depending on specific sampling designs. Specific places for grab sampling would often be well-calibrated hydrometric discharge stations, to associate turbidity measurements with accurate discharge measurements (Anderson and Potts 1987, Fahey and Coker 1992, Martin and Hornbeck 1994). Other locations would, e.g., include soil run-off plots where water and sediments would be trapped with large drums or buckets (Fahey and Coker 1992).

In order to overcome:

- high costs of retrieving grab samples,
- problems from missing major run-off events, and
- considerable variations in sampling and turbidity measurement techniques,

several means were devised to determine in-situ stream turbidity signatures. For example, Fattorelli *et al.* (1988) utilized ultrasonic sensors for coarse sediment recordings, and in-situ turbidity sensors for fine sediment recordings. Data were at first recorded with magnetic tape, and later with solid-state memory chips. In-situ nephelometric turbidity sensors were described

for the first time in 1989 (Downing 1989). Gippel (1995) demonstrated that nephelometric sensors could be used to adequately track suspended solids concentrations by way of continuous turbidity measurements.

Nephelometer, (NTU); is a standard measurement of the optical properties of a water sample (Standard Methods 1971). This method is based on the comparison of the intensity of light scattered by a sample under defined conditions with the intensity of light scattered from a standard reference suspension.

Modern turbidimeters generally use one or two sensors to measure transmitted light or scattered light. The turbidity sensors used for this case study use two nephelometric sensors to measure light scattered at 90 and 180 degrees to the light source (Fig. 4.1). These sensors are part of the automatically recording Hydrolab multiprobe (Fig. 4.2), which, in addition to turbidity, measures specific conductance ($\mu\text{S cm}^{-1}$), pH, dissolved oxygen (mg l^{-1}), and temperature ($^{\circ}\text{C}$) (HydroLab 1993), every hour (e.g.), and the results are recorded digitally on a data logger.

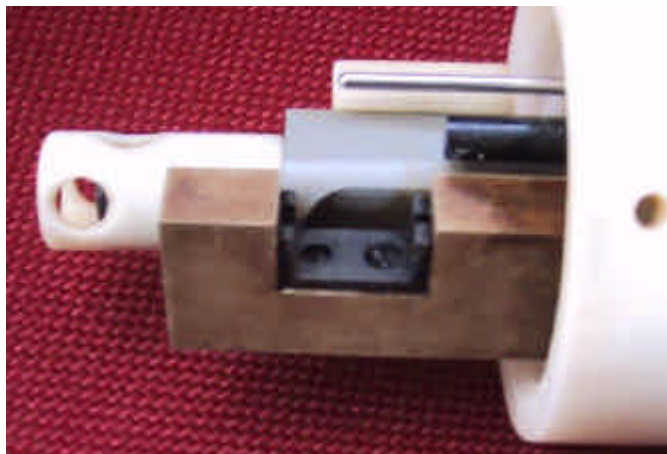


Fig. 4.1. Nephelometric turbidity sensor.

SELECTION OF FIELD LOCATIONS

Within the Hayward Watershed Study area, 5 watersheds were selected for hydrometric measurements and turbidity according to the following criteria:

- Forest cover in watersheds up to second stream order or more needed to be mature,
- Some of these watersheds would be subject to forest harvesting within the 6-year study period, as part of the current management plan for that area,
- The landowner would be willing to cooperate by providing continued and unrestricted access to the study area, and would protect these locations from unwanted machine traffic and other interferences.



Fig. 4.2. Hydrolab water quality multiprobe as used in the
Hayward Brook Watershed Study Area.

Potential locations for probe installation within each of the 5 streams were limited to pools of sufficient width (1 to 5 m), and minimum water depth (>20cm) at low flow; these conditions could not be found in first order streams, but became available along second order streams.

INSTALLATIONS AND MAINTENANCE

Next, each of the most suitable probe location per stream needed to be supplied with electrical power. This was done by installing a tower to support solar panels, with each panel connected to a 12 volt gel-cel battery. Each of these five solar panel – battery assemblies needed to supply sufficient year-round power (about 40 watts maximum, Fig. 4.3). All probes were set to record on an hourly schedule (Horowitz *et al.* 1989, Brabben *et al.* 1991, Whitfield 1995). Each probe location was visited regularly once every 6 to 12 weeks, to check calibration and integrity of each sensor on each multiprobe head, and to take corrective actions, as needed. Timing between visits was longer during winter when probe locations were covered by a layer of ice. Maintenance required:

- rinsing each turbidity sensor three times with distilled water to remove large pieces of debris,
- calibrating the readings of each turbidity sensor with 2 formazin turbidity standards (0.0 and 65 NTU),
- manually cleaning each turbidity sensor using cotton swabs and paper towels.

Calibration date, site and probe conditions were recorded in field notes. During additional inter-calibration visits, sensors were washed with stream-water to provide additional

cleaning. The other sensors on each Hydrolab probe were also serviced and calibrated at the same time.



Fig. 4.3. Water quality monitoring station found in the Hayward Brook Watershed Study Area.

DATA RETRIEVAL AND DATA QUALITY CONTROL

Recorded sensor data were downloaded at each site visit, in a format that identified date, sensor location, sensor type, and sensor reading. Data quality control measures involved cross-checking data against each other for consistency, and with field notes and calibration sheets. Matters requiring corrective actions are summarized in Appendix 1. The following problems were encountered:

1. Lack of direct sunshine caused lost of power to batteries during the winter of the first year; removal of the forest canopy was required to increase power output of the solar panels; thereafter; supply of power to the data recording platform and all its sensors was reliable.
2. The turbidity sensors experienced sensor fouling problems throughout the study: silt often collected on the sensor lens, thereby causing false peaks in turbidity signatures of each stream; also small debris and organic matter would lodge or accumulate on sensor heads. To decrease lens fouling, probes were inspected and cleaned frequently. Also, each multi-head was placed facing down into the incoming stream column, within areas of highest stream velocity. The highest incidence of sensor fouling occurred in stream 6 as a result of continuously high stream turbidity. About 19 % of the data were severely affected by sensor fouling. Corrections were made to the resulting data to avoid turbidity overestimation or underestimation as much as possible. In this, background turbidity likely remained over-determined due to frequent lens clouding. Underestimation would occur with some of the high turbidity events because of the limited NTU range of the instrument. Some peaks may have been overestimated, because the turbidity sensors were blocked until the sensor could be cleaned again. For these reasons, the original turbidity signatures were treated in two ways: (1) partial clean up of the turbidity records as detailed in Appendix 1, and the resulting records are part of the data presentation and analysis in Chapters 5, 6 and 7; a complete clean-up was not possible due to inconsistent variations of background as well as episodic malfunctioning of the NTU sensors; (2) identifying all major and minor turbidity events that are free from sensor fouling, and using these for the analysis of peak height, duration, and peak-to-peak intervals, and subsequent model development (Chapters 8,9).

STREAM DISCHARGE

Stream discharge was measured at each probe location, using a Tavis nitrogen gas sensor (Pomeroy *et al.* 1997). Nitrogen gas was supplied to a stable location at the stream bottom near each of the 5 Hydrolab probes, by way of a tube and gas regulator assembly. Nitrogen gas was released into the stream at a set rate (namely 30 bubbles per minute). A baseline was established between recorded gas pressure and its water column (“stage height”) immediately above the location of the gas outlet, for the purpose of hydrometric calibration. Stage height records were then associated with stream velocity measurements, by developing the local and probe-location specific stage-discharge curve. These were supplemented with the customary stream channel measurements (Inland Waters 1982). Using these measurements, and following proper interfacing of bubble pressure, stream velocity and stream-channel geometry, continuous gas pressure records were then converted into stream discharge rates ($\text{m}^3 \text{s}^{-1}$). Stream velocity measurements were obtained during regular probe calibration visits, to ensure time-continuous integrity of all hydrometric measurements.

The Tavis discharge sensors developed gas leaks from time to time: this stopped the discharge sensor operations on a few occasions. The leakage was generally found to be a loose brass fitting at the nitrogen tank or at the nitrogen bubble regulator. Leakage occurred most frequently during the winter months of the first year of operation. Proper seating of fitting corrected this problem.

SUSPENDED SEDIMENT SAMPLING

Suspended sediment samples were collected from each probe locations during times of specific and appreciably large turbidity events. This was done with a depth-integrating hand sampler (Gray 1970, Inland Waters Directorate 1982, Scudato and Yogis 1988).

CHAPTER 5

TURBIDITY SIGNATURES

In this Chapter, the partially cleaned in-situ turbidity signatures from each of the five streams are presented by:

- displaying these signatures over the entire recording period,
- relating these signatures to within-watershed activities and road-stream configurations,
- comparing the five stream signatures with one another, and with the stream discharge signatures, by way of simple correlation,
- ranking the five streams by turbidity intensity, from lowest to highest.

METHODS

Hourly stream turbidity and discharge rates were compiled in chronological order. Partially cleaned hourly records were then used to determine daily, seasonal and annual turbidity means, and daily discharge totals. Also, cumulative turbidity was calculated per watershed, for the simple purpose of watershed ranking. Daily turbidity and stream discharge compilations were plotted against one another for any combination of streams, and the resulting scatter plots were displayed in matrix form, one for turbidity, and one for stream discharge. Also part of the matrix display were the frequency distributions of stream discharge and stream turbidity.

To facilitate relating stream turbidity to within watershed activities and stream-road configurations, special maps were prepared to allow for a general interpretation of each of the stream turbidity signatures. These maps were prepared digitally with ArcView, using a special watershed delineation function based on the flow accumulation concept and based on the digital elevation model for the general area of HBWS. The streams that were derived from the DEM via the flow accumulation function were forced to exactly coincide with the already existing stream maps. The final maps showed actual watershed contours, with each watershed defined to be above each hydrometric probe location, and actual stream and road locations.

RESULTS AND DISCUSSION.

Based on turbidity signature intensity, and cumulative stream turbidity, it can be concluded that the 5 streams followed the following turbidity sequence (Fig. 5.1):

$$\text{Stream 1} < \text{Stream 5} < \text{Stream 9} < \text{Stream 4} < \text{Stream 6}$$

Inspection of the stream-road maps for each watershed generally supports this order: turbidity was low in basins with roads far from the stream, and especially far from the turbidity probe location. For Streams 1 and 5, roads were mainly running along the upper part of the watershed. Also, road-stream crossings were relatively far from each of the probe locations. For Stream 9, there were two road-stream crossings, with one very near the turbidity probe. With Stream 6, two of the roads ran parallel to the stream near the probe location, and fairly closely to or somewhat beyond the stream buffer distance. Stream 4, however, is not dissected

by any road, and should – in principle – have the clearest water. However, there was a gradually eroding stream bank near the probe location.

Stream to stream correlations revealed that stream discharge rates are, in general, correlated across basins, but this is not the case for the stream-to-stream turbidity correlations. This means that turbidity events in one watershed occur essentially independent of turbidity events in other watersheds, for the most part (Table 5.1). This, in turn, means that turbidity events are also, for the most part, not causally driven by the weather and season dependent stream flow rate. However, stream discharge has been identified as a major force driving turbidity concentrations (Lawler 1986, Rogers and Singh 1986). This study shows that high stream discharge does not always mean high turbidity, and vice versa. Instead, triggers beyond stream discharge are necessary to cause a major turbidity event, even during periods of high flow. However, one can anticipate that triggers during high flow and during periods of high soil water saturation would unleash much more turbidity than a similar trigger during low flow.

Table 5.1: Correlation between daily turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for streams of the Hayward Brook Watershed Study Area.

Stream	Turbidity (NTU) versus stream discharge ($\text{m}^3 \text{s}^{-1}$)
1	0.33
4	0.07
5	0.01
6	0.36
9	0.35

Examining the frequency distributions in Figure 5.2 shows that most turbidity and stream discharge events occur at low intensity. Turbidity and stream discharge events of

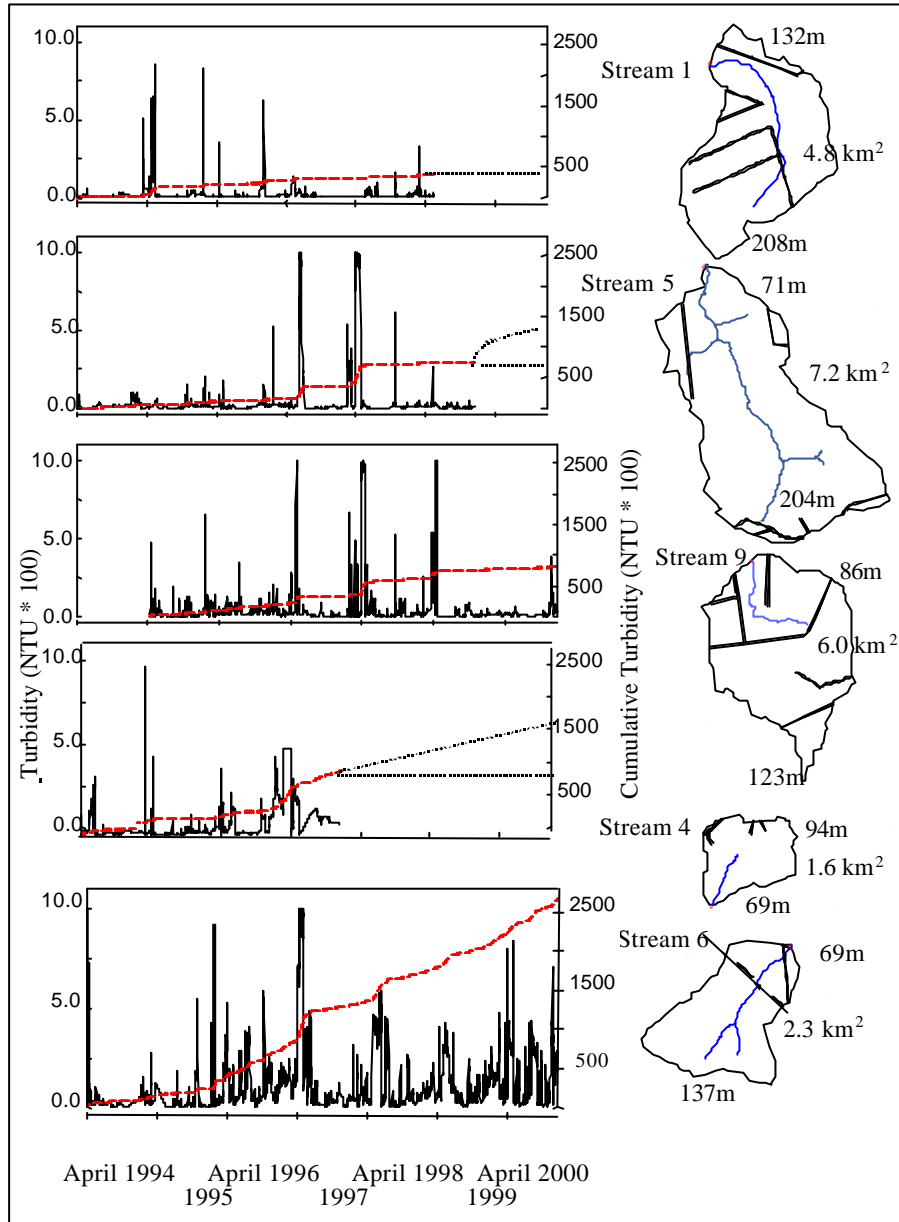


Fig. 5.1. Comparison of stream characteristics and stream turbidity during April 1994 to December 2000. The dashed line represents cumulative turbidity.

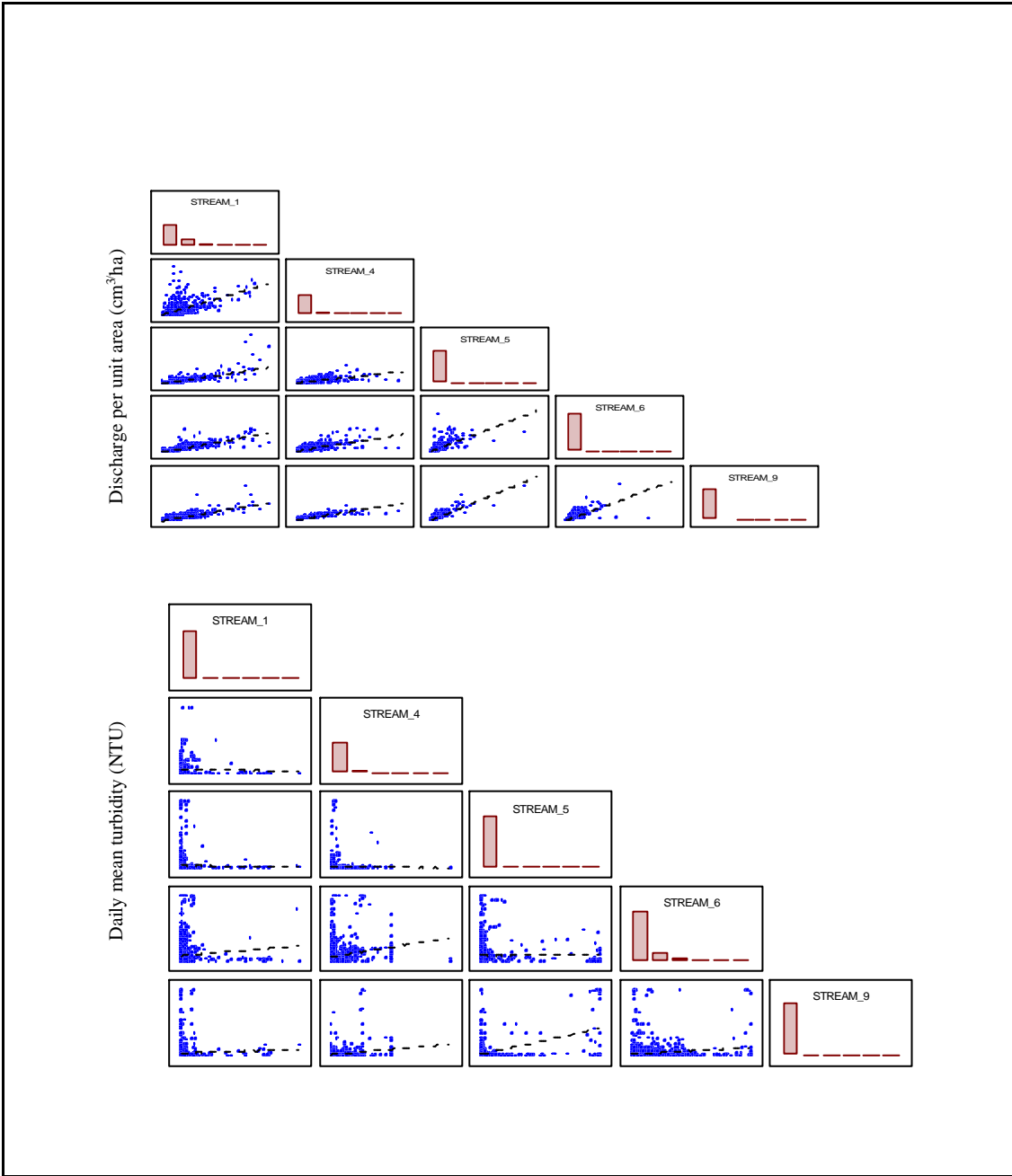


Fig. 5.2. Matrix plots of discharge per unit area (cm³ ha⁻¹) and daily mean turbidity (NTU).

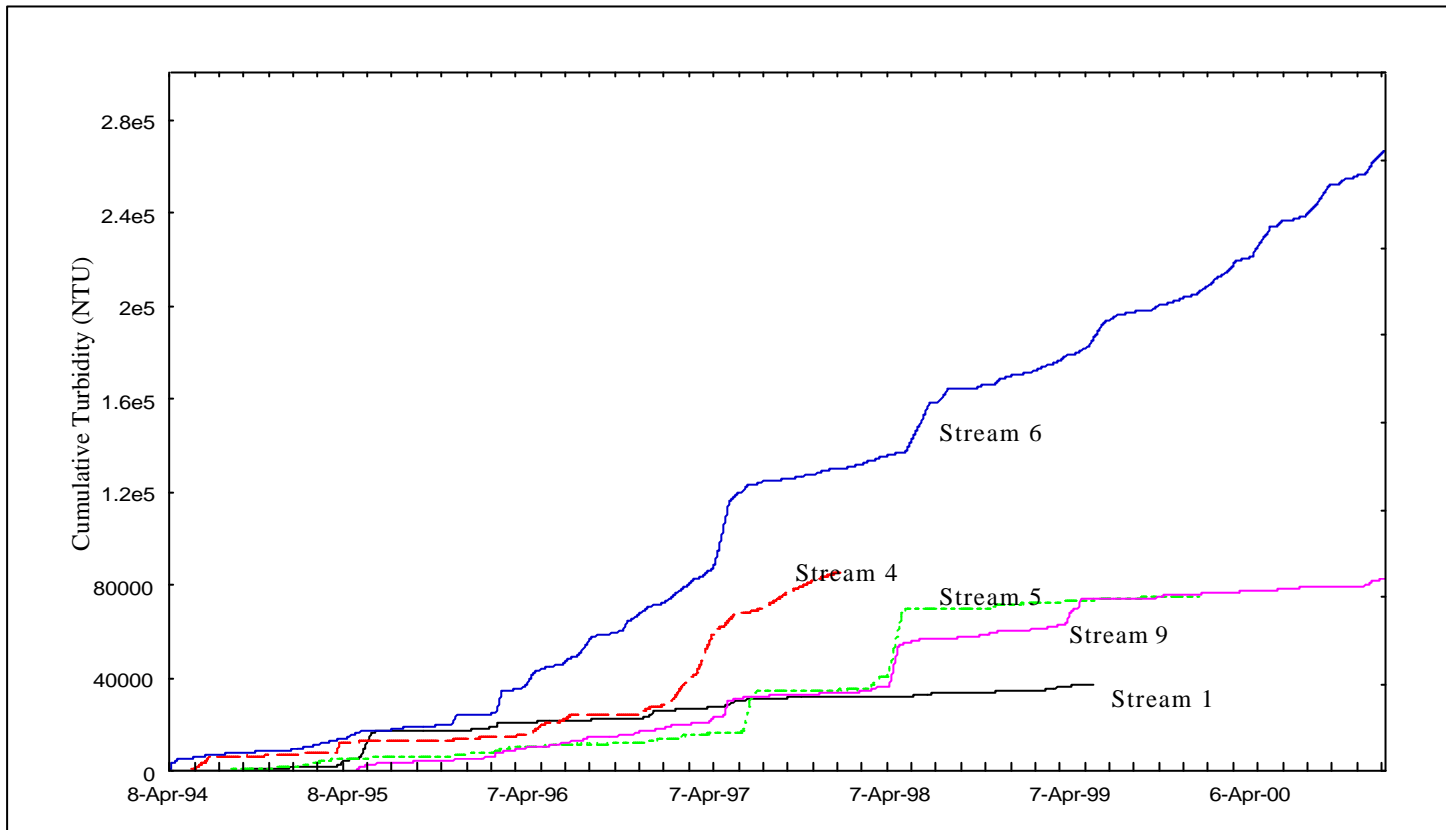


Fig. 5. 3. Cumulative daily turbidity (NTU) for streams in the Hayward Brook Watershed Study Area during 1994 to 2000, showing Streams 5 and 9 as the cleanest stream except for a few turbidity episodes, and Stream 6 as the most turbid stream.

intermediate and high intensity are generally infrequent. The low level of correlation between turbidity and stream discharge means that the highest peaks for turbidity do not generally coincide with the highest peaks for stream discharge.

Seasonally, turbidity was highest from January to March, and April to June (Table 5.2). These periods are generally associated with periods of high degrees of soil saturation, snowmelt, ice, and floods. Frost has been identified as a major erosion factor causing stream banks to become unstable (Lawler 1986, Fahey and Coker 1992). Loosened material is then washed away by spring floods. In Streams 1,5,9, turbidity values during the snow melt seasons were at least 50 % greater than turbidity values in other seasons. In Streams 4 and 6, the differences in seasonal turbidity were least, indicating a continuous source of eroding material within these streams. High summer turbidity in Stream 6 would be due to dust being washed from the nearby road and adjacent vegetation.

Table 5.2: Mean and standard mean error for turbidity per season (NTU) for five streams in Hayward Brook Watershed Study Area during 1994 to 2000.

Season	Stream 1	Stream 4	Stream 5	Stream 6	Stream 9
Spring (April-June)	38 ± 5	84 ± 6	89 ± 11	181 ± 9	88 ± 9
Summer (July-September)	5 ± 1	29 ± 3	7 ± 1	71 ± 4	13 ± 2
Fall (October-December)	16 ± 2	38 ± 2	14 ± 2	77 ± 4	22 ± 2
Winter (January - March)	19 ± 3	117 ± 11	34 ± 4	108 ± 6	38 ± 4

DETAILS, BY WATERSHED

Stream 1

Stream 1 was monitored from April 1994 to March 1999 (Fig. 5.1 - top). The cumulative turbidity concentration (NTU - dotted line) was two to five times lower than found in the other streams. Most turbidity events occurred as quick spikes. Turbidity concentrations showed minimal change in turbidity until the April 1995 construction of haul roads (Fig. 5.3, 5.4). After this period, larger turbidity events were well spaced, generally being associated with storms (Fig. 5.5). The culvert that was installed in the headwaters below an 8 % slope was identified as the major cause of elevated stream turbidity in this stream (Figs. 3.8, 5.6). The location of this culvert directed the flow of water into a bank on the lower side of the culvert. Major stream bank erosion occurred at this location only during the first year. Minor sediment deposits on leaves within the stream showed that stream bank erosion was still occurring in 1999 (Fig. 5.6 -Photo 2 and 3).

The overall lack of available material for erosion may be due to the prevalence of the Sunbury forest soil in this basin (Figure 3.4). These soils have a loamy-sand consistency and drain rapidly because of high soil permeability. These conditions allow roads and exposed soils to remain relatively firm, even during wet periods. This minimizes surface runoff and associated erosion.

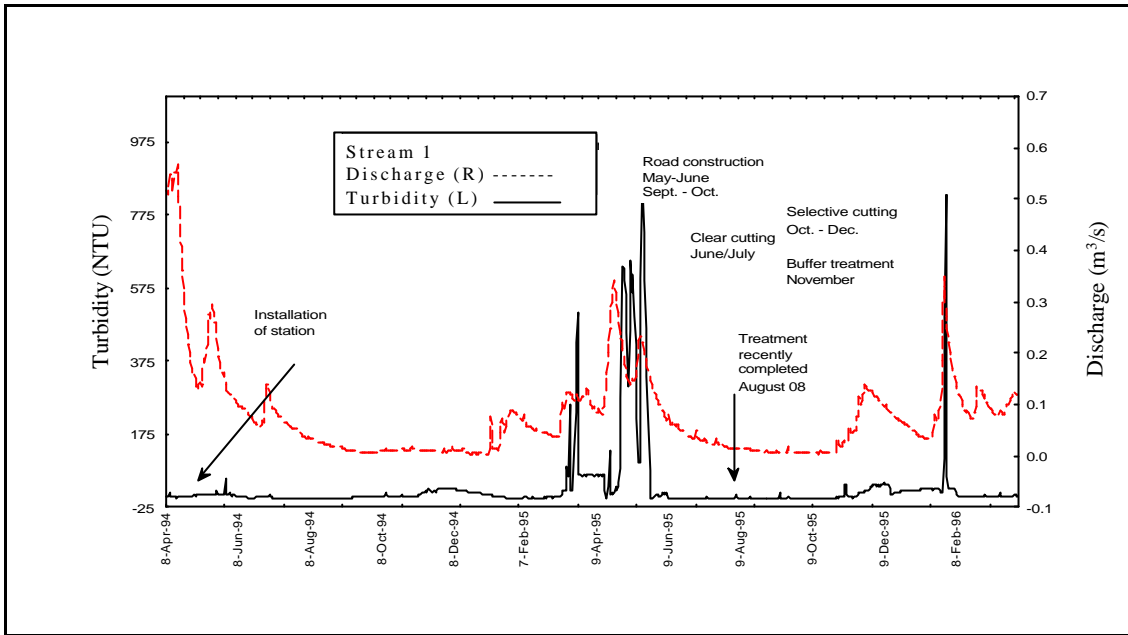


Fig. 5.4. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 1 of Hayward Brook during April 1994 to March 1996.

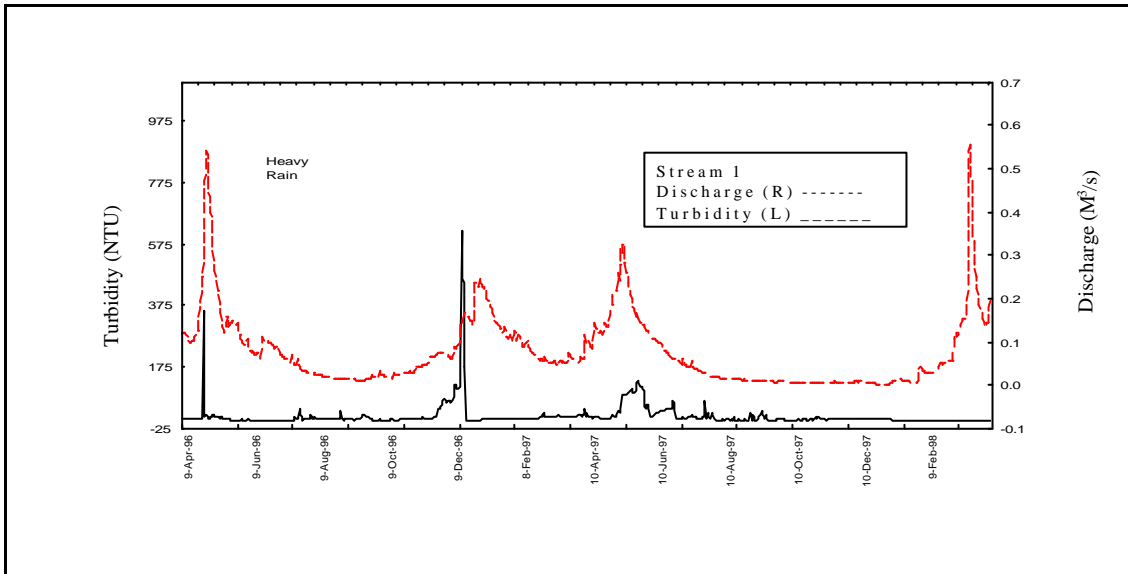


Fig. 5.5. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 1 of Hayward Brook during April 1996 to March 1997.

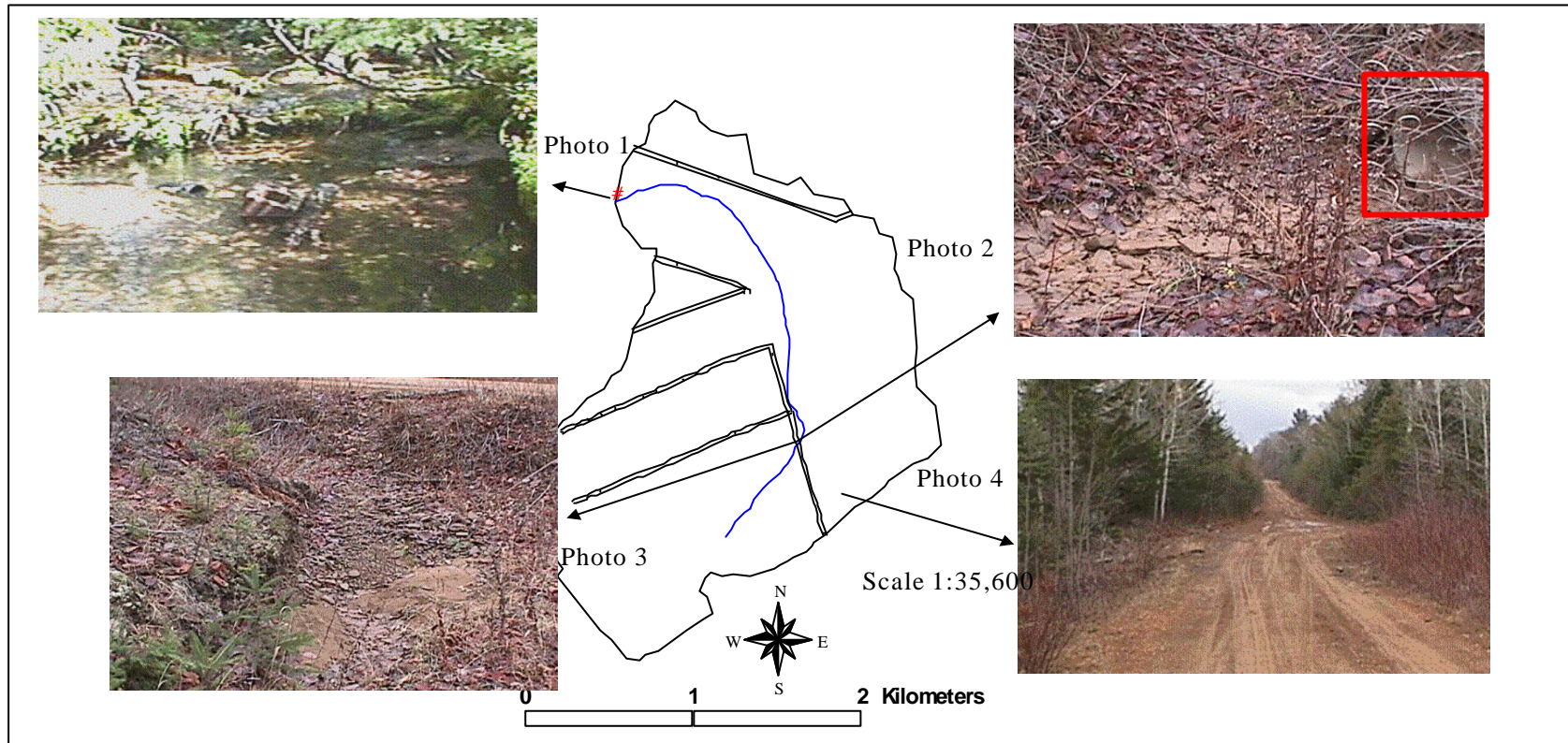


Fig. 5.6. Minor land-use in Stream 1 of Hayward Brook (size– 4.8 km²).
 Photo 1: (see arrow) – water monitoring probe in sandy pool.
 Photo 2: (see red square) - Cement culvert on commercial and recreational road.
 Photo 3: Sediment deposits 10 m below culvert.
 Photo 4: Commercial and recreational roads.

Stream 5

The watershed of Stream 5 is the largest within the case study. Stream turbidity was generally low. In May 1995, sections of the basin were harvested. This activity did not lead to major turbidity events. Instead, the first major turbidity event occurred in June 1997, followed by a second major event in March 1998 (Fig. 5.8). The cause of the first event was not determined, but the March event was due a wash-out event within the stream above the sensor. Together, these two events contributed to a considerable cumulative turbidity increase above the 1997 baseline (Fig. 5.1). Because these two events occurred two years after the 1995 road construction and harvest, land-use change was not expected to be a major factor in the elevated turbidity (Fig 5.10 - photo 3).

The most significant factor contributing to elevated turbidity events in the signature is inappropriate monitoring location. The monitoring site was initially selected because of the large pool created by a log dam. The flow of water over the dam maintained a deep pool that had cobble-sand substrate and rapid flow. The stability of the dam was not realized until a storm removed the log in March of 1998 (Fig. 5.10 - photo 1). Had the monitoring site been located in a natural pool the signature for this stream would have shown a low baseline throughout the study. The wash-out changed the stream flow dynamics and bed composition. The change in flow direction caused the once sandy stream bed to be flushed away leaving a deep cobble bed pool. The changes were severe enough that monitoring sensors were relocated. Post effect of the wash-out bank showed elevated turbidity events up to June 1998 (Fig. 5.9). A fine coating of silt

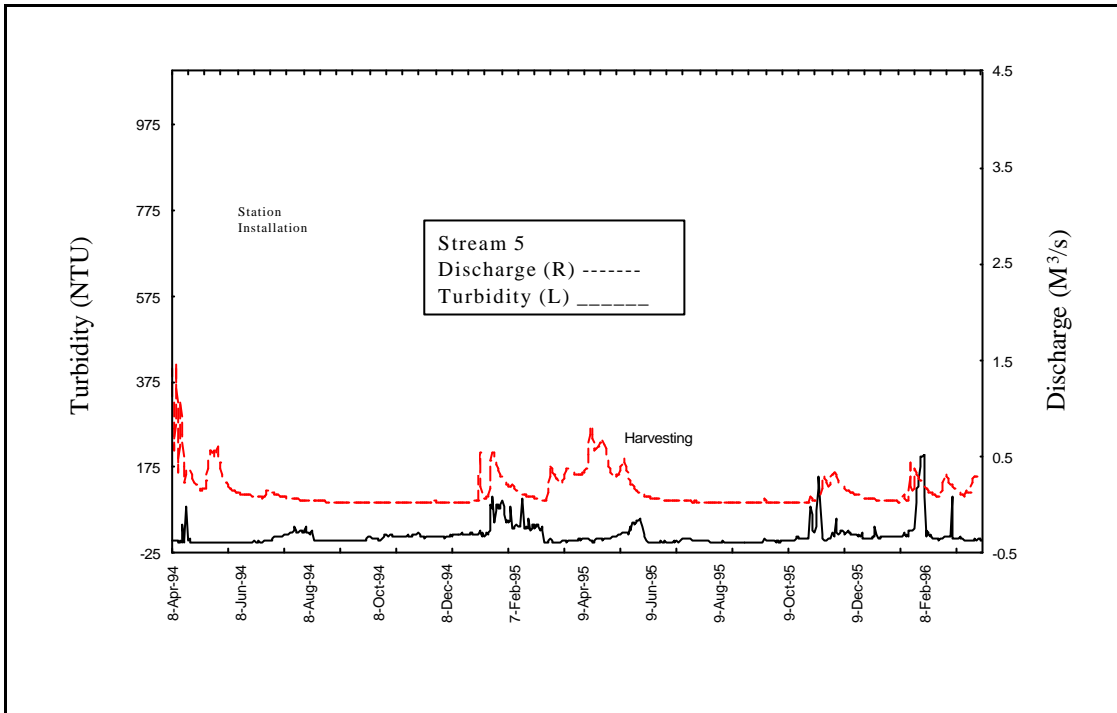


Fig. 5.7. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 5 of Hayward Brook during April 1994 to March 1996.

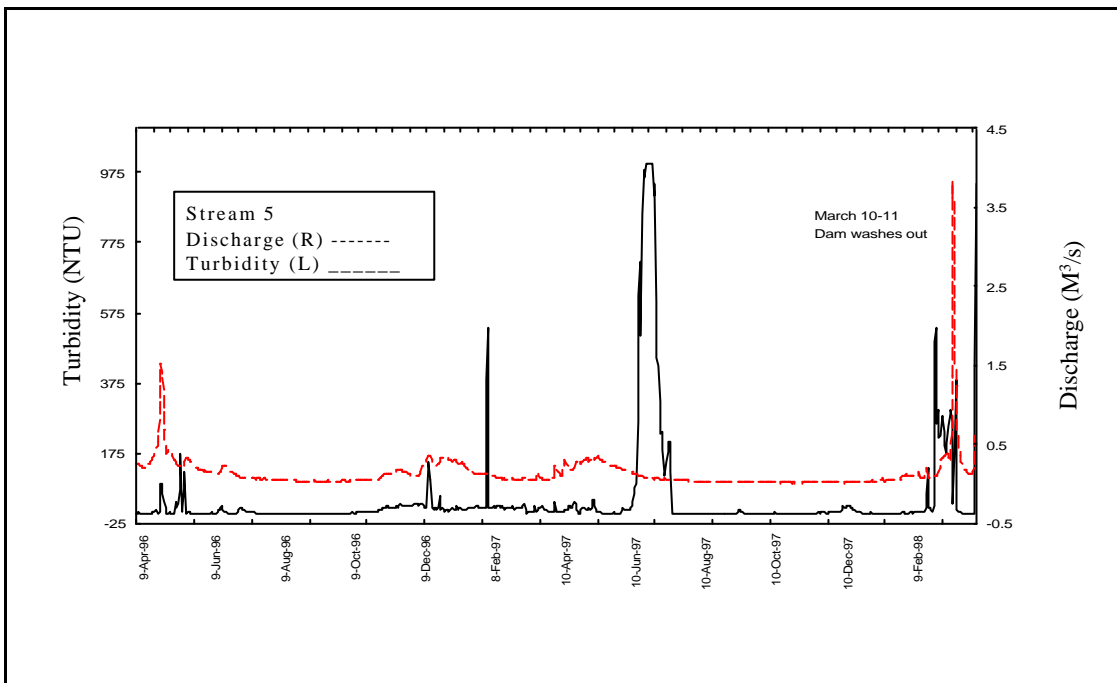


Fig. 5.8. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 5 of Hayward Brook during April 1996 to March 1998.

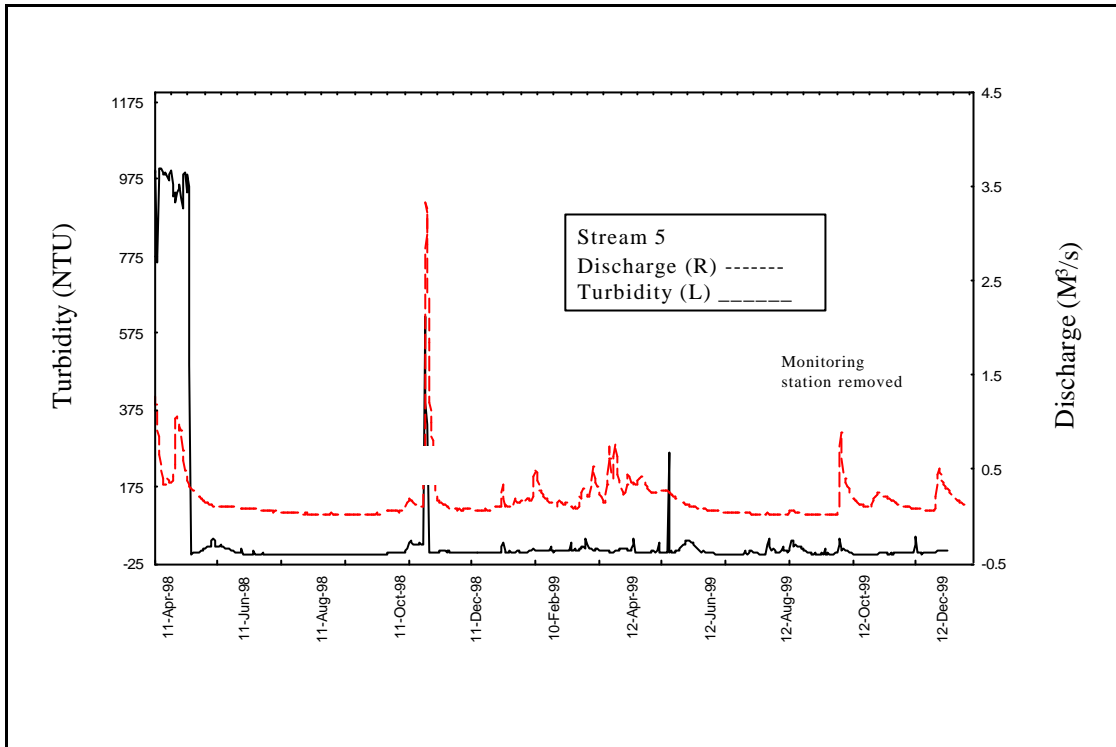


Fig. 5.9. Land-use and associated (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 5 of Hayward Brook during April 1998 to March 1999.

generally found on the sensor during low flow was attributed to bank erosion and occasional use of a recreational road (Fig.5.10 - photo 2).

The lack of corridors in this basin is considered to be one of the main reasons for low turbidity. The Parry forest soil units (Fig.3.4) located in this watershed have a loamy-sand consistency and moderate drainage (Fig. 3.5). These conditions normally enhance erosion. Had more soil been exposed, increased turbidity and sedimentation would be expected. Poor drainage is often seen in this watershed during wet periods when the road conditions quickly change from dry to greasy and, heavy rutting occurs (Fig 5.10 - photo 3).

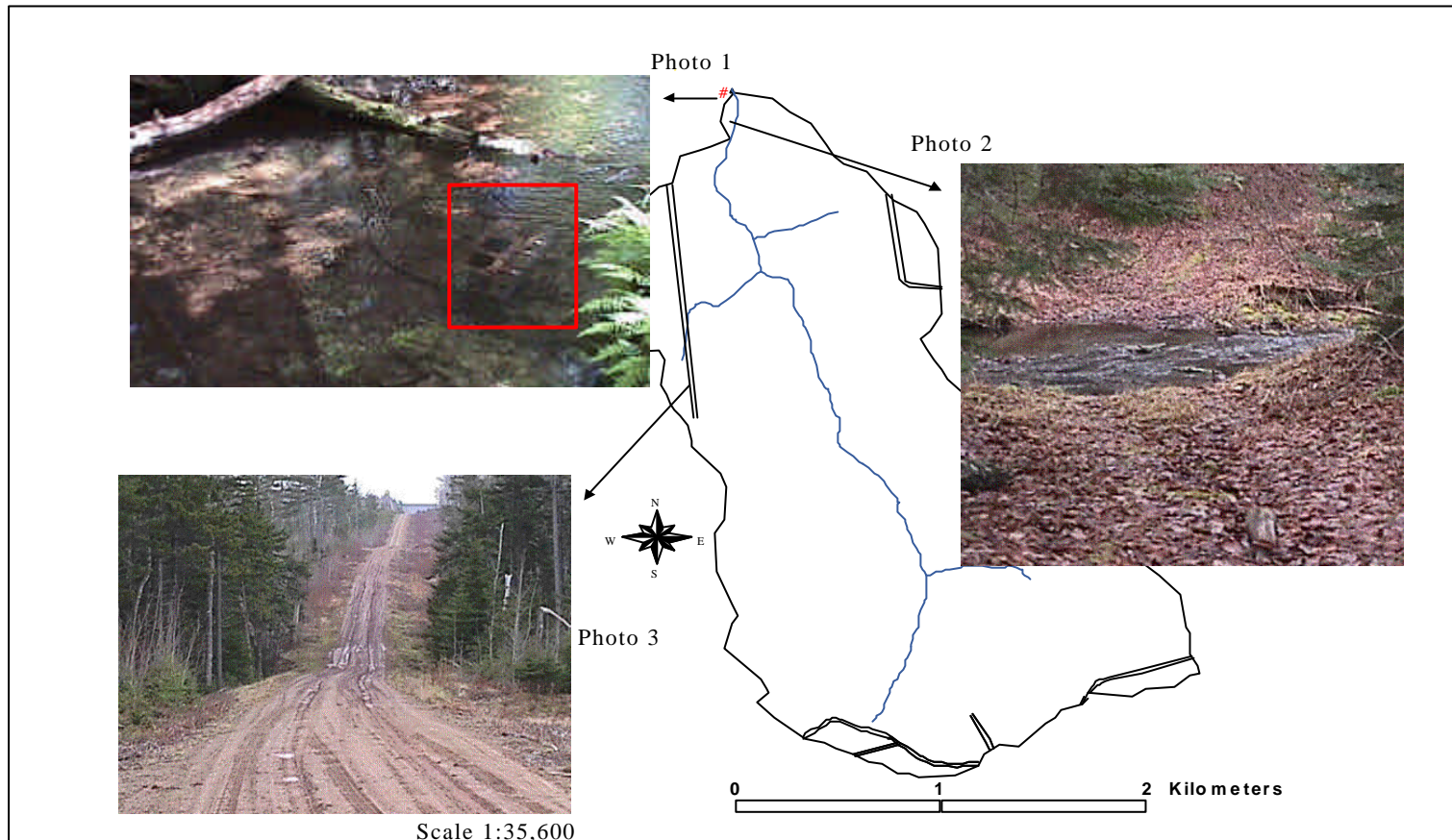


Fig. 5.10. Minor land-use in Stream 5 of Hayward Brook (size – 7.2 km²).

Photo 1: (see red square) - water monitoring probe.

Photo 2: Infrequent used recreational road located 50 meters above monitoring pool.

Photo 3: Commercial road intersecting watersheds 5 and 6. Stream 9

Stream 9

Monitoring in stream 9 began in 1995, a year later than in the other streams. This delay resulted in monitoring beginning two months before major land-use change. The watershed is the second largest within the study area, and shows a highly active turbidity signature (Fig. 5.2 – third from top). Elevated turbidity events are found throughout the study (Figs. 5.11, 5.12, 5.13).

Elevated turbidity within the stream is caused by high amount of newly exposed soils from commercial roads (Fig. 5.14). One major source of erosion was from an access road built in April 1995 (Fig. 5.14 - photo 3). Although ditches were placed along each side of the road, they provided little resistance to water flow because of the high slope (Fig. 3.8). Large amounts of soil were eroded with each storm (Fig. 5.14 - photos 2,5). Poor culvert location was also found to cause high stream turbidity. The culverts were placed perpendicular to the stream allowing high runoffs to flow through the stream buffer (Fig. 5.14 - photos 5). Large turbidity events were recorded each spring (Fig. 5.12, 5.13).

A second area of high erosion was a culvert on a main commercial road (Fig. 5.14 – photo 4). The photograph shows exposed soil that was washed into this tributary with each storm. This area was expected to be responsible for the April 1998 turbidity event (Fig. 5.13).

The monitored pool was not considered as a sediment source for it was located within a straight stretch of stream, and had a sandy-cobble substrate and vegetated banks (Fig. 5.14 - Photo 1).

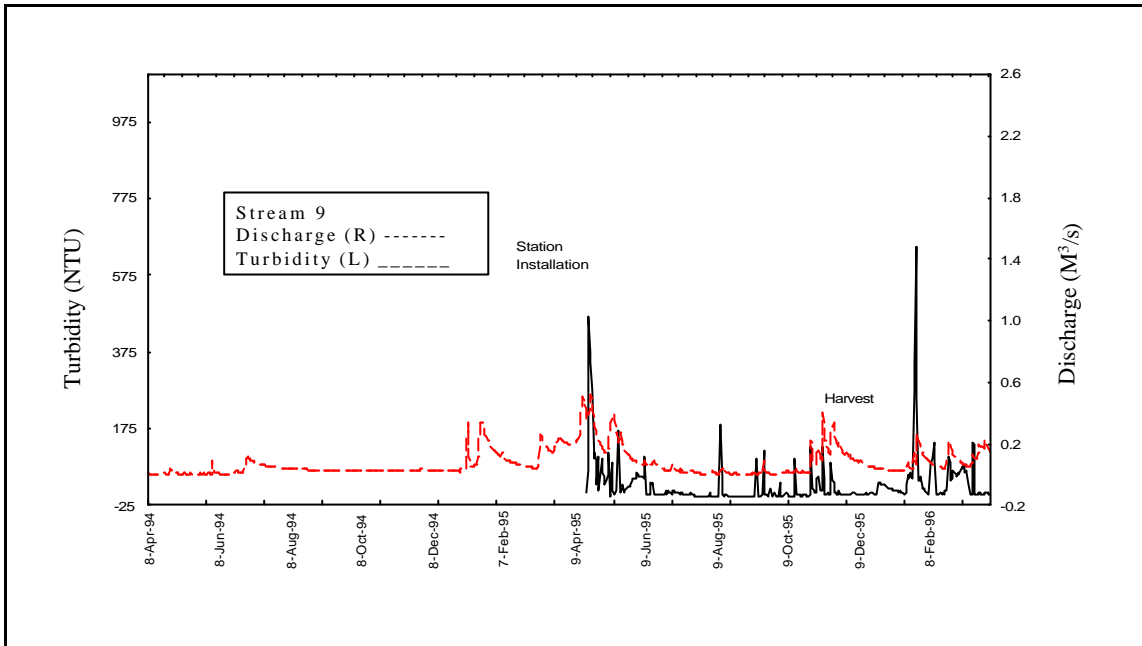


Fig. 5.11. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 9 of Hayward Brook during April 1994 to March 1996.

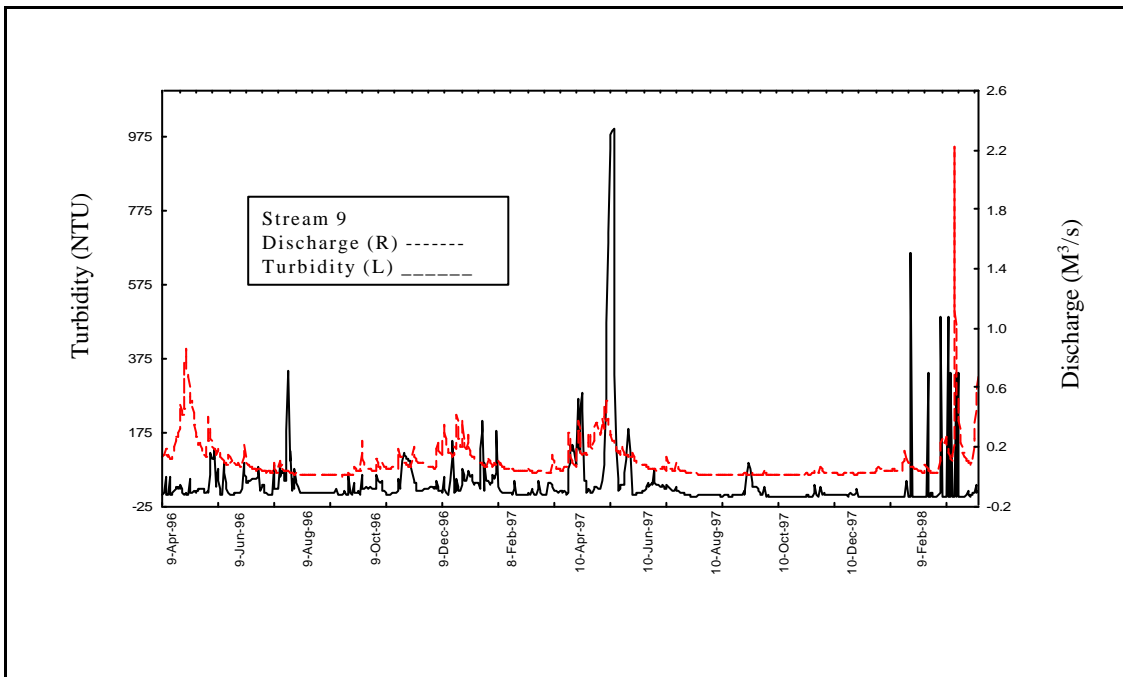


Fig. 5.12. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 9 of Hayward Brook during April 1996 to March 1998.

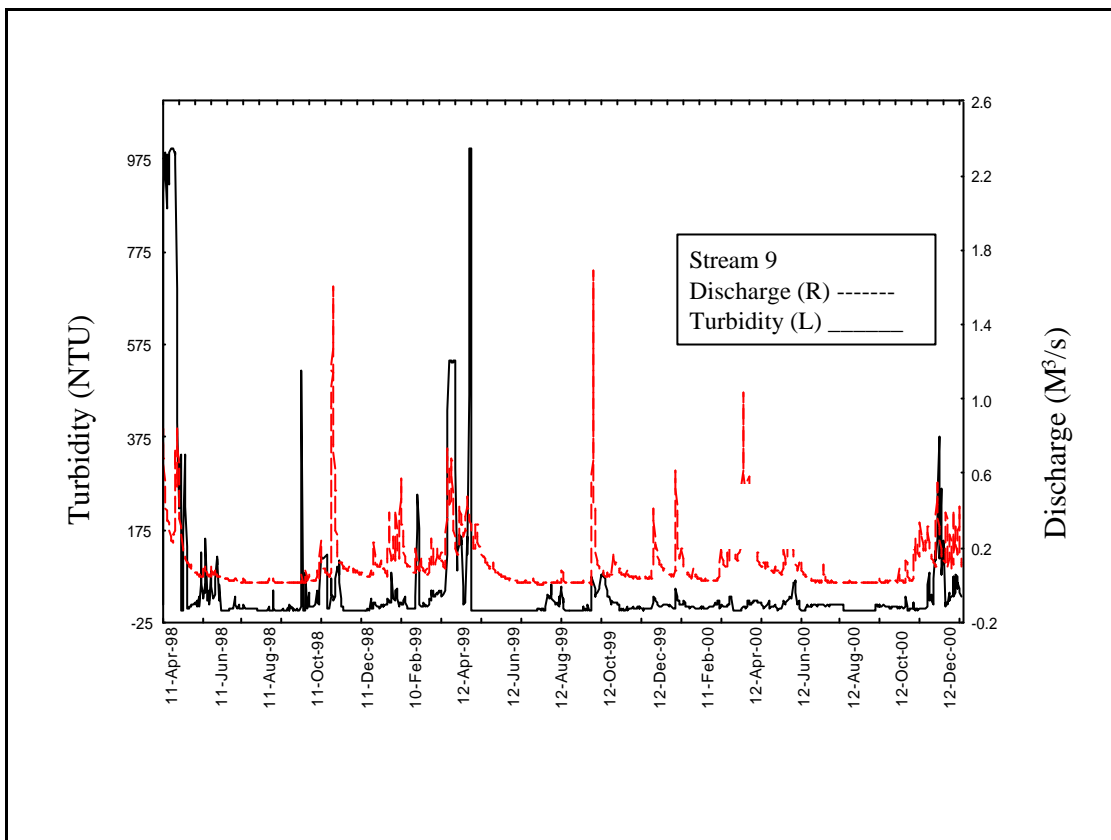


Fig. 5.13. Land-use and associated turbidity (NTU) and daily ($\text{m}^3 \text{s}^{-1}$) for Stream 9 of Hayward Brook during April 1998 to March 2000.

The elevated turbidity found in this stream is enhanced by the varying slope and sandy-clay-loam Salisbury soils, which become saturated quickly causing increased surface runoff and soil erosion (Figs. 3.3, 3.8).

Stream 4

Streams 4, the smallest watershed in the study produced the second most active turbidity signature (Fig. 5.2 – fourth from top). The slope of the cumulative turbidity curve is similar to Stream 6 indicating the similarities between turbidity concentrations

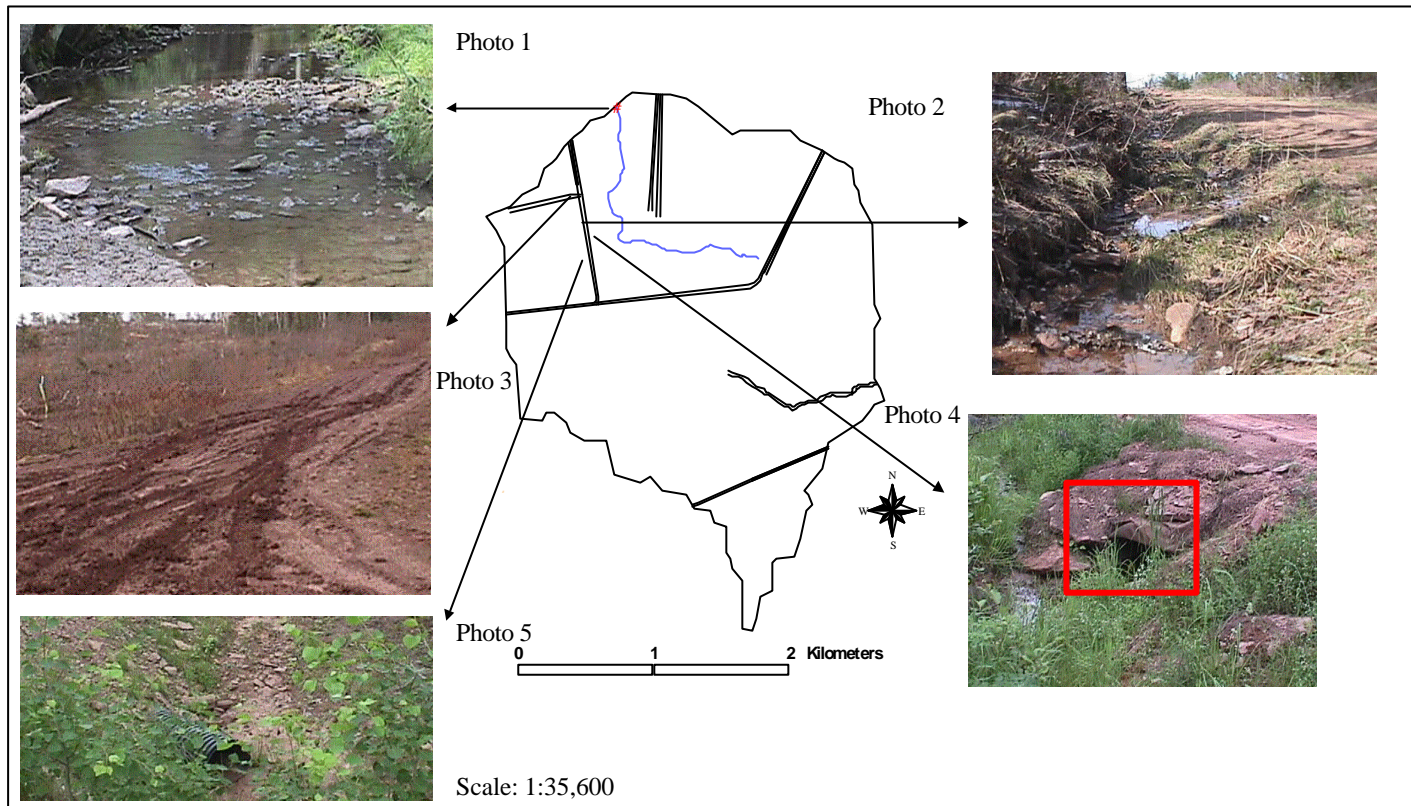


Fig. 5.14. High land-use in Stream 9 of Holmes Brook (size – 6.0 km²).
 Photo 1: monitoring pool. Photo 2: Ditch erosion. Photo 3: Rutting.
 Photo 4: (see red square) - Culvert erosion. Photo 5: Sediment filled ditch.

resulting from natural and land-use changes. The cumulative turbidity curve when extended past the 1997 data, shows concentrations up to 150,000 NTU may have occurred by the year 2000 (Fig. 5.2).

Turbidity concentrations were normally low with clusters of elevated concentrations (Figs. 5.15, 5.16). As no land-use had occurred in this basin during the study period the major causes of turbidity were bank erosion adjacent to the monitoring pool (Fig. 5.17 – photo 2), and the pool acting as a sediment sink.

Bank erosion resulted from incoming water flowing directly into a stream bank (Fig. 5.17 – photo 2). The freed sediment are captured in a vortex created by the L –shaped pool, causing elevated concentrations to remain longer. The pool becomes a sediment sink. The series of elevated turbidity events that occurred over several months in 1996 and 1997 are in response to road construction (Fig. 5.16, 3.11). Had monitoring for this stream occurred in straight pool the turbidity signature would have been significantly less active.

Stream 6

Stream 6 is the second smallest watershed, and had the most active turbidity signature (Fig. 5.2). Elevated turbidity events were found during station installation, road construction, and during forest harvesting (Figs. 5.18, 5.19, 5.20). This watershed has a large area in corridors, and continuous usage by commercial or recreational vehicles provide a continuous source of newly exposed soils. A county road located in the high

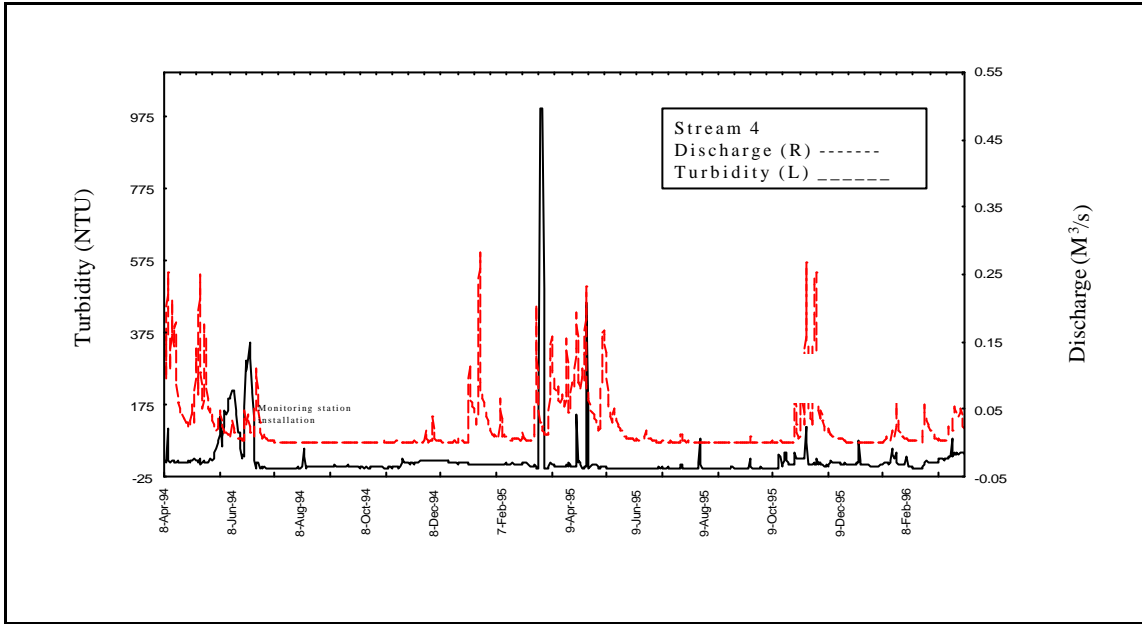


Fig. 5.15. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) in Stream 4 of Hayward Brook during April 1994 to March 1996.

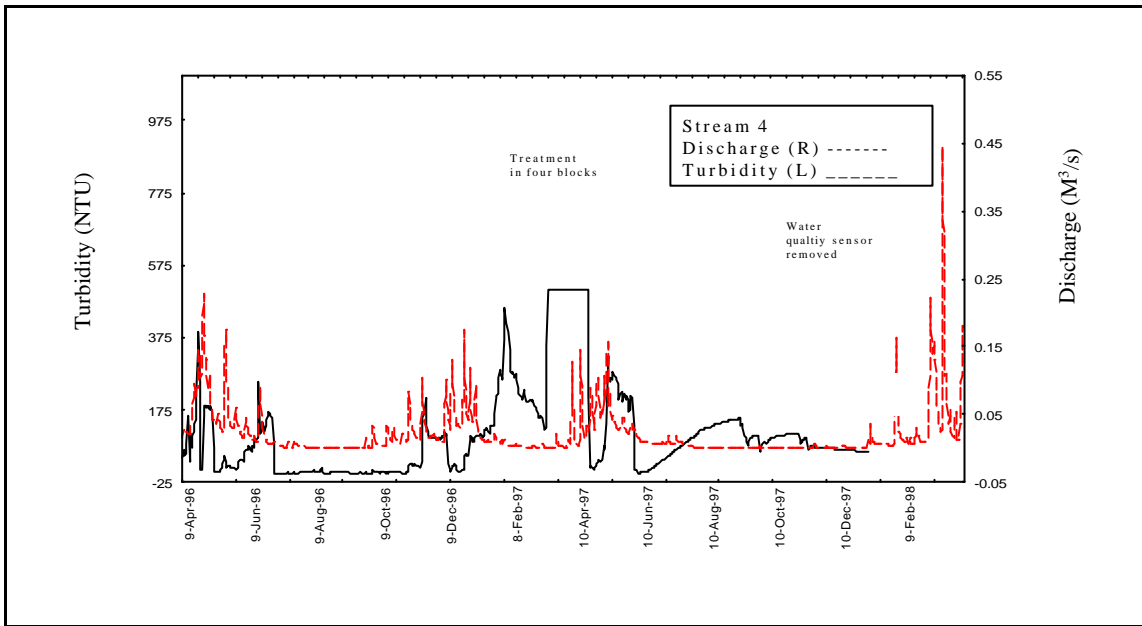


Fig. 5.16. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 4 of Hayward Brook during April 1996 to March 1998.

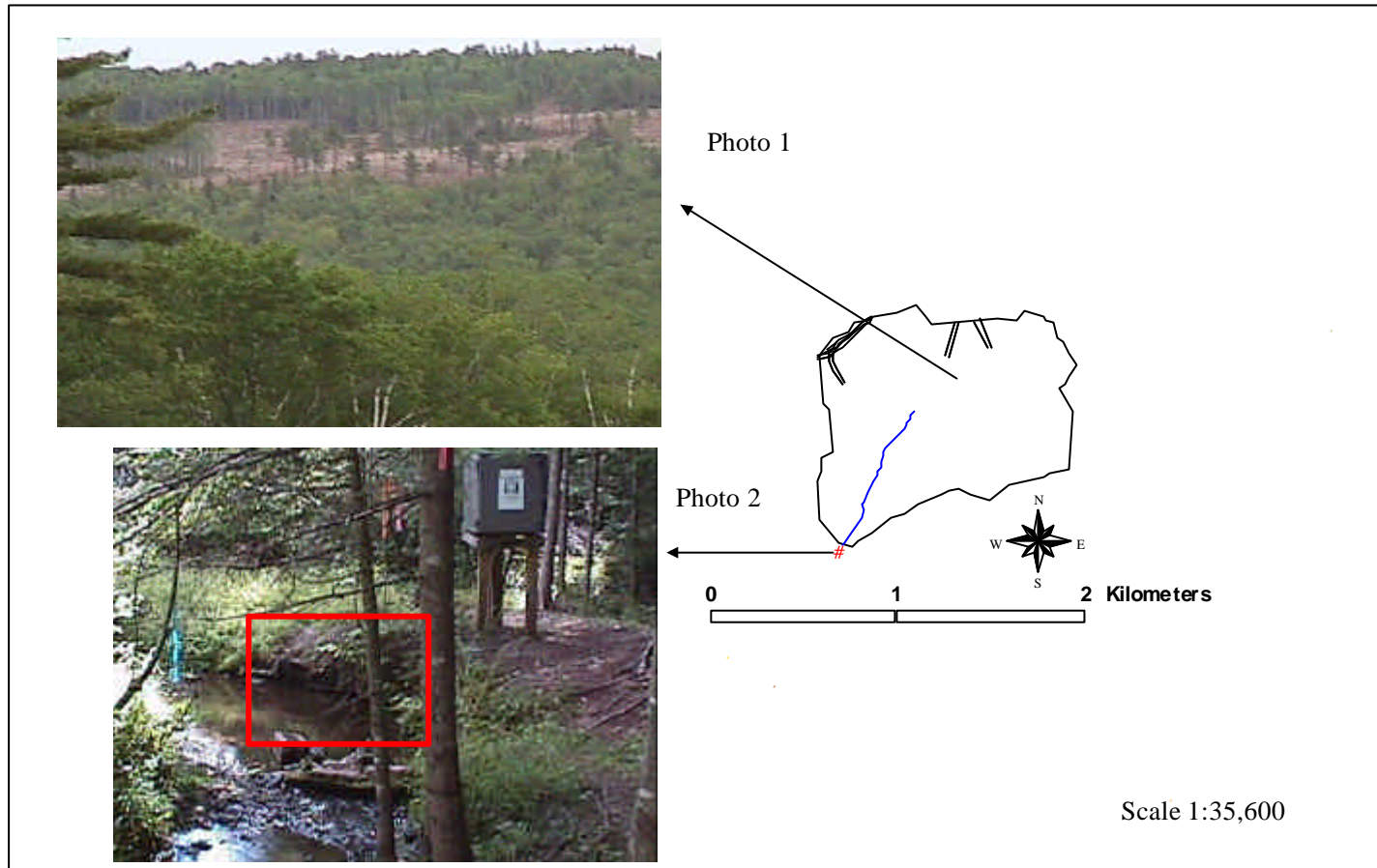


Fig. 5.17. Stream 4 of Hayward Brook (size - 1.6 km²).
Photo 1: Blocks of forest harvested in 1998.
Photo 2: (see red square) - Bank erosion in the monitoring pool.

slopes of the north-west region was the main source of sediments throughout the study period (Fig. 5.21 - photo 3, Fig. 3.8). Each time a vehicle drove over the road more sediment was exposed and loosened, allowing significant amounts to flow downward and into the stream.

Other structures such as a galvanized culvert installed in a commercial road (Fig. 5.21 - photo 1), and a geo-textile road-bank cover (Fig. 5.21 - photo 2) did not appear to be a sediment source.

Probe location was not a sediment source although, sand did collect in the lower end of the pool. Fine sediments and silts were generally washed away by high discharge events.

SUMMARY

The turbidity signatures for each of the HBWS streams indicate that concentrations within each basin are primarily driven by watershed attributes and land-use change. In highly used basins, the turbidity signature is very active throughout the year. Whereas, in basins with low activity the signatures were generally mild. In this case study both historic and new roads were found to be major sources of sediments. The amount of sediment from each was determined by the amount of road usage. Commercial roads were generally found to be a sediment source over a short period. These roads could be used often or seasonally, but in both cases, problems were quickly fixed once identified.

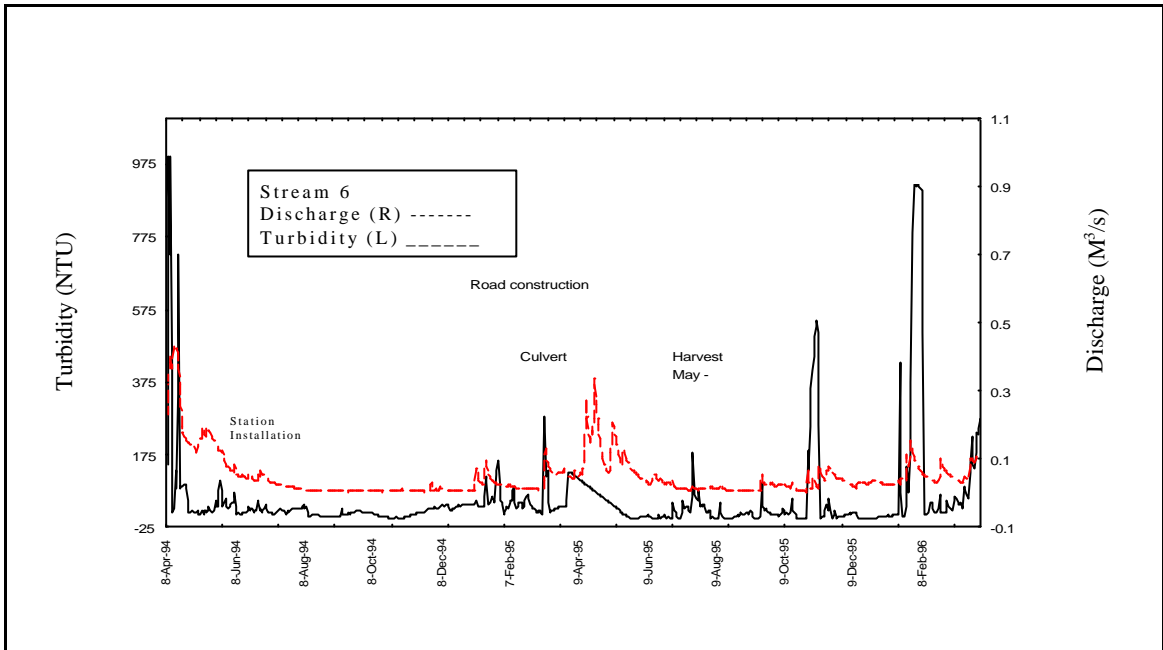


Fig. 5.18. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 6 of Hayward Brook during April 1994 to March 1996.

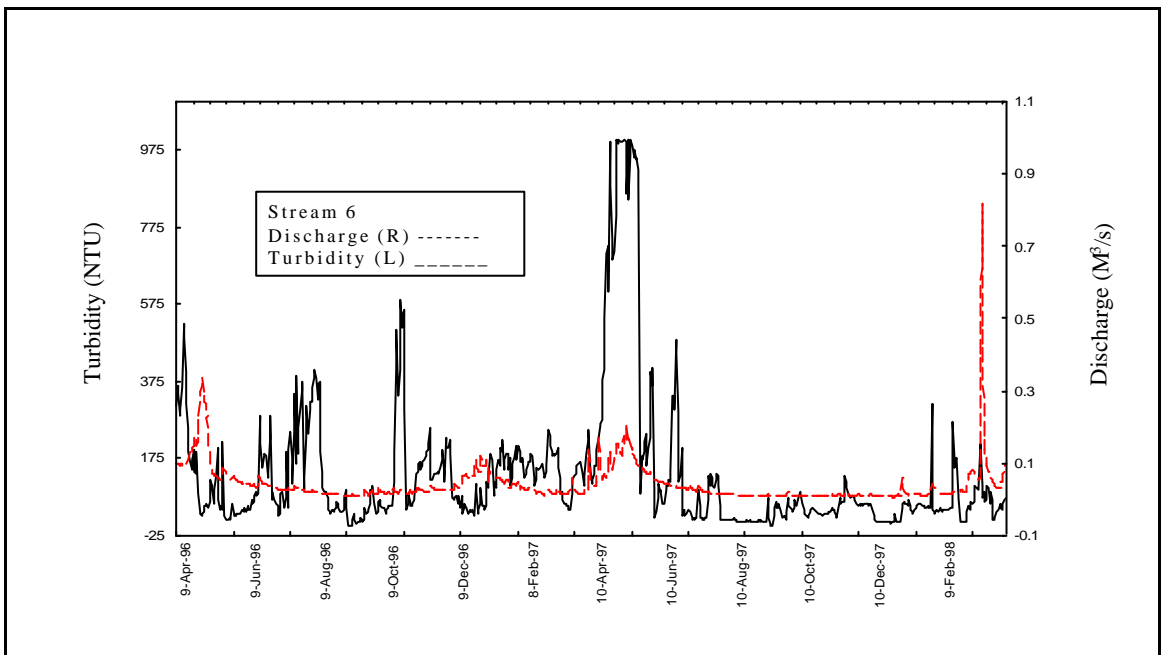


Fig. 5.19. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 6 of Hayward Brook during April 1996 to March 1998.

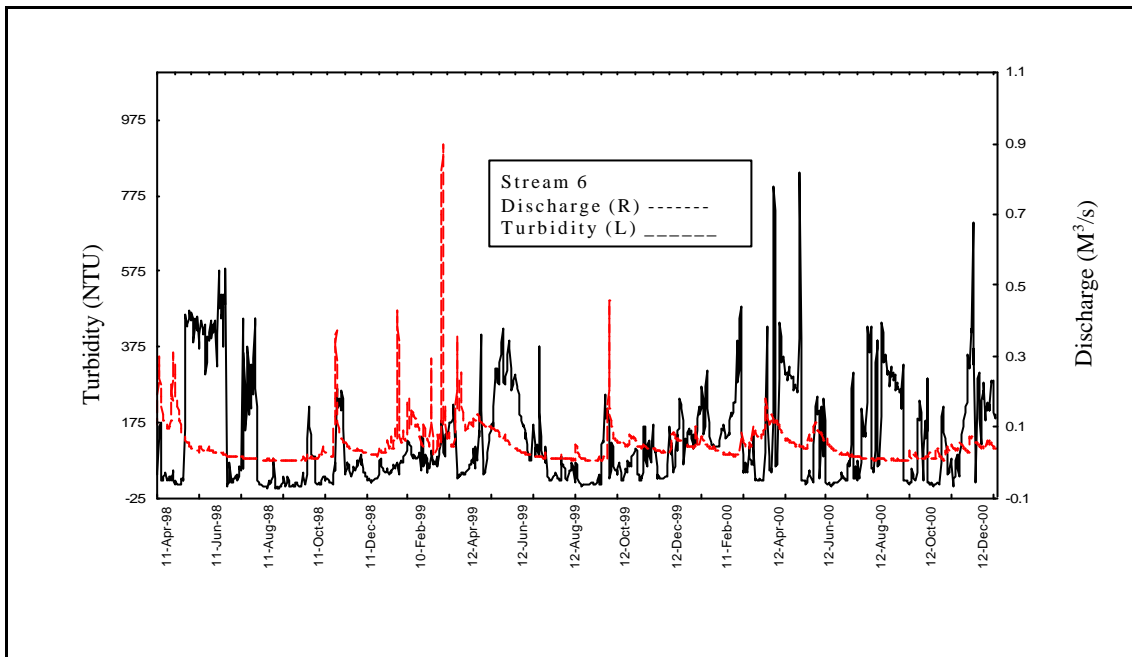


Fig. 5.20. Land-use and associated turbidity (NTU) and discharge ($\text{m}^3 \text{s}^{-1}$) for Stream 6 of Hayward Brook during April 1998 to March 2000.

Historically placed roads which were generally built on high slopes, and without culverts are continuously used by recreational users. This usage continuously loosens and exposes soils causing a continuous sediment source. Problems identified on these roads are generally not fixed, and provide high sediment to adjacent streams throughout the year. Probe location was also found to be significant when monitoring stream turbidity. The stability of stream banks and stream structures are difficult to determine, and eventually were found to collapse causing elevated turbidity.

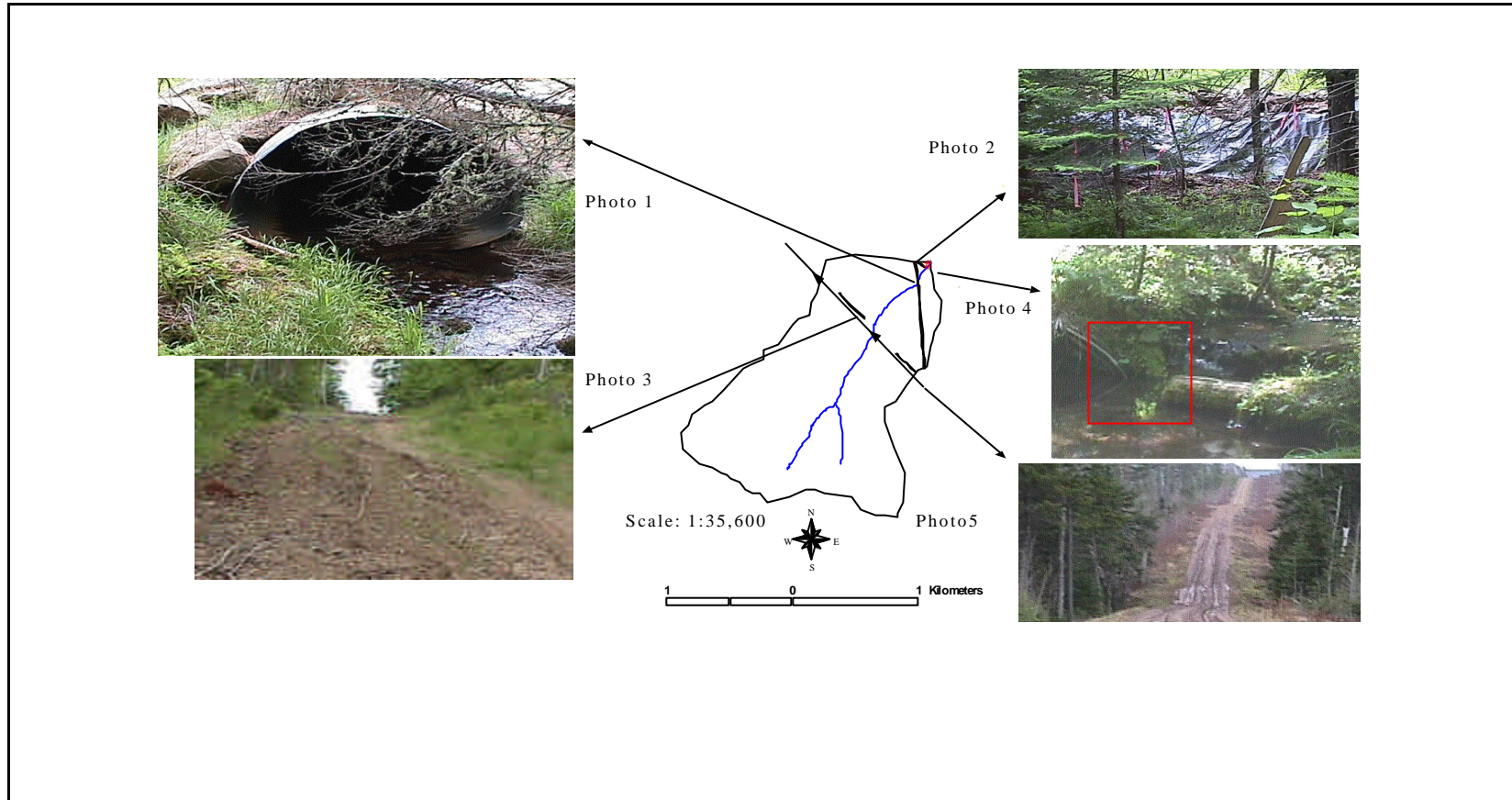


Fig. 5.21. High land-use in Stream 6 of Hayward Brook (size – 2.3 km²).

Photo 1: Galvanized road culvert placed 100 meters above monitoring station.

Photo 2: Geo-textile placed 50 meter above monitoring station.

Photo 3: Heavy erosion from a recreational road located 1000 meters above monitoring station.

Photo 4: (see red square) - Water monitoring probe at lower left.

Photo 5: Commercial road built in May 1995.

CHAPTER 6

SUSPENDED SEDIMENT FLUX

INTRODUCTION

Turbidity has been shown to be a useful index variable for assessing the amount of suspended sediment in stream water (Gray 1970, Inland Waters 1979, Fattorelli *et al.* 1988, Gomez and Church 1989). This was found to be particularly true when particle properties remain relatively constant over a wide range of sediment concentrations (Gippel 1995). Assuming this to be true for the streams of this case study, then the turbidity signature from each of the HBWS streams could potentially be used to estimate the corresponding amounts of suspended sediments. This Chapter deals with:

- establishing the relationship between suspended sediment concentrations (SSC) and stream turbidity,
- calculating the annual sediment flux for each of the five streams,
- calculating the seasonal sediment flux for each of the five streams.

METHOD

Seventy suspended sediment samples were collected from the five streams in the HBWS case study over the course of 6 years. Sampling was aimed at incorporating as many periods as possible during which high turbidity events occurred, or when high events would be a

distinct possibility, based on on-going activities within the watersheds. Sampling involved a hand-held sampler and 1 litre glass bottle which was moved up and down the water- column within a one minute interval (Inland Waters 1982). Glass bottles were used to prevent suspended material from adhering to the container walls. The amount of suspended sediment and volume of water were used to calculate the suspended sediment concentration in mg l¹ (Environment Canada 1999).

The amount of suspended sediment was determined gravimetrically. The technique involved:

- Removal of non-homogenous materials;
- Samples need to be stored at 4° Celsius to minimize microbiological growth;
- Analyses within 24 hours of collection;
- Filtration at room temperature;
- Prior to use, filters need to be washed in de-ionized water, and dried for 2 hours at 105 +/- ° C.
- Filters need to be weighed to +/- 20 mg and stored in desiccator;
- Samples need to be inverted 20 times, and then poured through the filter. Filtration should be completed within one minute.
- Filters need to be dried in an oven for 2 hours prior to weighting.

Concentrations were calculated in terms of mg total suspended solids / sample volume filtered (ml).

SUSPENDED SEDIMENT REGRESSION

Inspecting the results indicated that suspended sediment concentration range in the Hayward Brook study was between 1 to 32 mg l⁻¹, and only one other concentration at 272 mg l⁻¹. The lack of samples that represent high suspended sediment concentrations was problematic in terms of establishing a reliable regression equation between turbidity and sediment concentration: essentially, the entire regression results would simply depend on only the highest concentration sample. Since the relationship between sediment concentration and turbidity should be the same for forest streams in general, a search for additional data was initiated, and an extensive dataset for turbidity and suspended sediment concentrations was obtained for the Fresh Water Creek Study in California (PALCO 2002). The Fresh Water Creek data provided a wide range of sediment concentrations that would allow the regression to better represent high suspended sediment concentrations (Fig. 6.1, Appendix 3).

The HBWS turbidity values are generally lower for the corresponding suspended sediment value when compared to the Freshwater Creek data (Fig. 6.1). Further investigation into this relationship revealed that a sampling inconsistency was present in the protocol used in the HBWS. In this protocol, turbidity values were based on averaged daily turbidity, whereas, the suspended sediment sample represents one instant within the 24 hour period. From this dataset, the following non-linear equation was obtained by way of non-linear regression:

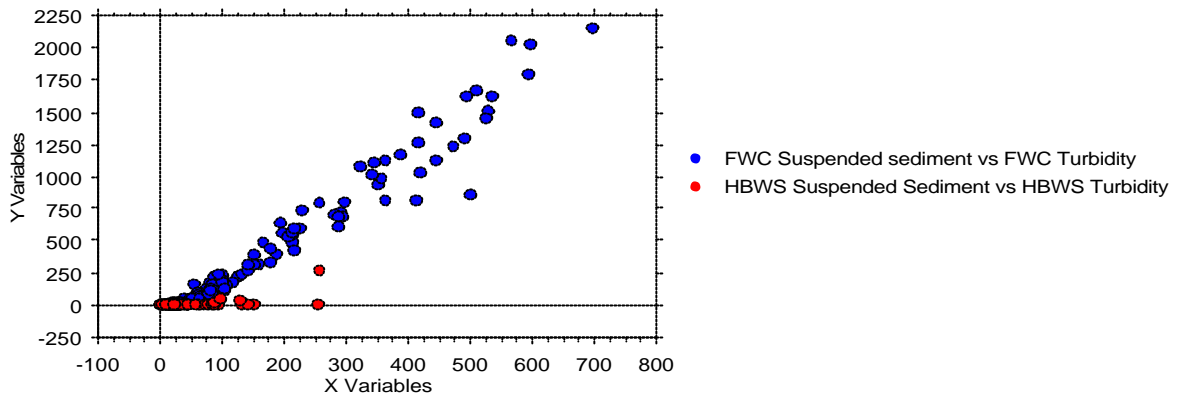


Fig. 6.1. Scatterplots of suspended sediment (mg l^{-1}) versus turbidity (NTU) for streams of the Hayward Brook Watershed Study and the Fresh Water Creek Study.

Suspended sediment concentrations (SSC, mg/l) =

$$(2.79 \pm 0.05) * \text{turbidity (NTU)} * \{1 - \exp [- (0.0069 \pm 0.0004) * \text{turbidity (NTU)}]\}$$

($r^2 = 0.978$) Eq. 6.1

The resulting scatterplot of observed versus predicted concentrations of suspended sediment is linear, and passes through the origin (Fig. 6.2).

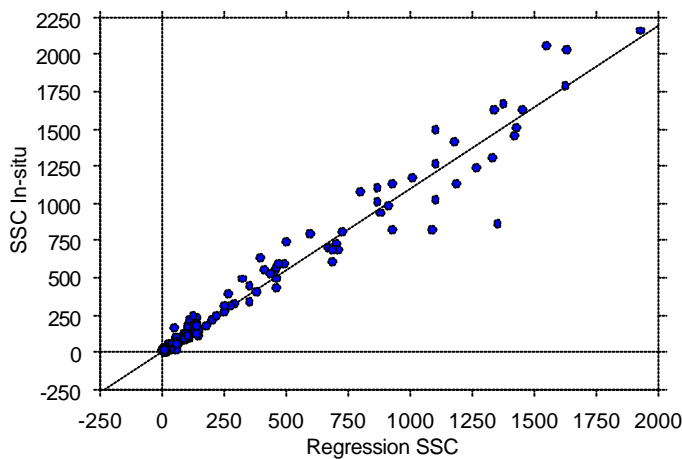


Fig. 6.2. Scatterplot of actual versus best-fitted suspended turbidity-derived sediment concentrations, using Equation 6.1. The effectiveness of Equation 6.1 is demonstrated by the fact that this scatter plot is linear, and passes through the origin.

The non-linearity of Equation 6.1 prohibits a straightforward conversion of averaged turbidity measurements to average suspended sediment concentrations. Instead, it is necessary to convert each individual turbidity measurement into an equivalent suspended sediment concentration number.

SUSPENDED SEDIMENT FLUX CALCULATIONS

Each consecutive stream turbidity reading was converted into its corresponding suspended sediment concentration with equation 6.1. Daily sediment fluxes were then calculated as follows (Gray 1970, Porterfield 1972, Inland Waters 1982):

$$Q_s = Q_w * SSC * K \quad (6.2)$$

where

Q_s = sediment [$Mg \text{ day}^{-1}$],

Q_w = mean daily discharge ($m^3 \text{ s}^{-1}$),

SSC = mean daily suspended sediment ($mg \text{ l}^{-1}$),

K = unit conversion factor 0.0864 (= $60 * 60 * 24 / 1,000,000$)

Summing daily discharge over the days of turbidity record gives total sediment loss from each basin. Dividing the resulting numbers by watershed area and years of recording gives average annual sediment loss for each watershed, per hectare.

RESULTS AND DISCUSSION

Performing multiple regression analyses on the Fresh Water Creek data revealed that turbidity was strongly associated with the suspended sediment concentrations ($r^2 = 0.978$). The analyses further revealed that the relationship between suspended sediment concentration (SSC) and turbidity is essentially linear, except near the origin, where SSC approaches 0 asymptotically with decreasing turbidity. A near linear relationship at high SSC values is to be expected, because increasing particle concentrations would linearly increase the overall contribution of scattered light from the individual particle surfaces near the light source and near the light detector. At low concentrations, light scattered from a few suspended particles reaches the light detector in the least obstructed way from the entire volume of sample. Some of the unaccounted variation in the actual versus predicted regression plot are likely due to temporal and spatial variations; eg. the influence of colour, particle composition, refractive index, and size and shape of the suspended sediments, as well as dissolved air, including gas bubbles on the turbidity sensor lens (Anderson and Potts 1987, Gippel 1995). Studies have found that stream water composition strongly varies between low and high flow conditions, containing increased concentrations of organic and inorganic material under low flow conditions (Bilby and Likens 1979). Organic particles have a greater total scattering area than mineral particles due to their fluffy surface texture (Gippel 1995). Season also adds to overall turbidity causing more particles of lower density to be present in stream water during periods of rain, due to atmospheric deposition and due to surface run-off from organic soil surface layers.

ANNUAL AND SEASONAL SUSPENDED SEDIMENT FLUX

Annual sediment fluxes for the 5 streams ranged between 0.3 to 2.14 Mg ha⁻¹ yr⁻¹ (Table 6.1). The highest flux was found on the stream with the most active turbidity signature (Fig. 5.1). For example, the frequent use of the roads lead to Stream 6 causes the flux to be twice as much in this stream than in the other four streams. The lowest sediment fluxes occurred in Stream 1. Although harvesting occurred in this watershed, road construction was minimal.

Table 6.1: Sediment losses from each of the 5 streams in the Hayward Brook Watershed Study Area (1994 to 2000).

	1	4	5	6	9
Total loss (Mg) over recorded period	837	336	6112	3223	4062
Watershed area (ha)	480	160	720	230	600
Period of record (year)	5.1	3.7	5.7	6.7	6.7
Total loss [Mg/ (ha year)]	0.34	0.56	1.49	2.08	1.01

The second lowest flux found in Stream 4 was the result of stream channel erosion. The flux of 1.49 and 1.01 Mg ha⁻¹ yr⁻¹ found in Streams 5 and 9 resulted from changes in channel structure and road induced erosion. The difference between these scenarios is that - in Stream 5 - the flux resulted from a one or two single events of high turbidity whereas - in Stream 9 - elevated turbidity was more frequent.

Seasonal sediment fluxes were highest during April to June (Table 6.2). Snow-melt and heavier rains, plus loosening of stream banks and streambeds during periods of turbulent and forceful streamflow, were likely responsible for elevating these fluxes. The lowest flux occurred during the drier summer season. Although sediment flux was low during this period, road construction, and dust generated from road traffic loosened soils and provided ample supply of

sediments for the fall season. In the fall, the reduced evapotranspiration, and increasing soil saturation flush loosened sediments into the streams where they were then transported downstream.

Table 6.2: Seasonal sediment flux ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) for streams in the Hayward Brook Watershed Study Area (1994 to 2000).

	1	4	5	6	9
January – March	0.0001	0.0009	0.0003	0.002	0.0004
April – June	0.0004	0.0020	0.0001	0.0060	0.0010
July – September	<0.0001	<0.0001	<0.0001	0.0003	<0.0001
October – December	0.0002	0.0002	0.0002	0.0008	<0.0001

*Season is based $\frac{1}{4}$ year

CONCLUDING REMARKS

The use of the Fresh Water Creek dataset to estimate suspended sediment concentrations for the Hayward Brook Watershed Study produced a non-linear regression equation between suspended sediment concentrations and stream turbidity measurements, with an $r^2 = 0.978$. This non-linearity prohibits a straightforward conversion of averaged turbidity measurements to average suspended sediment concentrations. Instead, it is necessary to convert each individual turbidity measurement into an equivalent suspended sediment concentration number.

The final sediment yield numbers in Tables 6.1. and 6.2 must be considered as setting upper limits of the actual sediment yields that may have occurred in each of the 5 streams. The label “over-estimate” is used to account for the uncorrected and inconsistently high background

levels of the various turbidity signatures. These backgrounds would mainly be due to slow but persistent fouling of the NTU sensors. Occasionally, the NTU sensors may have missing the upper portions of high turbidity events, because of the upper detection limit of 1000 NTU. On balance, however, some of these events may also have been over-determined due to extended blockages of the sensors.

CHAPTER 7

UNIVERSAL SOIL LOSS EQUATION

INTRODUCTION

In this Chapter, the Universal Soil Loss Equation (USLE) is applied to the watersheds of the Hayward Brook Watershed Study to determine suspended sediment flux as expected for this configuration. The USLE and revised equation (RUSLE) are decision-making tools generally used for soil conservation planning on agricultural lands (USDA 2000). It has been shown to be applicable for estimating erosion and sediment yields on rangelands, forested areas, and urban sites (Kirby and Mehuys 1987, Chow *et al.* 1990, Salehi *et al.* 1990, Renard *et al.* 1991, Coote *et al.* 1992, Wang *et al.* 2000).

With the application of the USLE to the conditions within the HBWS, marked differences in each setting must be noted. The USLE was designed to predict erosion from an open field configuration where sheet, rill, and gully erosion are the major causes for soil erosion. Values used in each of the USLE factors are calculated in experimental settings. Each setting allows characterization of a particular soil and land-cover type, within a standardized study plot of 9% slope and 22 meters in length. By applying USLE factor values to best fit the conditions within an area, the USLE provides an estimate of soil loss.

Several combinations of conditions exist within the HBWS. Within the 30 km² area, a mixed Acadian forest grows on one of three forest soil units (see Chapter 4). Soil erosion within each watershed is not uniform, but occurs in selected areas of exposed soils; e.g. roads.

The slope and slope-length is not uniform, but changes significantly throughout the watershed, and within erosion areas.

Generally, the landscape condition within the HBWS could be best described as natural, and observed sediment flux is the result of erosion from specific areas, and stream structure change. In selected watersheds continuous road usage by commercial and/or recreational vehicles, plus road-related maintenance are the major causes exposing soil.

Briefly the USLE uses five variables to estimate potential soil loss (PSL) as follows (Table 7.1):

$$\text{PSL (Mg ha}^{-1} \text{ yr}^{-1}) = \text{rainfall erosivity [MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}] * \text{soil erodibility [Mg h MJ}^{-1} \text{ mm}^{-1}]$$

* slope length-steepness factor * cover type factor * supporting practices factor (7.1).

Table 7.1: Watershed specific properties in the Hayward Brook Watershed Study Area.

	1	4	5	6	9
Rainfall erosivity	2000	2000	2000	2000	2000
Soil erodibility	0.03	0.03	0.03	0.03	0.03
Slope-length factor	3.0	4.0	5.0	5.0	3.0
Cover type factor	0.001	0.001	0.001	0.001	0.001
Watershed area (ha)	480	160	720	230	600
Slope length (km)	1.0	0.5	0.25	1.0	0.5
Area harvested (%)	2.0	0.0	7.0	17	12
Exposed soils (ha)	38	26	29	9	60
Land-use rating	min.	min.	min.	high	med.

RAINFALL EROSION INDEX (R-FACTOR)

The rainfall erosivity factor [MJ mm ha⁻¹ h⁻¹ yr⁻¹] characterizes impact of rainfall energy on soil erosion using maximum 30 minute storm intensity (mm h⁻¹), and rainstorm kinetic energy

(MJ ha⁻¹) (Gordon and Madramootoo 1988). Large amounts of soil are lost when intense rainfalls occur over bare soils. Such intense rain events destroy soil granulation, splashing particles up to 70 cm vertically, and 200 centimeters horizontally (Renard *et al.* 1991, Brady and Weil 1999). The dispersed soil dries into a hard crust, which in-turn interferes with seed emergence, vegetation growth, and enhances runoff (Brady and Weil 1999). Values for this factor can vary, being affected by climate, seasonal rainfall distribution, and the ability of soil substrate to absorb the raindrop impacts (Renard *et al.* 1991, Brady and Weil 1999). In northern New Brunswick, 72% of seasonal variations in soil loss were explained by the rainfall erosivity factor (Chow *et al.* 1990).

The HBWS area is represented by a 35.4 km² polygon in the Canadian soil erosivity maps (Coote *et al.* 1992). This area has erosivity value of 2000 MJ mm ha⁻¹ h⁻¹ yr⁻¹, thus representing a 'severe risk' for soil erosion. Most of New Brunswick is rated high, with only an area near Tracadie (northern N.B.) being rated as low. The Fredericton area is rated slightly lower at 1550 MJ mm ha⁻¹ h⁻¹ yr⁻¹. In northern NB, lower slopes cause erosivity to be at 930 MJ mm ha⁻¹ h⁻¹ yr⁻¹. In P.E.I., values ranges between 1000 to 1100 MJ mm ha⁻¹ h⁻¹ yr⁻¹.

Gordon and Madramootoo (1988) recalculated the erosivity values for Atlantic Canada adjusting for snowmelt and runoff from unfrozen ground. These adjustments increased erosivity expectations by 300 to 500 MJ mm ha⁻¹ h⁻¹ yr⁻¹. These values are similar to the 1720 MJ mm ha⁻¹ h⁻¹ yr⁻¹ calculated for northern Maine, U.S.A. (Brady and Weil 1999).

OIL ERODIBILITY (K-FACTOR)

Soil erodibility is a measure of the inherent susceptibility of soils with respect to particle detachment and transport (Brady and Weil 1999, Kesteren 2000). Values range from 0.1 to 0.45 Mg h MJ⁻¹ mm⁻¹, and these values represent soil loss per unit of erosive-rainfall-energy. Soils containing organics, clays and granular structure generally have high rates of water infiltration, and a K-value of < 0.025. (Renard *et al.* 1991, Brady and Weil 1999). Soils composed of silts, fine sand, and clay minerals, generally have a low infiltration rate, and a K-value = > 0.04 (Brady and Weil 1999).

Soil erodibility varies seasonally, with higher values occurring in spring when soils have reduced water infiltration rates due to high water saturation, and low shear strengths. Lower values occur in the fall and winter following periods of rainfall or frozen soil (Kirby and Mehuys 1987, Renard *et al.* 1991).

According to the Canadian Soil Maps, the HBWS area has a erodibility value of 0.018 Mg h MJ⁻¹ mm⁻¹, for the Fredericton area the value is 0.042 Mg h MJ⁻¹ mm⁻¹. For northern N.B. the value is 0.033 Mg h MJ⁻¹ mm⁻¹ (Coote *et al.* 1992). At the smaller forest soil unit scale the Parry forest soils should have a value of 0.027 Mg h MJ⁻¹ mm⁻¹. The Sunbury should have values of 0.025 Mg h MJ⁻¹ mm⁻¹, and the Salisbury should have a values of 0.031 Mg h MJ⁻¹ mm⁻¹ (Aalund and Wicklund 1950, Wickund and Langmaid 1953, Coote *et al.* 1992).

SLOPE LENGTH - STEEPNESS (L-S FACTOR)

This factor represents the influence that the length and steepness of a slope has on soil erosion (Agassi *et al.* 1988, Renard *et al.* 1991, Naslas *et al.* 1994, Brady and Weil 1999). A 10 % error in slope length can result in a 5 % error in computed soil loss, a ten % error in steepness can cause a 20 % error in soil loss (Renard *et al.* 1991).

For the Maritimes the Soil Landscape of Canada maps show an L-S factor of 0.26 at level ground, and a L-S factor of 25 for ridged land (Coote *et al.* 1992). The value for the HBWS area is 5.29. This is much higher than the 0.37 value for Fredericton, and the 1.63 value for northern New Brunswick (Coote *et al.* 1992).

To provide a more accurate estimate of L-S values for each of the HBWS watersheds, hydraulic gradient values as calculated by Bourque and Pomeroy (2001) are used. These values represent a change in hydraulic head per unit length between 3.4 to 5.2 (Gray 1970).

COVER TYPE (C-FACTOR)

The cover factor uses canopy structure, ground cover, and soil type to characterize soil loss due to land-use change (Renard *et al.* 1991). Values range from 0 for well-protected soils, 1 for bare soils, and 1.5 for soils highly susceptible to erosion. C-factor values for forests and range-lands in mid-western USA are (Brady and Weil 1999):

- 0.09 for forests with 75% canopy and 40% litter,
- 0.032 for range grass (<1m) with 75% cover and 60% decaying litter cover,
- 0.003 for forests with 75% canopy and 100% litter,

- 0.001 for forests with 90% canopy and 100% litter.

Land cover within the HBWS area is estimated at 90 % canopy cover and 100% litter cover. This condition is best represented by a C-value of 0.001.

SUPPORTING PRACTICES (P-FACTOR)

Supporting practices includes physical structures that assist in managing erosion. The value represents a ratio of soil loss with and without the supporting practice, taking into account surface roughness, runoff reduction, and slope. It is the least reliable factor because the user sets values. A value of 1 represents situations where no conservation practices are applied (Robertson 1996, Brady and Weil 1999). Values for tilled fields with soil-conservation practices can range from 0.6 (1-2 % slope) to 0.9 (21-25 % slope) (NSERL 2002).

The supporting practices factor will not be used in the calculation of USLE because each watershed is generally forest-covered, providing better natural erosion control structures than could be obtained through management.

Based on the values in Table 7.1 the USLE generates a potential soil loss that ranges between of 0.15 to 0.27 Mg ha⁻¹ yr⁻¹ (first line -Table 7.3).

Table 7.2: USLE and field estimated potential soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) for the 5 watersheds in the Hayward Brook Watershed Study.

Watershed	1	4	5	6	9
USLE soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	0.18	0.24	0.15	0.27	0.16
Field estimated soil loss ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	0.34	0.56	1.49	2.08	1.01
Difference ($\text{Mg ha}^{-1} \text{ yr}^{-1}$)	0.16	0.32	1.34	1.81	0.85
Likely source of sediment	stream channel	stream channel	stream channel	forest road	forest road

DISCUSSION

The calculated USLE soil losses are all much lower than the $23 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ potential soil loss values that are predicted for the Sunbury and Parry forest soils when under agricultural conditions (Aalund and Wicklund 1950, Krause, 1998). This difference demonstrates the high level of natural soil erosion control within the forested landscape. The USLE generated soil loss values represent the lowest limit of soil loss estimations and as a result, were all lower than the field - estimated soil loss values of Chapter 6 (line 2 – Table 7.3). The field – estimated concentrations on the other hand represent the upper limit of soil loss estimation, and the true concentrations are expected to be within these limits. The difference between the two limits (line 3 – Table 7.3) is based on:

- the fact that the USLE calculates uniform soil loss across a watershed, whereas the field-estimated sediment yield as registered at the location of each turbidity probe: at these locations, and as discussed in Chapter 5, extra inputs due to stream channel erosion (Watersheds 1,4,5) and input from road/stream crossings (Watersheds 6,9) must have added to the overall sediment loads;

- the conversion of the partially cleaned turbidity signatures into suspended sediment yields may have generated an over-estimate of the actual sediment yields per stream.

Overall, and within the limits of analytical uncertainties, Table 7.2 likely portrays the upper and lower limits of stream sediment yields for each of these streams.

CONCLUSIONS

The Universal Soil Loss Equation (USLE) uses five factors to calculate an index of soil loss. In most applications, values for each factor are calculated at a gross scale causing spatial differences at lower scales to be missed. With the HBWS application, efforts values for the USLE factors were obtained at the watershed scale.

Results using the USLE provided general estimates of soil loss for the HBWS conditions. Estimates were lower than the field-derived values because of the inability of the USLE to consider soil loss from specific areas such as stream channels, and special considerations are required to estimate soil loss from bare soil on roads.

CHAPTER 8

TURBIDITY SIGNATURES: PEAK-BY-PEAK ANALYSIS

INTRODUCTION

In this Chapter, the five stream turbidity signatures of the Hayward Brook Watershed Study are re-analyzed peak-by-peak, by determining peak height, peak shape, peak duration, and interval time between peaks for all those peaks that would not be affected by sensor fowling.

The reason for doing this is to generate a parametric means by which:

- the above-background events of the stream-specific turbidity signatures can be simulated mathematically, through stochastic means, one peak at a time, and in a manner that resembles real-time peak-to-peak occurrences (Chapter 9),
- turbidity peak parameters can be inferred from overall land-use patterns and road-stream attributes within each basin.

METHODS

The above-background events five stream turbidity signatures were analyzed, one peak at a time, by noting peak height, shape, duration and peak to peak interval, as follows:

- peak height refers to NTU difference between measured turbidity baseline and measured turbidity peak,

- peak shape refers to peak skewness, i.e., whether peaks are skewed to the left (slow to rise, sharp to drop), skewed to the right (sharp to rise, slow to drop), or non-skewed (rate of peak rise is similar or same as rate of peak drop),
- peak duration refers to the time between the beginning of a peak, and the time when the same peak returns to baseline level,
- peak-to-peak interval (days) refers to beginning of one peak to the beginning of the next peak.

Peak shape was used as part of the turbidity data quality control, to determine which peaks would be genuine, and which peaks were likely due to probe malfunctioning. Three shape classes were identified (Fig. 8.1):

- Class 1: slow rise in turbidity and subsequent quick drop,
- Class 2: sharp increase and subsequent decrease,
- Class 3: sharp rise and subsequent slow drop.

Class 1 events were likely due to gradual sensor fouling at first, followed by a sharp drop due to lens cleaning. Hence, Class 1 peaks were also generally associated with time of probe maintenance. Class 1 events were removed from the 460 registered turbidity events, leaving 238 events for further analysis (Fig. 8.2). Of these, 200 events were Class 2; i.e., Class 2 events occurred four times more than Class 1 and Class 3 events (Fig.8.3). Class 3 events were typically associated with large storms (Fig. 8.1). Streams 6 and 9 had the most events (see Chapter 5). Peak heights ranged between 25 to 750 NTU, with most events occurring between 25 to 250 NTU. Most events lasted for three days, with longer durations becoming fairly infrequent. The longest turbidity event lasted fourteen days. The turbidity peaks, once

identified by height, shape and duration and displayed in terms of frequency histogram, were then further analyzed to determine to what extent the frequency histograms would be influenced by watershed, by year, and by season (Figures 8.4 to 8.9). Viewing these histograms revealed that each of the turbidity peak attributes were mainly influenced by watershed, and not by year or season. Hence, further analysis was restricted to characterize and parameterize each stream signature by watershed only (and not by season also). This parameterization was done as follows:

Stream-specific tables were constructed to list daily NTU readings for each event, with day 0 marking the beginning of each event; these tables were analyzed for peak height, peak duration and peak shape; peaks per watershed were fitted with the following equation to represent peak shape, height and duration

$$\text{Turbidity (NTU records)} = a * \text{max_peak_height} * \text{time} * \exp^{(-k * \text{time})} \quad \text{Eq. 8.1}$$

Here, time represents time (days) since peak initiation, and “a” and “k” are watershed-specific parameters. Maximum peak heights, in turn, were analyzed in terms of their cumulative frequency distribution, which was best represented by:

$$\begin{aligned} \text{Cumulative frequency distribution of max. peak heights} \\ = [1 - \exp(-b * \text{max_peak_height})]^d \end{aligned} \quad \text{Eq. 8.2}$$

with “b” and “d” as watershed-specific parameters.

The cumulative frequency distribution of the peak-to-peak intervals was fitted with the following expression:

$$\begin{aligned} &\text{Cumulative frequency distribution of peak-to-peak intervals} \\ &= [1 - \exp(-c * \text{peak_to_peak_interval})]^e \end{aligned} \quad \text{Eq. 8.3}$$

with “c” and “e” as watershed-specific parameters.

Parameters a, b, c, d, e, and k were obtained by fitting Equations 8.1, 8.2, 8.3, to actual observations, i.e. NTU readings versus time t for all peaks within each of the five stream signatures, cumulative frequency distributions (histogram) of maximum peak heights for each of the five stream signatures, and cumulative frequency distribution of peak-to-peak intervals for each of the five stream signatures

The fitting was done by way of non-linear regression analysis, in each case.

RESULTS

Frequencies of maximum turbidity heights, duration and shape were plotted by watershed, by season and by year (Figs 8.4 to 8.9). The following was found:

- Class 2 was the dominant peak shape in all watersheds across all years, except Stream 1 (Fig. 8.4). Most observations were obtained for Streams 6 and 9.
- Frequency distributions of max. peak height were highly variable across watersheds and years, with highest number of peak events occurring in Streams 6 and 9 (Fig. 8.5).

- Most streams contained peak events that generally occurred over a 3 to 5 day period. Longest events were found in Stream 6 (Fig. 8.6). In Stream 9, the majority of events lasted 3 days.

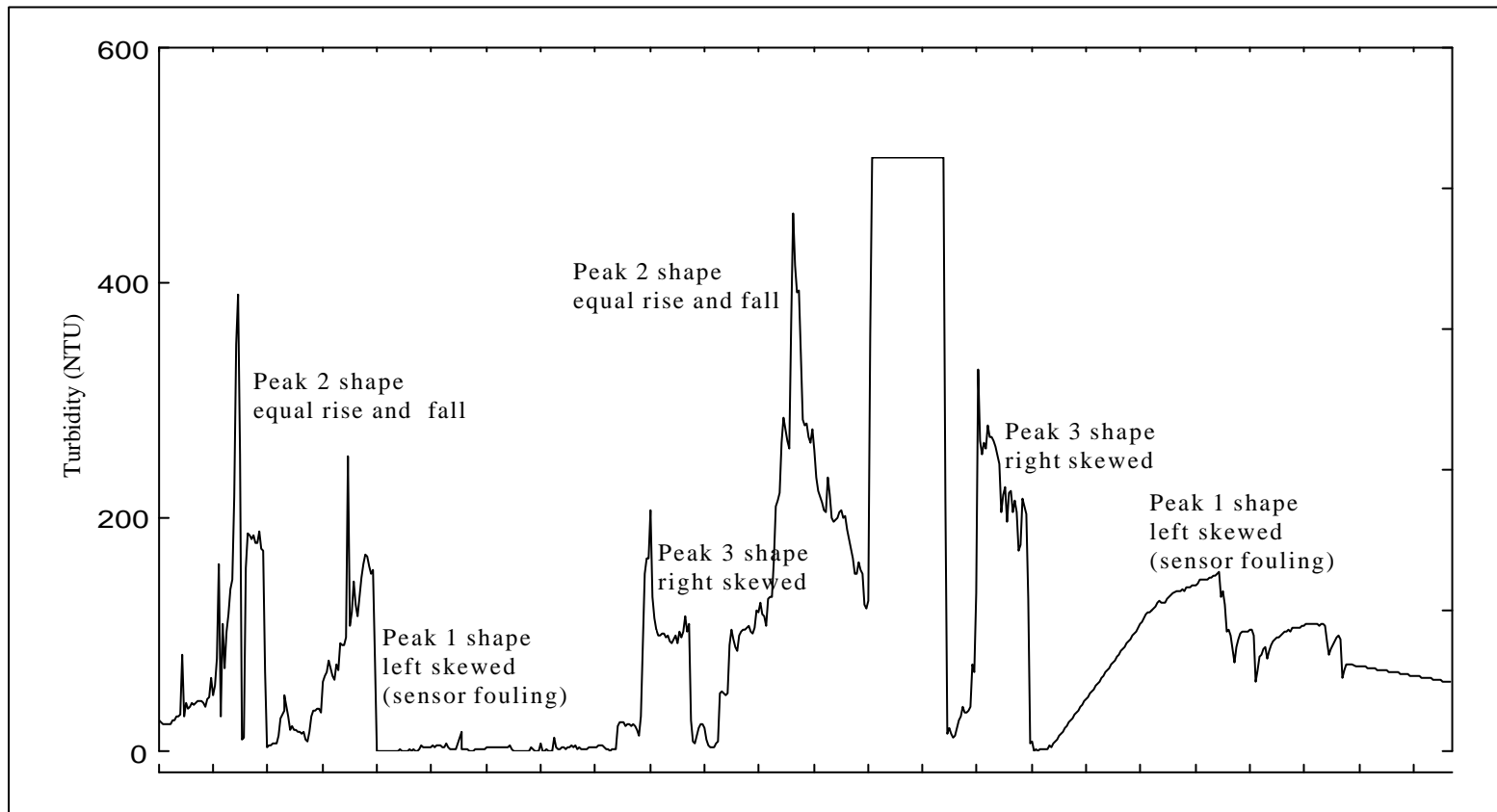


Fig. 8.1. Turbidity event classes within the Hayward Brook Watershed Study Area.
(class 1 = left skewed; class 2 = equal rise and fall; class 3 = right skewed)

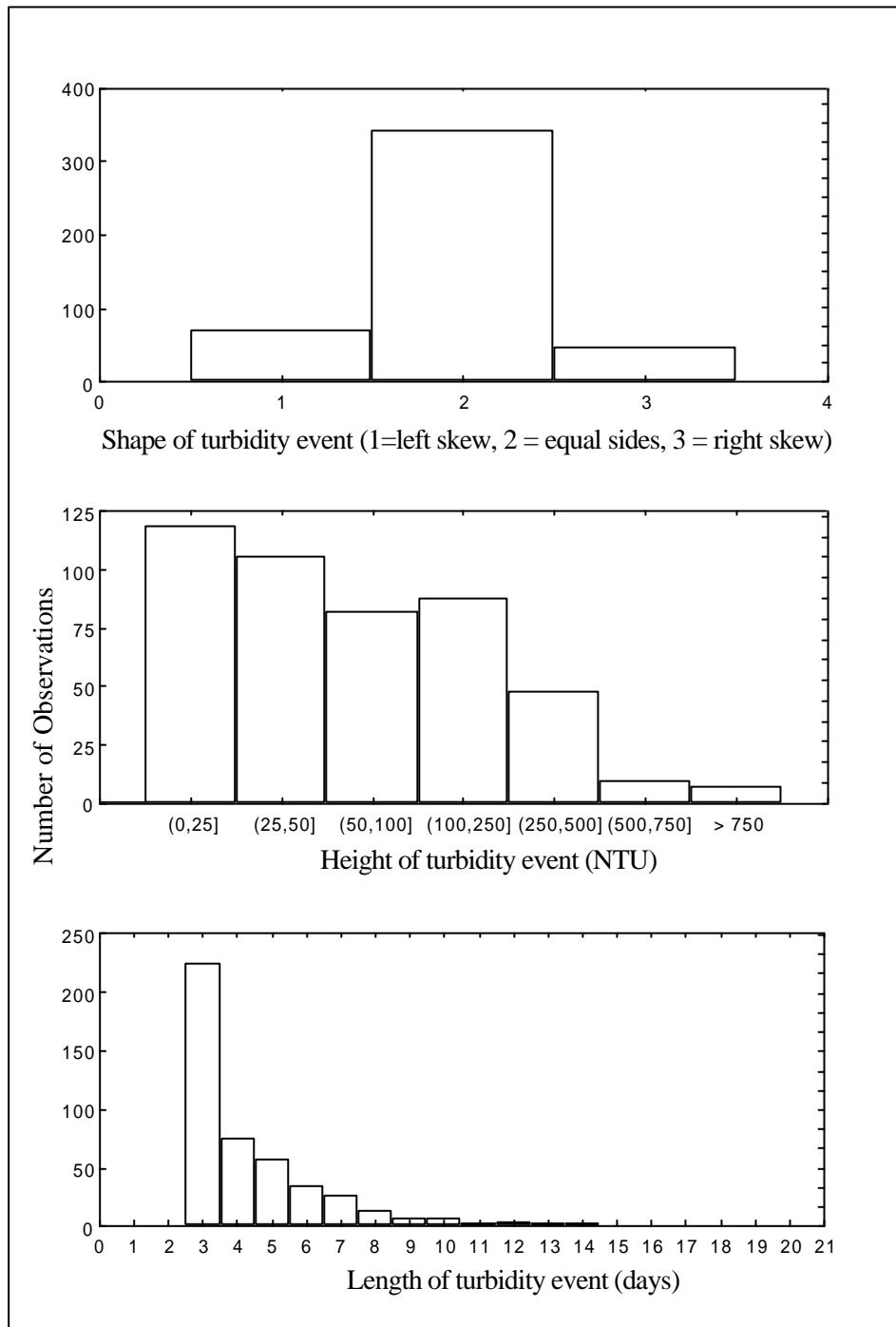


Fig. 8.2. Histogram of uncorrected turbidity (NTU) characteristics for each stream in the Hayward Brook Watershed Study Area. (460 events)

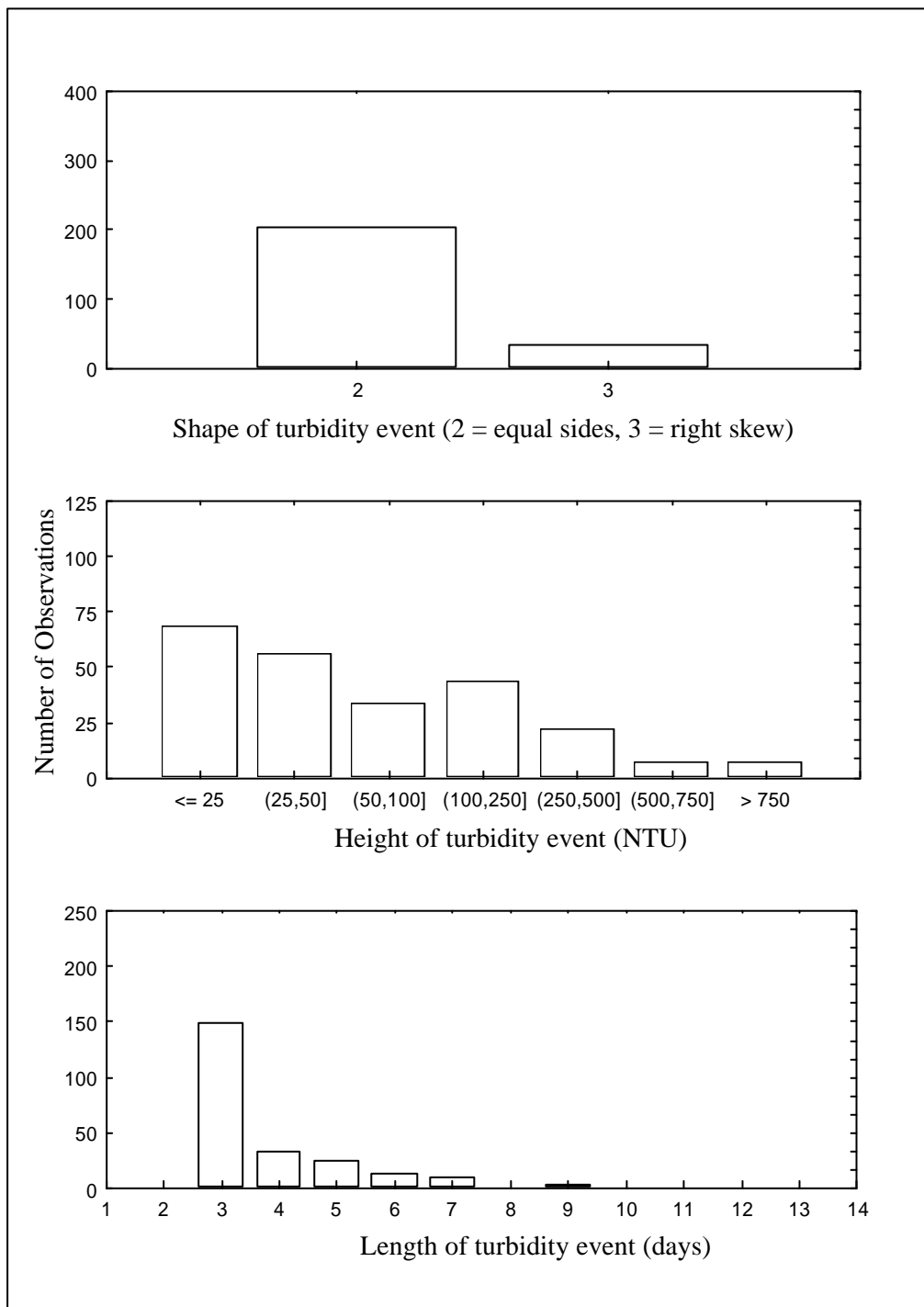


Fig. 8.3. Histogram of corrected turbidity (NTU) characteristics for each stream in the Hayward Brook Watershed Study Area. (238 events)

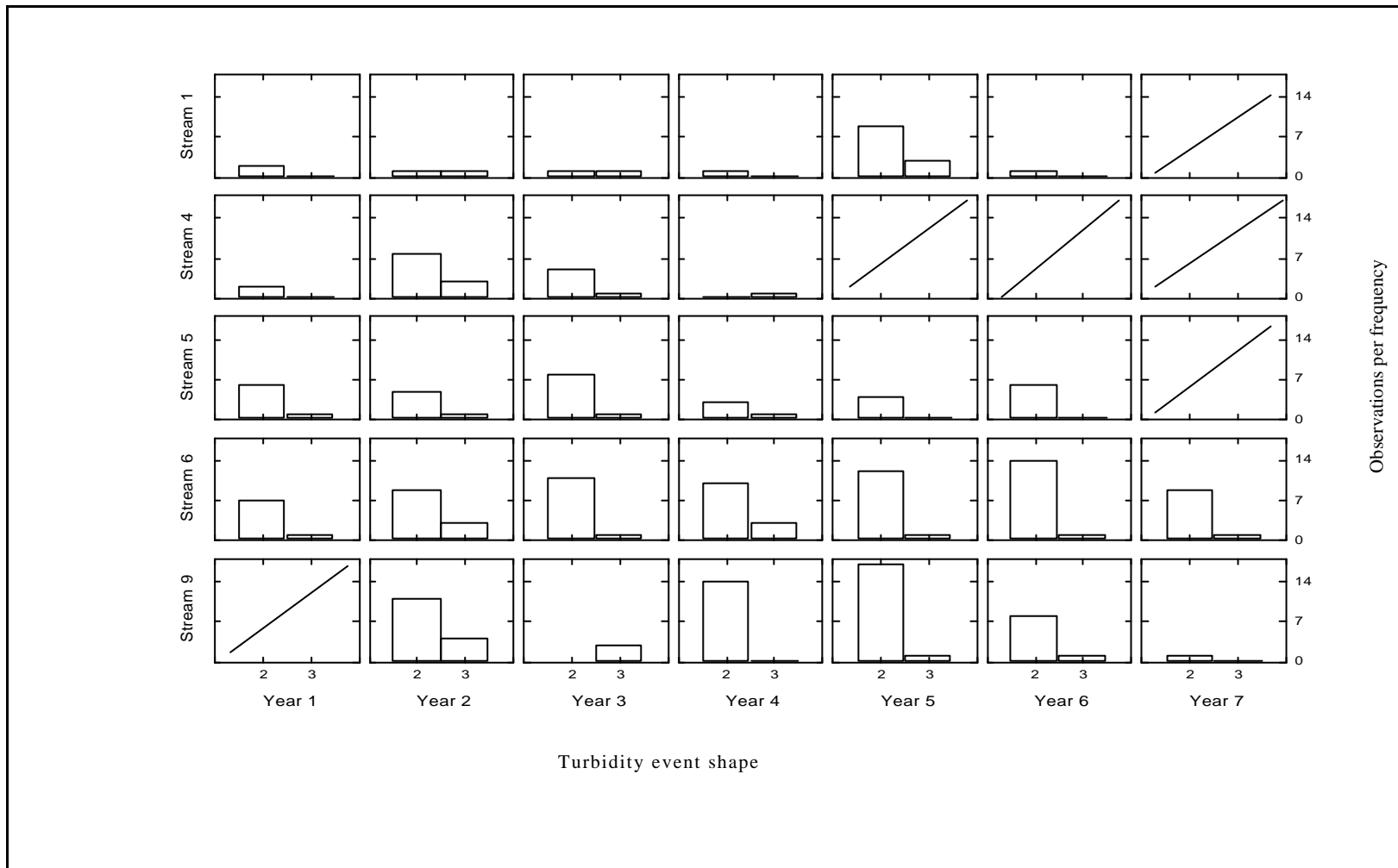


Fig. 8.4. Histograms of turbidity event shape (2 = equal sides; 3 = skewed right) during

each year of the Hayward Brook Watershed Study Area.

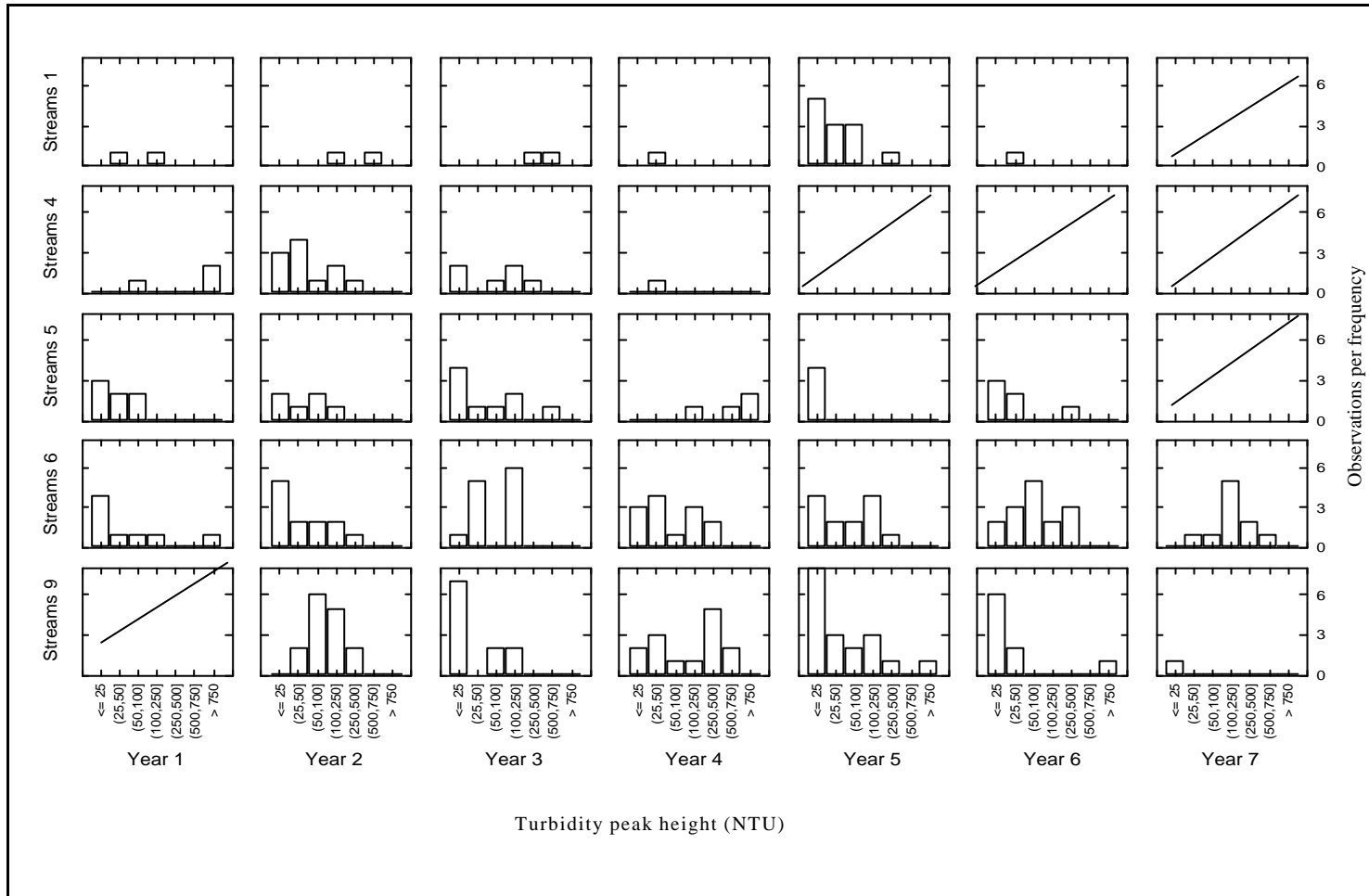


Fig. 8.5. Histograms of turbidity event peak height (NTU) during each year of the Hayward Brook Watershed Study Area.

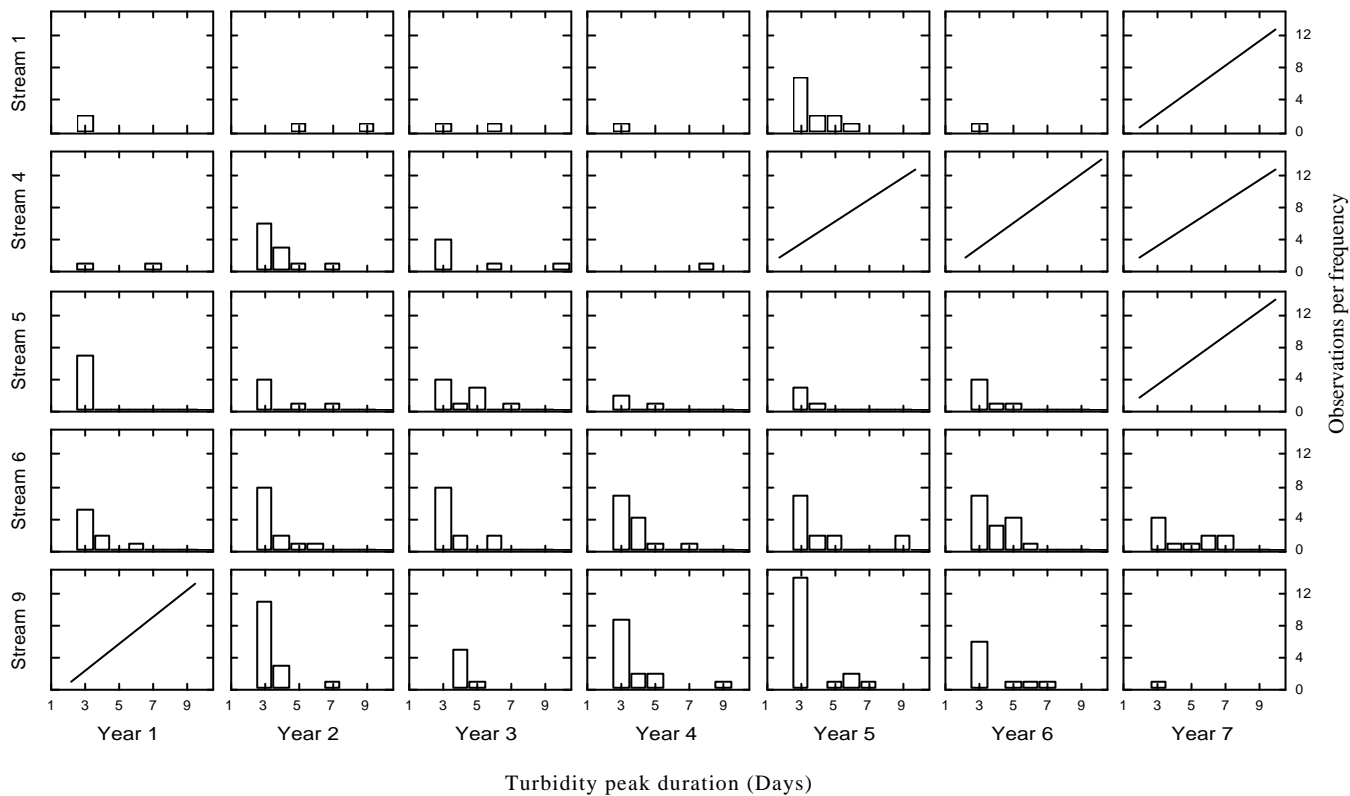


Fig. 8.6. Histograms of turbidity event duration (days) which occurred during each year of the Hayward Brook Watershed Study Area.

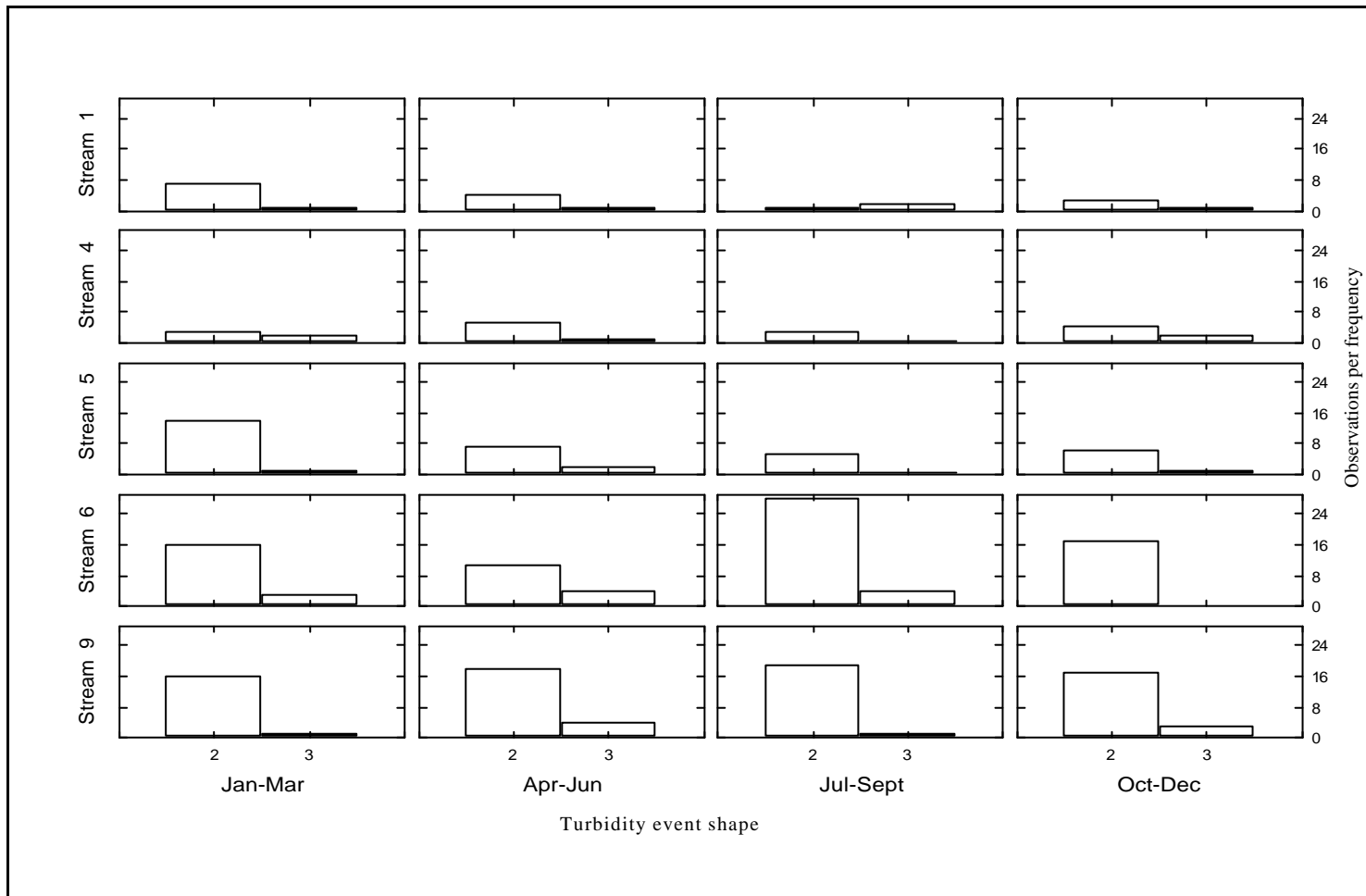


Fig. 8.7. Histogram of turbidity event shape (2 = equal sides, 3 = skewed right) during each season of the Hayward Brook Watershed Study Area.

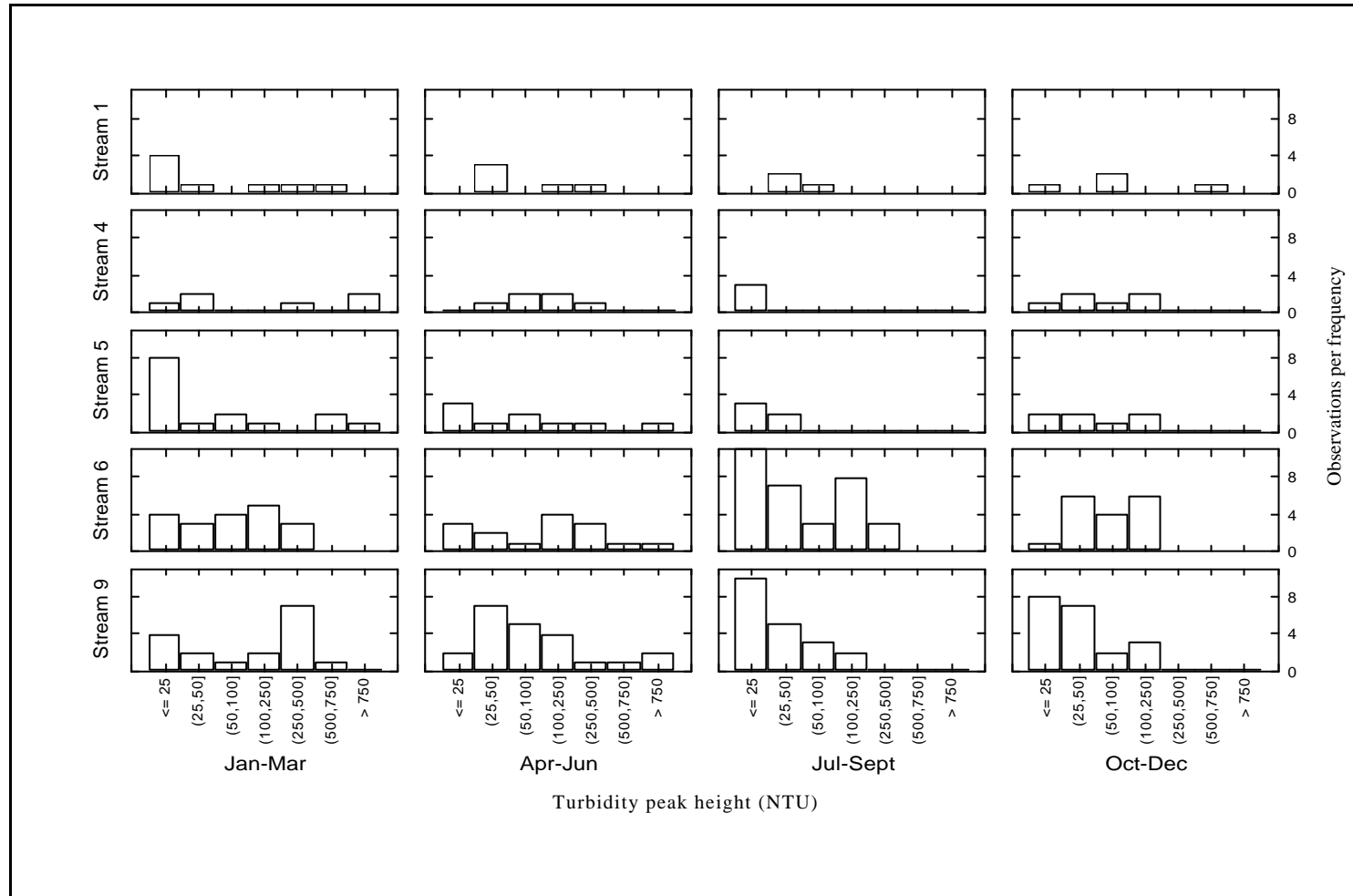


Fig. 8.8. Histogram of turbidity height (NTU) during each season of the Hayward Brook Watershed Study Area.

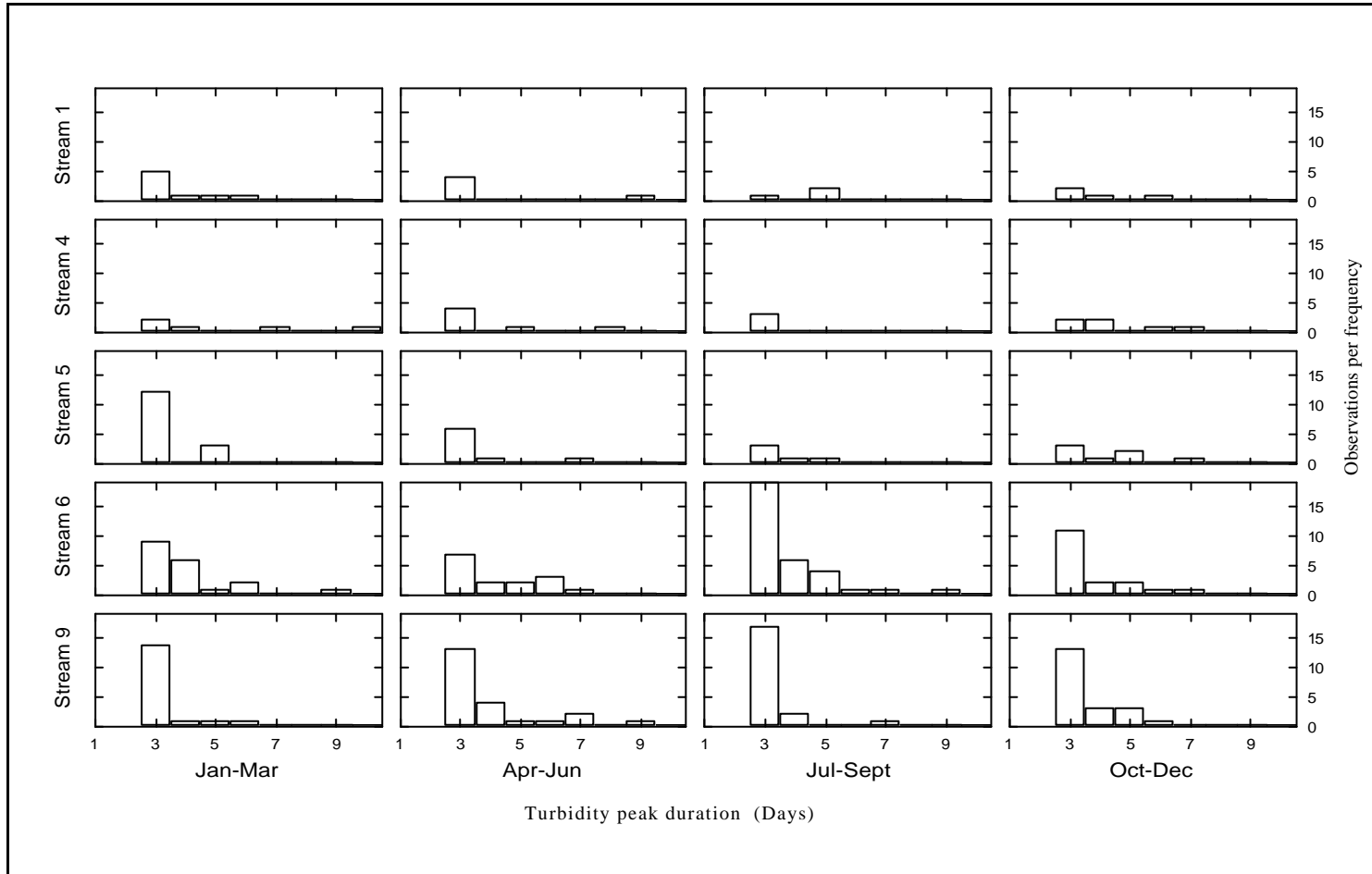


Fig. 8.9. Histogram of turbidity event duration (days) during each season of the Hayward Brook Watershed Study Area.

- Event attributes generally had slightly elevated frequencies in spring and fall (Figs. 8.7, 8.8, 8.9). Also, these periods contained more class 2 shapes, possibly as a result of high precipitation, saturated ground, and/or snowmelt.

The best-fitted “a” and “k” parameters for all of the individual turbidity peaks are listed in Table 8.1, by watershed. Inspection of these results showed that “k” increases with “a”. A closer examination revealed that

$$k = 0.72 * a^{0.5}$$

The turbidity shape of each peak can thus be represented by

Turbidity peak shape =

$$a * \text{max_peak_height} * \text{time} * \exp(-0.72 * a^{0.5} * \text{time}) \quad \text{Eq. 8.4}$$

Hence, parameter “a” essentially determines the general shape of each turbidity event in each stream, in a watershed specific way. According to Table 8.1, turbidity peaks are generally sharpest in Stream 1, and least sharp in Stream 6 and 4.

Table 8.1. Parameters “a” and “k” for determining the turbidity peaks of the 5 streams of the Hayward Brook Watershed Study.

Stream	a	k	r2
1	15.3 ± 4.0	2.8 ± 0.3	0.96
4	5.0 ± 0.5	1.6 ± 0.1	0.94
5	9.3 ± 5.0	2.1 ± 0.5	0.89
6	4.0 ± 0.3	1.4 ± 0.1	0.87
9	13.2 ± 2.1	2.6 ± 0.2	0.93

(n = 58 events; with a total of 519 peak height values)

The best-fitted values for the “b” and “d” parameters concerning the peak height cumulative frequency distributions are listed in Table 8.2. In this case, the “d” parameter appears to be independent of “b”. The average value for “d” is 0.35. The best-fitted equation to the peak height cumulative frequency distribution is therefore given by

Cumulative frequency distribution for max. peak height

$$= [(1-\exp(-b * \text{max.}_\text{peak_height}))]^{0.35} \quad \text{Eq. 8.5}$$

Table 8.2. Parameters “b” and “d” for maximum peak height for each of the 5 streams of the Hayward Brook Watershed Study.

Stream	d	b	b recalculated
1	0.35 ± 0.04	0.0066 ± 0.01	0.0067 ± 0.0003
4	0.45 ± 0.06	0.0083 ± 0.001	0.0064 ± 0.001
5	0.26 ± 0.03	0.0073 ± 0.001	0.0099 ± 0.001
6	0.40 ± 0.04	0.0058 ± 0.001	0.0051 ± 0.0003
9	0.28 ± 0.02	0.0053 ± 0.001	0.0067 ± 0.0003

This simplified equation was then used to re-calculate “b” for each watershed. The resulting values are listed in Table 8.2 as “b recalculated”. Here, large “b” values imply that most

maximum peak heights are small; low “b” values imply a wide range of max peak heights from small to large. Hence, Stream 5 has turbidity peaks that are generally small, while Stream 6 has turbidity peaks with a wide range of maximum height. It should be noted that the peak height data covers only the range of the turbidity sensor which in this case study was 0-1000 NTU.

The best-fitted values for the “c” and “e” parameters of the cumulative frequency distribution for the peak-to-peak intervals are listed in Table 8.3. In this case, the “e” parameter appears to be independent of the “c” value. The average value of “e” is 0.32.

Table 8.3: Parameters for the cumulative frequency distributions for the peak-to-peak intervals for each of the 5 streams of the Hayward Brook Watershed Study.

Stream	e	c	c recalculated
1	0.20 ± 0.04	0.0029 ± 0.0007	0.0055 ± 0.0007
4	0.39 ± 0.06	0.0099 ± 0.0017	0.0098 ± 0.0008
5	0.30 ± 0.05	0.0046 ± 0.0009	0.0058 ± 0.0006
6	0.32 ± 0.02	0.0210 ± 0.0014	0.0244 ± 0.0007
9	0.40 ± 0.03	0.0322 ± 0.0023	0.0307 ± 0.0007

The peak-to-peak cumulative frequency distribution equation therefore becomes

Cumulative frequency distribution for the peak-to-peak intervals

$$= [1 - \exp(-c * \text{peak_to_peak_interval})]^{0.32} \quad \text{Eq. 8.6}$$

This simplified equation was used to re-calculate “c” for each watershed. The resulting values are listed in Table 8.3 as “c recalculated”. High “c” values imply that most peak-to-peak intervals are short, i.e., a particular stream has many recurring turbidity events, as is the case for Stream 6 and 9; low “c” values imply that turbidity events are well spaced, on average, as is the

case for streams 1 and 5. It should be noted that the peak_to_peak parameter is based on 'cleaned' data that had 238 unnatural events removed (Figs. 8.2, 8.3). As a result this parameter is subject to a degree of variation. Another source of variation is due to several smaller peaks occurring within larger peaks. It was not possible to separate these, and as a result the peak_to_peak parameter is based on 'best possible data'.

In summary, Equations 8.4, 8.5, and 8.6 provide a mathematical description of the turbidity signature of each of the five streams. Each of these streams can be represented by a unique combination of values for "a", "b", and "c", as listed in Tables 8.1, 8.2 and 8.3. According to the observed relationships between land-use activities and stream-road configuration, one can now generalize this information as follows:

CONCLUSIONS

The analyses of each of the five turbidity signatures indicated that stream turbidity events within the HBWS can be classed into one of three shapes. The most common event type is Class 2. This shape quickly increases and decreases. Most events generally have a peak height ranging between 50 to 250 NTU, but can range up to 750 NTU. The most common event occurs over three days, with longer events occurring less frequently. Turbidity events, unlike discharge events, varied considerably among the five watersheds. Turbidity events were most frequent during the spring and fall seasons.

Stream turbidity events within the HBWS can be characterized using three mathematical functions: one for turbidity shape, one for cumulative frequency of peak height, and one for

peak-to-peak intervals. Parameterization of these functions provide – in principle - a method to quantify impacts of specific land and channel erosion events on stream turbidity signatures and sediment yields. Generally, intense land-use patterns and unstable road and stream-channel conditions produce frequent and sharp peaks that decay slowly. Low intensity land-use and stable road and stream channel conditions cause small peaks that decay quickly, and occur less often.

CHAPTER 9

RANDOM PULSE TURBIDITY MODEL

INTRODUCTION

Several models exist that simulate within-stream processes, such as USLE, RUSLE, WEPPS, CREAMS, ANSWERS, and SEDIMOT-2, (Renard *et al.* 1991, Kusumandari and Mitchell 1997, Mitasova *et al.* 1997, Cochrane and Flanagan 1999, Wang *et al.* 2000). These models are generally applied to situation where there is a need to predict changes in sediment flux or water quality in a particular watershed. The USLE, or RUSLE, its revised version, use six factors to calculate soil loss from specific slopes or fields. Values for these factors have been calculated for most of North America Chapter 7). Results are very approximate, but are appropriate for estimating soil loss from sheet, rill, and gully erosion. The CREAMS model (Chemical, Runoff, and Erosion from Agricultural Management Systems) utilizes the USLE factors to predict water quality per storm event, at the field scale. The WEPP (Water Erosion Prediction Project), and Answers (Areal Nonpoint Source Watershed Response Simulation) models predict soil loss at the watershed scale. Unlike the empirical USLE, these models are process- based, and can be used to assess soil loss by storm event. Sedimot-2 (Sedimentology

by Distributed Model Treatment) predicts soil loss on mined lands. This model is also process-based, but is applicable to single events only.

Although the above models simulate field and watershed erosion processes, they do not include process formulations for stream turbidity and related sediment yields. This thesis has shown that turbidity signatures appear to occur in random patterns, and that these patterns can be quantified and used for estimating suspended sediment concentrations and yields (Chapters 6, 8), and that a connection can be made between these calculations and those that generated from general soil loss expectations (Chapter 7). The simulation of successive turbidity events, however, is difficult, especially when time, location, type and extent of the occurrences that produce these events are essentially unknown (Chapter 5). The purpose of this Chapter is to develop, use and document a means to simulate stream turbidity signatures and sediment fluxes in forest streams, based on a detailed analysis of the preceding 5-stream case study. Specifically, the model of this Chapter is constructed:

- To simulate the above-ground turbidity signatures for each of the HBWS streams based on the peak height, duration, and peak-to-peak interval frequency distributions of these streams.
- To estimate the cumulative suspended sediment flux of these streams, and other similar streams, for general conditions that are essentially limited to the conditions of this case study.

MODEL DESCRIPTION

To simulate specific turbidity signature for any particular forest stream, one must be able to capture the apparent randomness of the successive turbidity events as these unfold for particular stream and watershed conditions. This task was addressed through the development of the “Random Pulse Turbidity Model”, or RPTM for short. This model links the turbidity peak, duration, and peak-to-peak interval equations of Chapter 8 to a pulsed random number generator. This generator is designed to draw uniformly random numbers from the cumulative frequency distributions of each peak-to-peak interval frequency distribution, to initiate a time-successive train of new turbidity event. To do this, the occurrence of each new turbidity event is drawn from a uniformly random number generator as follows:

$$\begin{aligned} \text{peak_to_peak_interval} \\ = - (1/c) * \text{logn} [1-\text{uniform random number}^{1/0.32}] \end{aligned} \quad (9.1)$$

The occurrence of each new turbidity event is – in turn – defined through another random number drawn, this time drawn from the cumulative peak height frequency distribution, i.e.,

$$\begin{aligned} \text{max_peak_height} \\ = - (1/b) * \text{logn} [1-\text{uniform random number}^{1/0.35}] \end{aligned} \quad (9.2)$$

The resulting peak height is then used to calculate the shape of the new turbidity event, i.e.,

$$\text{turbidity peak shape} =$$

$$a * \text{max_peak_height} * \text{time} * \exp(-0.72 * a^{0.5} * \text{time}) \quad (9.3)$$

The RPTM model (Figure 9.1) was developed in Stella software (HPS 1997), using a series of dynamically linked mathematical expressions (see Appendix 2, Fig. 9.1). Stella software was selected because it is useful for constructing process-oriented computer models with considerable instructive value (Arp and Xiwei 1992, Meng *et al.* 1995). The RPTM model simulates randomly occurring turbidity events by producing a random sequence of random pulse based on equations 9.1, 9.2, and 9.3, and watershed-specific selections for parameters “a”, “b” and “c” (Table 9.1). With RPTM, each new peak is initiated with the peak_to_peak_interval_generator. Peak heights and shapes of each turbidity_peak are established at the beginning of each new turbidity event by the max_peak_height_initiator. Often, new peaks may form while the old peak is still decaying. In this case, a rapid succession of new peaks generates a spiky “peak envelop”, as observed in the field. The extent of these envelops is controlled by the peak-decay adjustor. A high value for this adjuster minimized peak-to-peak overlap. A low value decreases peak decay and increases peak-to-peak overlap.

Each turbidity value in the simulated turbidity signatures is converted into a corresponding suspended sediment concentration, by using the turbidity-sediment regression equation determined in Chapter 6 (Equation 6.1). The resulting values, in turn, are multiplied by the average value for daily stream discharge at the location of stream discharge and turbidity measurement, to determine the cumulative sediment flux for the desired duration at that location, up to, e.g., 2000 days. For further programming details, see Appendix 2.

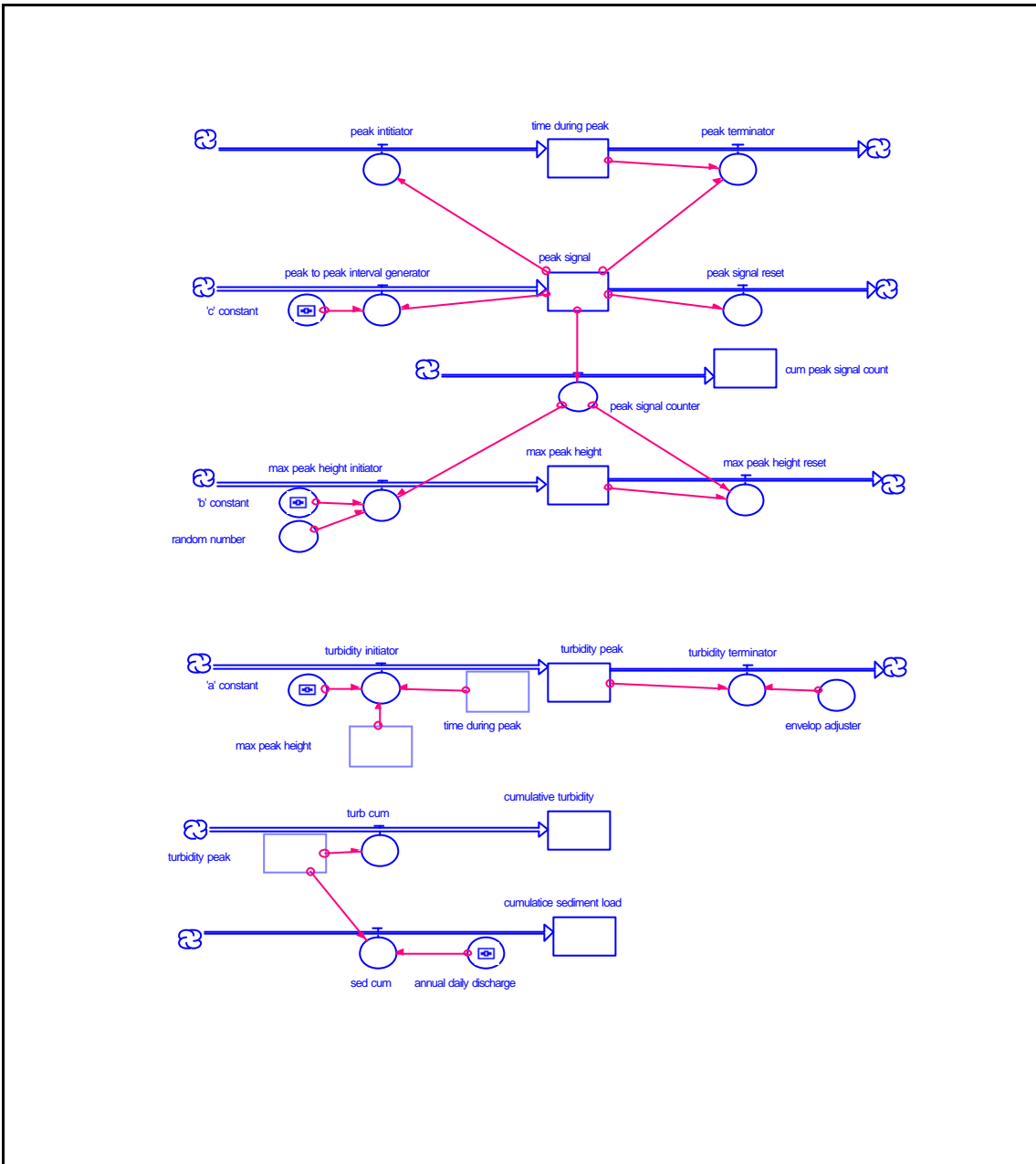


Fig. 9.1. Random Pulse Turbidity Model: Stella programming platform. Circles contain information about parameters and equations; boxes cumulate difference between inputs (broad arrows pointing towards box) and outputs (broad arrows pointing away from boxes). Individual turbidity events are cumulated to track cumulative sediment yields. For further details, see text.

RESULTS

Frequency distribution histograms for maximum peak height and peak-to-peak interval are shown in Figs 9.2, 9.3 for Stream 6, to illustrate that simulated frequency distributions for maximum peak height and peak-to-peak interval are similar to those observed in the field. These simulations were based on setting the “a”, “b”, “c”, and “peak_decay_adjustor” to their stream-specific values, as summarized in Table 9.1. In this, the “a”, “b”, “c” values are the same as the corresponding values listed in Chapter 8. The only adjustment done to ensure that the simulated cumulative turbidity and sediment yield values correspond to the field-observed values was done by setting the peak-decay adjustment factor to values ranging from 0.05 to 0.17. Actual simulations for each 2000 day run of the RPTM are plotted in Figures 9.4 to 9.8, with one simulation for each of the 5 streams, to illustrate general model behaviour. These plots are in general agreement with the field-derived plots in Chapter 5 in terms of turbidity peaks, and cumulative turbidity and cumulative sediment yield.

Table 9.1: RPTM parameter values for simulating cumulative turbidity (NTU), cumulative sediment load and turbidity peaks for streams in the Hayward Brook Watershed Study.

Watershed	1	4	5	6	9
Stream discharge at measurement location(tons/day)	7564	1821	12905	4039	7499
'a' peak height parm.	15.3	5	9.3	4	13.2
'b' peak duration parm.	0.0067	0.0064	0.0099	0.0051	0.0067
'c' peak interval parm.	0.0055	0.0098	0.0058	0.0244	0.0307
Daily turbidity (NTU)	19.9	27.3	17.9	15.1	15.1
Cumulative turbidity (NTU); 2000 days	39871	126669	72324	217540	67567
Cumulative sediment yield (tons/watershed); 2000 days	897	492	5876	2622	3305
Peak-decay adjustor	0.15	0.09	0.05	0.14	0.17

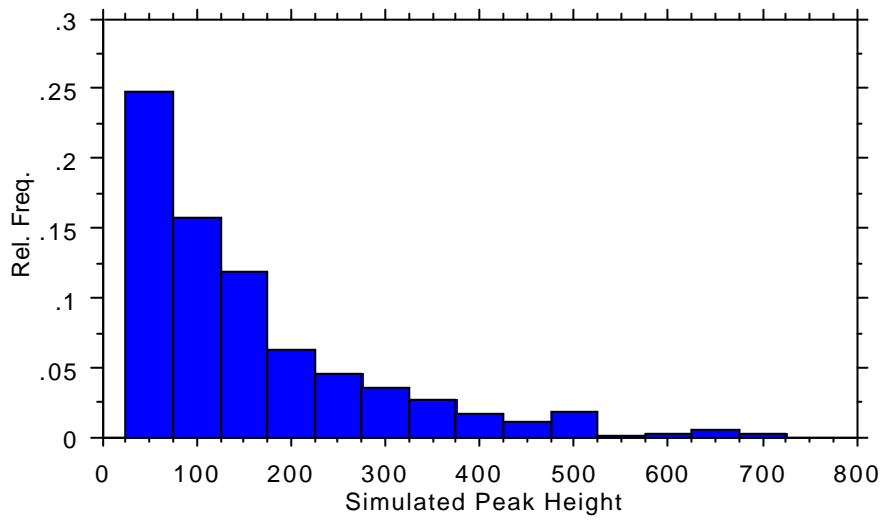
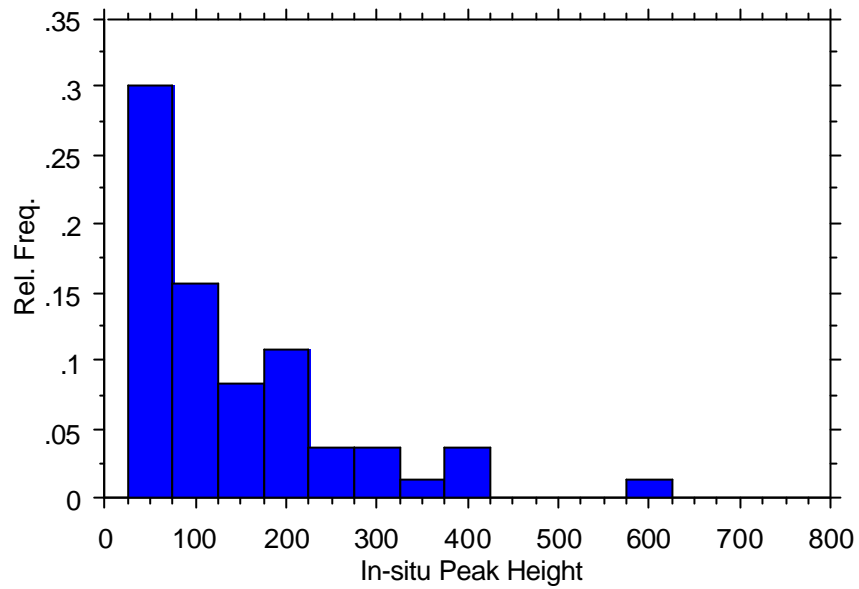


Fig. 9.2. Frequency distribution of peak height for Stream 6 of Hayward Brook Watershed Study.

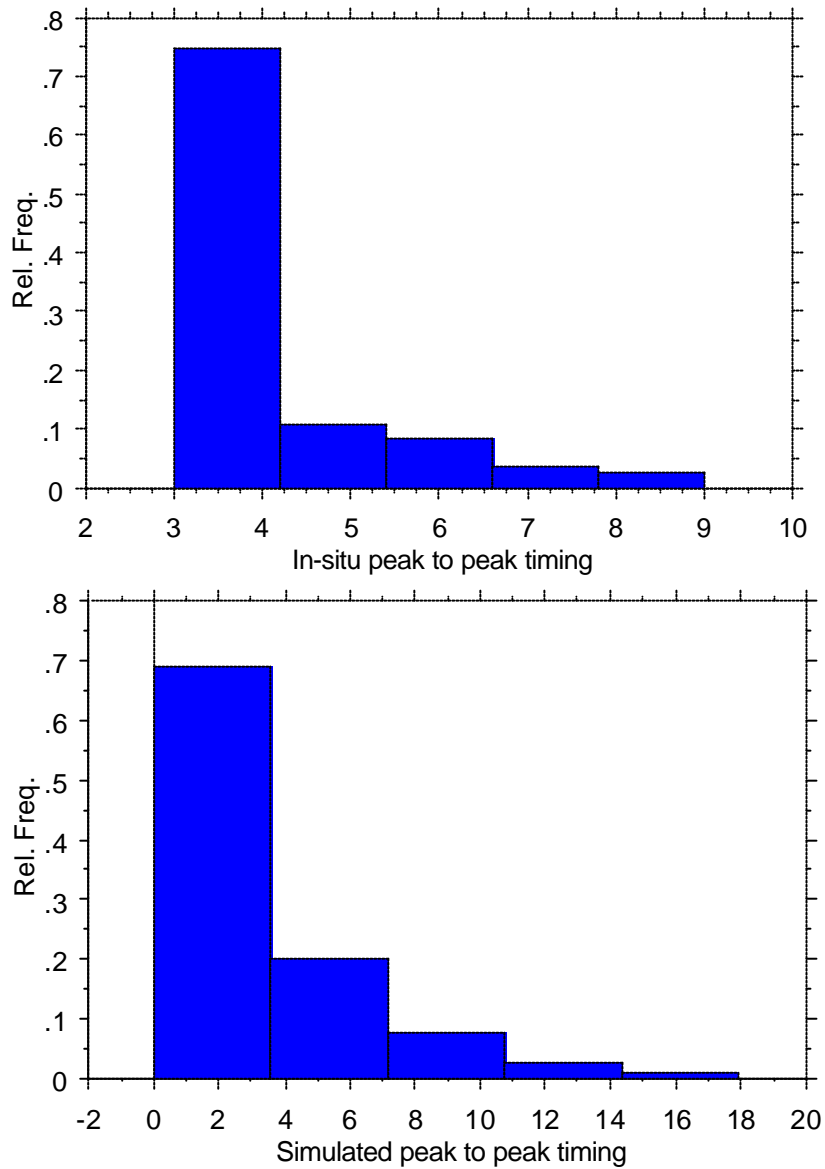


Fig. 9.3. Histogram of frequency distributions of peak to peak interval (days) for field and simulated signatures for stream 6, using RPTM.

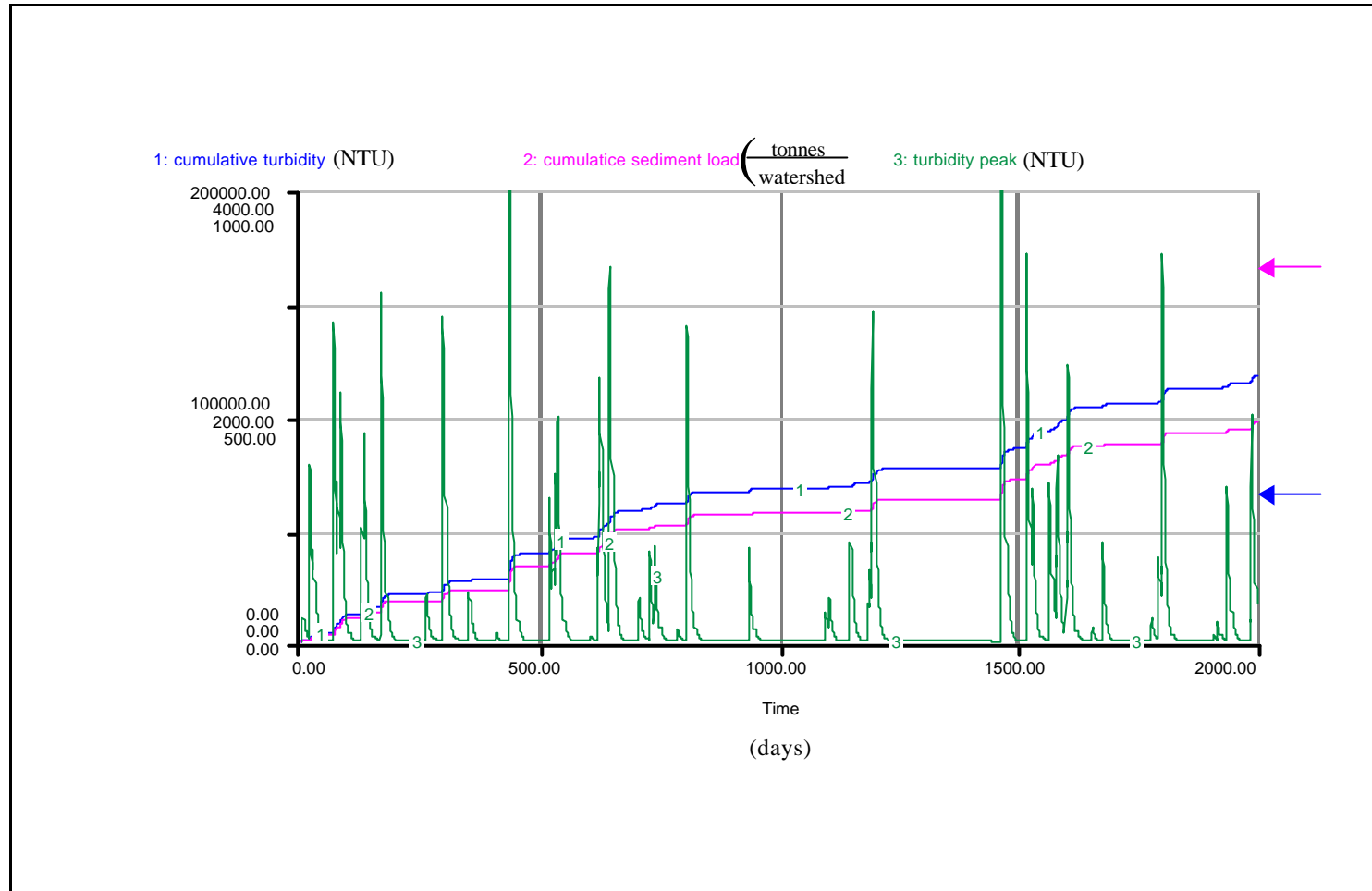


Fig. 9.4. Representative output from Random Pulse Turbidity Model: cumulative turbidity, cumulative sediment load and turbidity peaks for Stream 9 of the Hayward Brook Study. Arrows point at cumulative turbidity (blue) and cumulative sediment load (purple), for a cumulation period of 2000 days.

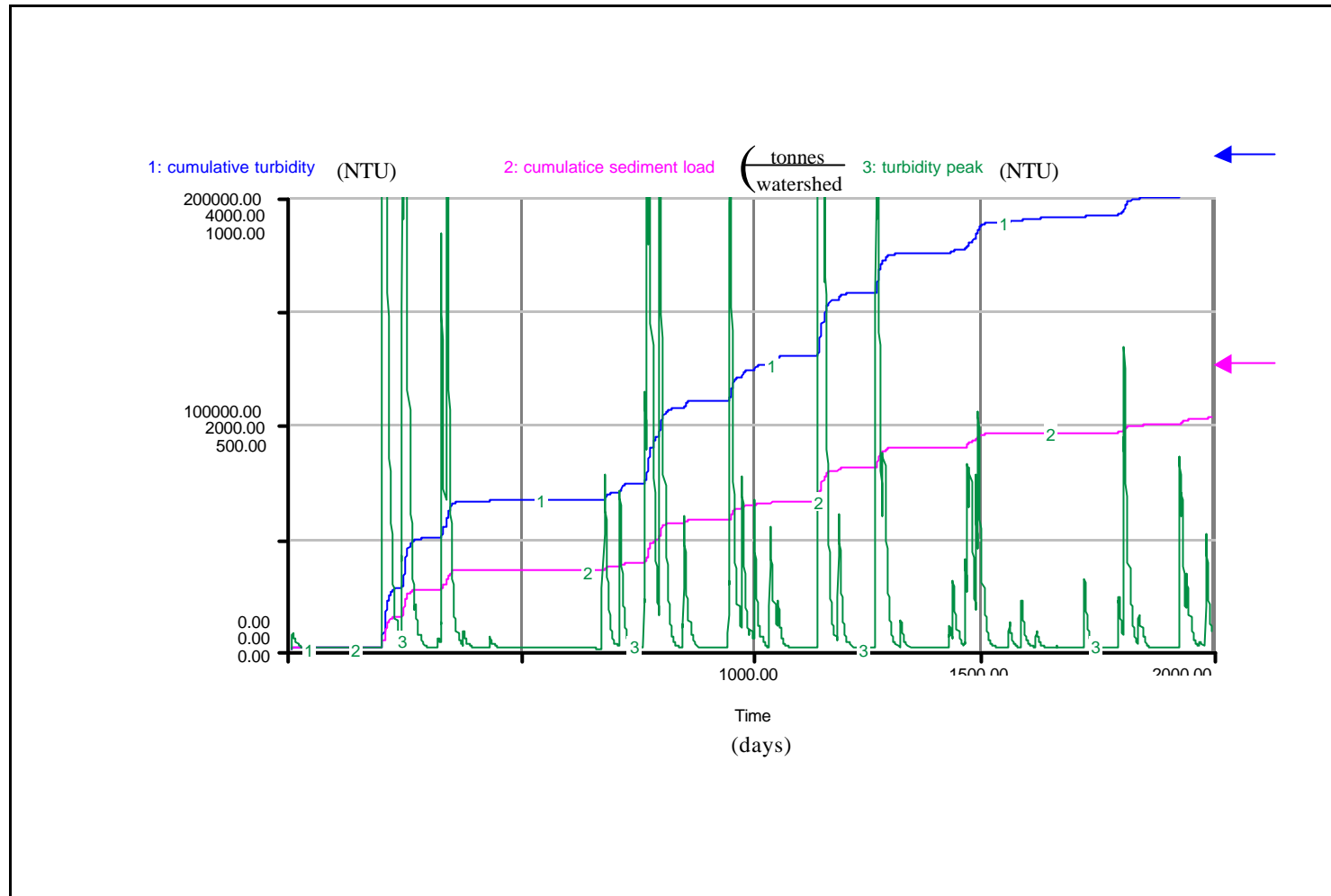


Fig. 9.5. Representative output from Random Pulse Turbidity Model: cumulative turbidity, cumulative sediment load and turbidity peaks for Stream 6 of the Hayward Brook Study. Arrows point at cumulative turbidity (blue) and cumulative sediment load (purple), for a cumulation period of 2000 days.

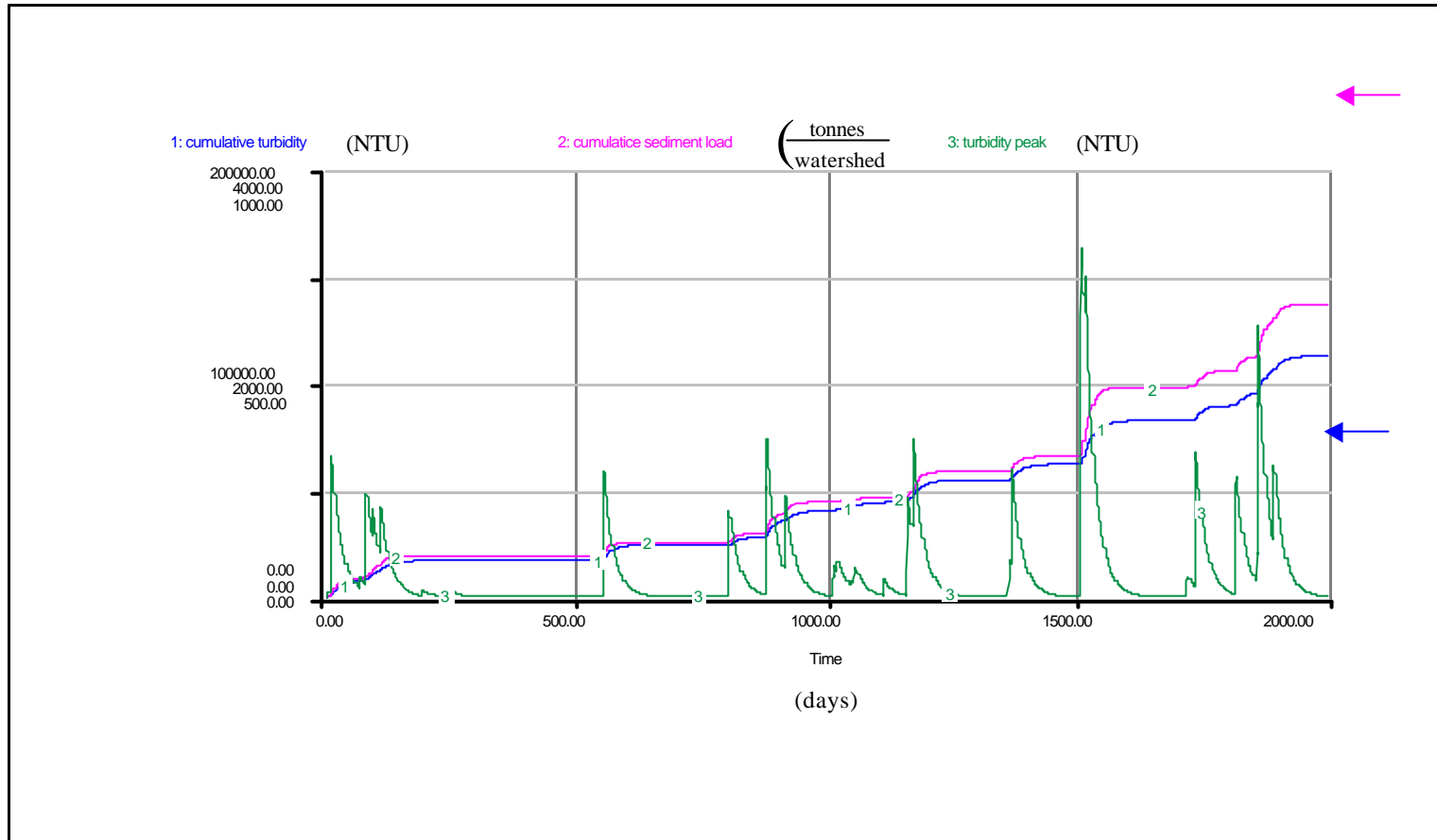


Fig. 9.6. Representative output from Random Pulse Turbidity Model: cumulative turbidity, cumulative sediment load and turbidity peaks for Stream 5 of the Hayward Brook Study. Arrows point at cumulative turbidity (blue) and cumulative sediment load (purple), for a cumulation period of 2000 days.

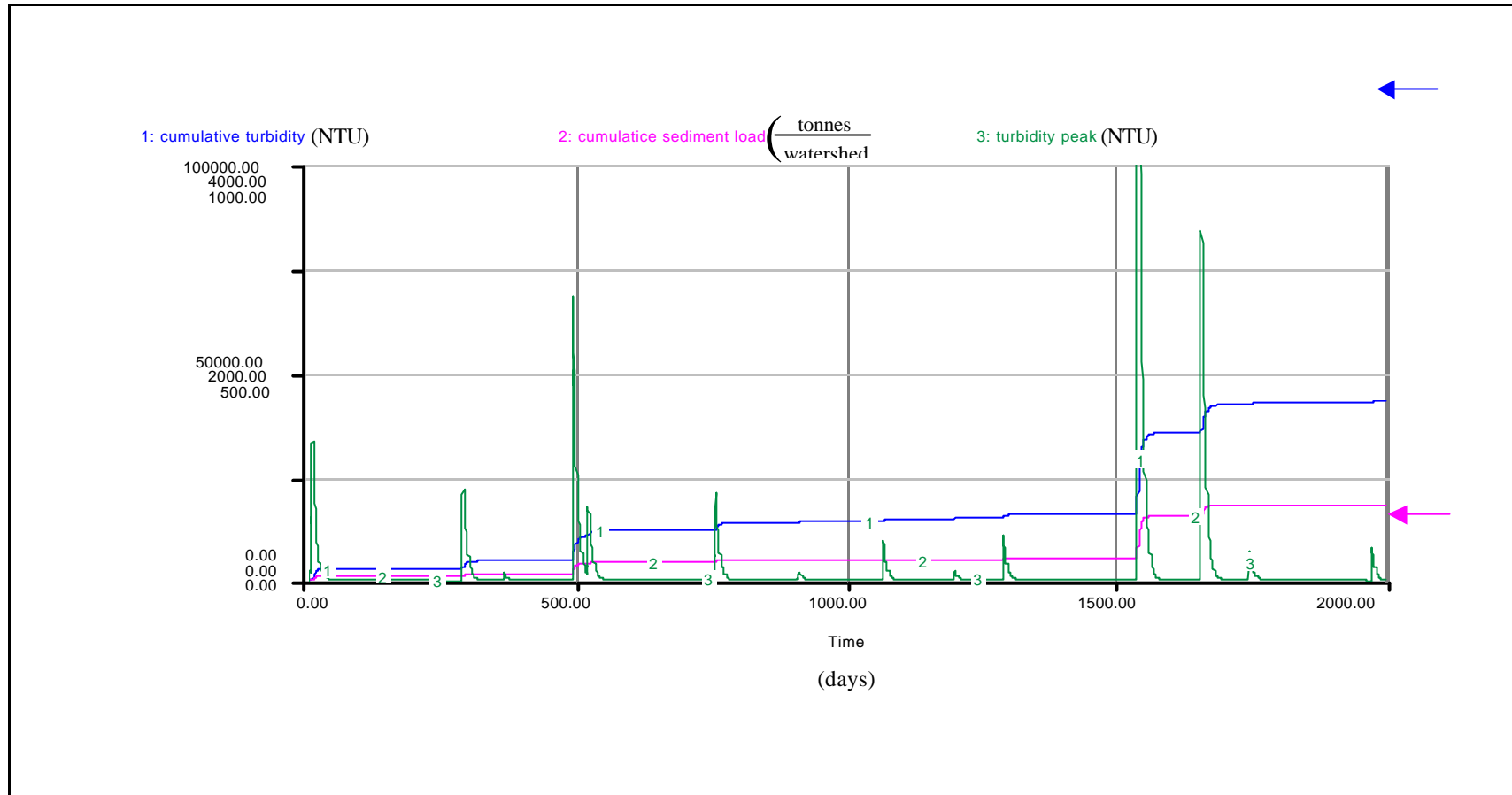


Fig. 9.7. Representative output from Random Pulse Turbidity Model: cumulative turbidity, cumulative sediment load and turbidity peaks for Stream 4 of the Hayward Brook Study. Arrows point at cumulative turbidity (blue) and cumulative sediment load (purple), for a cumulation period of 2000 days.

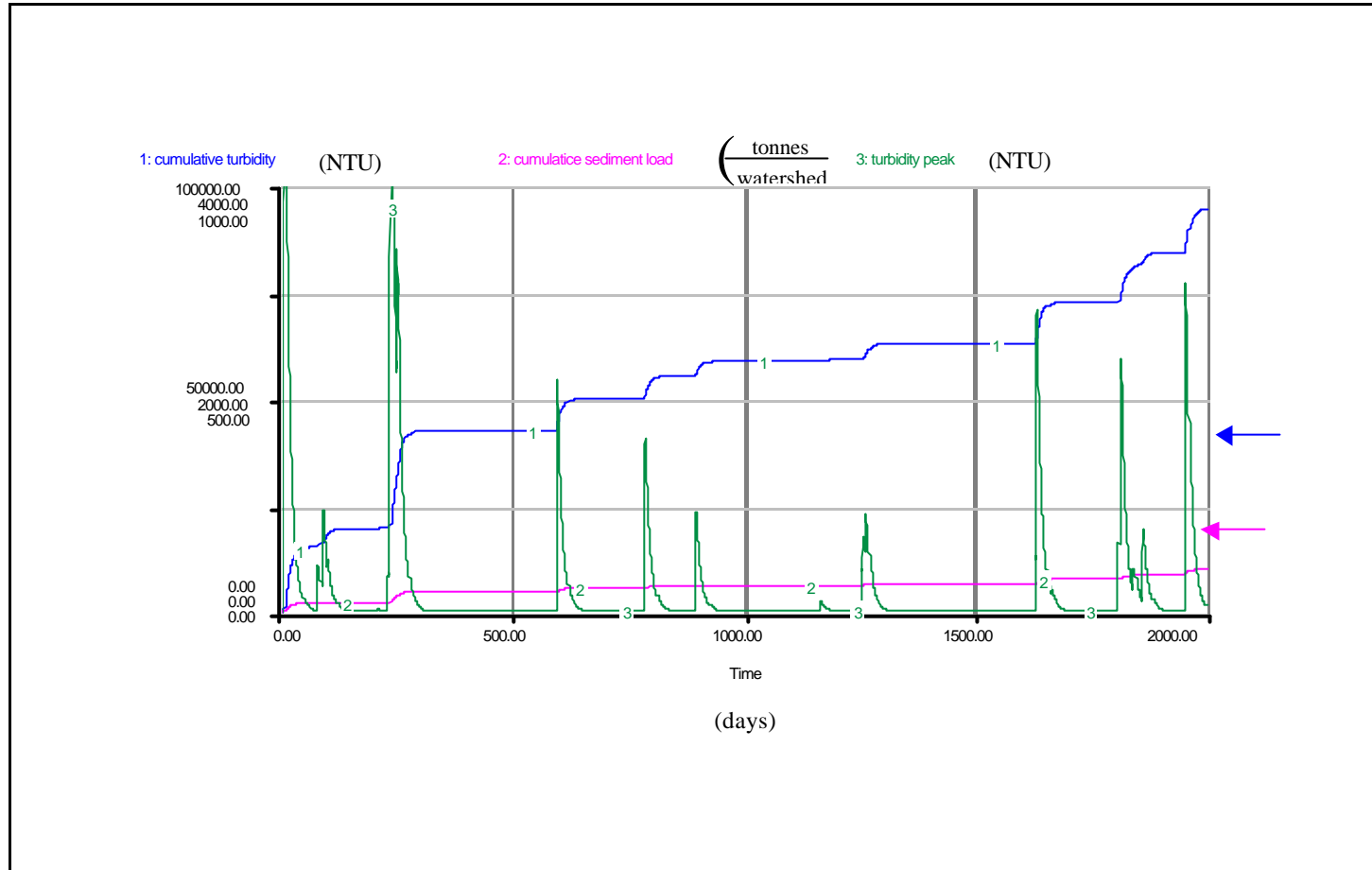


Fig. 9.8. Representative output from Random Pulse Turbidity Model: cumulative turbidity, cumulative sediment load and turbidity peaks for Stream 4 of the Hayward Brook Study. Arrows point at cumulative turbidity (blue) and cumulative sediment load (purple), for a cumulation period of 2000 days.

Details

Stream 9 contained an active turbidity signature during most of the study period (Fig. 5.1). The major source of turbidity was improper ditching, and only in the later part of the study did the turbidity activity drop. The simulation reproduced the signature of this stream showing times of elevated turbidity events, separated by times of low turbidity (Fig. 9.4). The model also confirmed that there should be many spiky peak envelopes in excess of 1000 NTU, i.e., the upper limit of the turbidity sensors that were used in the field.

Stream 6 had the most active turbidity signature, with several events occurring over a wide range of concentration, as shown in Fig. 5.1 and Fig. 9.5. As with Stream 9, and with the field situation, many simulated turbidity peaks exceeded 1000 NTUs. Stream 5 had generally one of the mildest turbidity signatures, with small and widely-spaced turbidity peaks (Fig. 5.1, Fig. 9.6). In this case, individual peaks were broadened by setting a low value for the peak-decay adjustor, to achieve overall correspondence with the field-determined values for cumulative turbulence and sediment load. However, this adjustment is somewhat artificial, because broadening each peak essentially accommodate the one-time release of sediments that occurred during a single major stream channel wash-out event washout event (Fig. 5.1, 5.8).

Stream 4 produced an active turbidity signature because of the location for turbidity sensor just below an actively eroding stream bank (Fig. 5.1). The overall sediment concentrations within this stream, however, were generally low and infrequent, and this is also seen in the simulations (Fig. 9.7).

Stream 1 had the least active turbidity signature during the study (Fig. 5.1). Turbidity in this stream mostly occurred during the road construction phase. The cumulative 2000 day turbidity was found to be the lowest, at 39871 NTU in the field. In general, the simulated data corresponded with the field observations (Fig. 9.8).

Also shown in Figures 9.4 to 9.8 are the field-derived values of cumulative turbidity and cumulative sediment loads for the 2000-day simulation period, as indicated by the arrows (cum. turbidity: blue; cum sediment load: purple). In these plots, there are - in several instances - considerable differences between the field-observed values, and the representative simulation runs. The calibration was done to provide an average agreement between field-observed and simulated cumulative turbidity. For streams, 9,6,5,4, and 1, the agreement of the simulations was within 0.6, 1.1, 0.7, 2.5, and 0.5 of the field-observed values, respectively. The greatest disagreement was with Stream 5, i.e., the situation where small and far-spaced turbidity events are interrupted by a one-time occurrence of a major turbidity event.

For the sediment loads, simulated values for the cumulative sediment loads differed from the field-derived values by 1.6, 1.2, 1.6, 0.9, and 2 for Streams 9, 6, 5, 4, and 1, respectively. Altogether, it can be concluded that the Random Pulse Turbidity Model realistically simulates expected sediment loads within a factor of two. Improvements can be made through further model calibration. Such calibrations should – in principle – be based on turbidity signatures that are essentially free of operational difficulties due to sensor malfunctioning.

CHAPTER 10

CONCLUSIONS

The analyses of stream turbidity within the Hayward Brook Watershed case study has provided an improved understanding of how land-use, soil erosion and natural stream dynamics cause variations in stream turbidity signatures and suspended sediment flux. This thesis has shown the following:

1. Stream turbidity events generally occur randomly, being influenced by land-use, soil erosion and stream dynamics.
2. Turbidity signatures vary in intensity across watersheds, whereas discharge was generally similar among the essentially neighbouring watersheds.
3. Roads in general are a major and chronic source of sediments; roads that are poorly maintained can be a major source of continuing stream turbidity and sediments.
4. Natural erosion within a stream channel; e.g., bank erosion or any change in stream structure can cause a turbidity signatures similar to those associated with upland soil erosion.
5. Stream turbidity was found to be strongly associated with suspended sediment concentrations, showing a linear relationship at high concentrations, and an asymptotic relationship at the origin.
6. Fluxes are higher in the spring season, although activities in the summer (traffic) and winter (ice, freezing and thawing) may loosen soils and stream structures, thereby providing a large source of sediments prior to fall rains.

7. Field observations about road conditions provide a quick method to predict degrees of road erosion potential and subsequent stream turbidity events. Greasy conditions during wet periods may produce particularly large generally and extensive turbidity events.
8. The Universal Soil Loss Equation was found to be a good indicator of baseline soil loss. Small scale spatial differences found within forested watersheds cannot be captured with USLE. This causes soil loss due to road and stream structure change to be missed.
9. Soil loss from road beds within each watershed can be calculated using the USLE as a baseline for soil loss.
10. Turbidity signatures for each of the five watersheds could be characterized by parameterizing turbidity shape, peak height and peak_to_peak interval using mathematical functions.
11. The development of a Random Pulse Turbidity Model was found to produce acceptable turbidity signature and sediment flux simulations for each of the five HBWS streams.

CLAIMS REGARDING ORIGINAL CONTRIBUTIONS

1. Documentation of protocol to monitor in-situ stream monitoring of turbidity in remote areas, and of quality control data procedures regarding hourly turbidity data.
2. Combining the use of the Universal Soil Loss Equation and the field observed soil loss concentrations to determine soil loss per area of exposed soil within watershed.
3. Analysis of stream turbidity signatures using an in-depth review of soil erosion and stream channel dynamics.

4. Analysis of turbidity signatures using a characterization of turbidity events based on event shape, height, and peak-to-peak intervals.
5. Development of a model that uses random peak height and peak interval initiators to simulate turbidity signatures and associated suspended sediment flux for particular forest streams.
6. A general evaluation of the parameters of the model, to allow for a general quantification of stream turbidity signatures and associated sediment fluxes based on a simple characterization of overall watershed conditions that would influence extent of turbidity occurrences.

RECOMMENDATIONS FOR FURTHER RESEARCH

1. Placement of turbidity probes: one must ensure that these probes are not influenced by excessive stream bank erosion nearby. Pools to be monitored should be in straight stretches of the stream.
2. Monitoring protocol of stream turbidity should include one stationary probe, and a portable probe to determine local sediment entry points along the stream.
3. Data logger downloading and calibration/cleaning of sensor should be frequent to enhance accuracy of sensor readings.
4. Watershed conditions and changes in land-use and stream structure should be routinely documented to ensure major events are all recorded by type, location, and date.

5. Suspended sediment samples should be collected to represent the natural range of turbidity over the hydrological cycle, to obtain a reliable turbidity – sediment concentration calibration plot.
6. The RPTM model should be evaluated at other locations, for further model testing and model refinement.

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APPENDIX 1

TURBIDITY CALIBRATION AND DATA QUALITY CONTROL

Introduction

In-situ turbidity readings were checked for quality control using sensor calibration data, and inter-calibration site visit information. Sensor fouling which occurs when particles settled on the sensor lens causes turbidity concentrations to be over-estimated. This was found to be the main cause of over-estimation of turbidity readings.

Data Management / Quality Control

Turbidity was recorded at 60 minute intervals and logged onto a VEDAS data logger. Data was stored according to stream identification, date and time. Each hourly turbidity reading was checked through the comparison to calibration and field notes, and comparisons with turbidity concentrations from adjacent streams. A correction was applied only if justified. The use of correction formulas and artificial neural networking was attempted, but found not to be a suitable technique for turbidity data (Simpson 1999). An automated correction formula could eliminate reading drift, but could not account for the hourly high to low turbidity fluctuation.

Calibration sheets were generally used as the major information for turbidity quality control (Table A1.1). For example, on September 04, 1996 the turbidity sensor at station 1

measured 64.5 NTU for a 74 NTU standard (Table A1.1, Fig. A1.1). The sensor was under-estimating the standard by 33 %. A correction was then applied back in time. The end point was chosen as an event that was significant enough to cause the recorded event. In this example the correction was applied back to the 750 NTU peak on August 22, 1996.

Readings of 9999 NTU were often recorded when the sensors became clogged. As these values are outside the sensor range (0 to 1000 NTU), an adjustment was applied. For example; in stream 1 on May 12, 1995 the turbidity reading increased sharply to 1000 NTU and remained till May 16, 1995 (Fig. A1.2). On May 16 the sensor was rinsed causing a sharp drop in sensor readings. This indicated a fouled sensor. A correction was applied by subtracting the lowest turbidity reading (899 NTU in this example) from each elevated reading. The drop from 1000 to 899 is assumed to be a authentic decrease in turbidity concentration. For those events which reached 1000 NTU over an extended period of time, but naturally dropped to zero no correction was applied (Fig. A1.3).

Comparison of raw in-situ and post quality control checked data for stream 1 shows most corrections occurred during periodic separated events (Figs. A1.4, A.1.5)

Summary

Quality control of the hourly turbidity data was completed manually according calibration sheets and inter-calibration site visit notes. Automated quality control techniques were not suitable because of the randomness of turbidity events.

Table A1.1: Calibration corrections and field notes applicable to stations 1,4,5,6,9 of the Hayward Brook Watershed Study.

Station 1				
Date	Calibration low	Calibration high	Field Notes and Corrections	Tech
March 22/94			Initial calibration	TS
June 10/94			June 10- July 05 - no data - log prob	TS
June 18/94			to July 05 = 0.5 NTU correction	
July 05/94			recalibrated	TS
August 16/94		80/84.2	Aug 16-24 - no data	TS
September 30/94		93/81	Sept 30- Oct 05 - no data - log prob	TS
November 08/94			no calibration numbers	TS
December 01/94		90/90.7	Probe out Dec 01- Jan 24- low wat	TS
March 03/95		83/95	Stream open	TS/JP
March 17/95			to March 20 = -976 NTUs	
March 23/95			to April 15 = -953 NTUs *1.33 NTU's	
April 15/95		83/62	to November 19 = *1.33 NTU's	TS/JP
May 12/95			to May 16 = -899 NTU's	
May 27/95			to June 08/95 = *1.19 NTU's	
June 08/95		76/63.8		JP
July 07/95		74/65.2		JP
August 08/95		76/35.2	maybe 76/75.2	JP
October 19/95		74/96.3		JP
November 16/95		74/74.8		JP
December 12/95		74/76.2	Dec 12- 14 - no data	JP
January 29/96			storm	
January 31/96			to February 07 = -980 * 1.23 NTU's	
February 07/96		74/60.1		JP
April 21/96			to June 25 = *1.85 NTU's	
June 25/96	0/0	74/39.9		JP
August 22/96			to September 04 = * 1.15 NTU's	
September 04/96	0/.07	74/64.5		JP
November 17/96			to December 12 = * 0.91 NTU's	

December 12/96	0/0	74/81.5	Dec 21-Feb 12/97 - no data	JP/GL
April 15/97	0/0	74/77	April 18 th cleaned probe	
June 19/97			to September 04 = * 1.37 NTU's	
September 04/97	0/0.2	74/54		GL
December 10/97	0/0	74/74	Nov 10- May 01 - no data	GL
May 01/98				
July 30/98	0/0	74/76	Aug 09- Sept 24 - no data	
December 03/98	0/0	74/75		GL
April 14/99	0/0.1	74/80	Probe out May 18, 1999	GL

Station 4

Date	Calibration low	Calibration high	Field Notes and Corrections	Tech
March 22/94	0/7	90/89	initial calibration	TS
June 15/94	0/1.4	79/104		TS
June 22/94			to July 06 = *1.26 NTU's	
July 06/94	0/0	84/66.6		TS
August 12/94		80/88.8		TS
September 30/94		93/86.5		TS
November 08/94				TS
December 01/94		90/95	Dec01-Jan 24 - no data - low water	TS
March 03/95	0/12	80/80.3	stream ice covered	TS
April 19/95		80/83		JP
May 09/95			to May 17 = *1.12 NTU's	
May 17/95	0/0	76/68.1		JP
June 28/95			to July 06 = *1.13 NTU's	
July 06/95		74/65.4		JP
August 03/95	0/0	74/78.3	Aug 03-05 - no data	JP
September 15/95	0/0	74/70		JP
October 16/95			to October 20 = * 0.89 NTU's	
October 20/95	0/0	74/83	large storm Nov 08	JP
November 16/95	0/0	74/76.5		JP
December 3/95		74/80.1		GL/JP
February 07/96			April 21-May 01- 9998.9 NTUs	
April 21/96			to May 01/96 = - *811 NTU's	
June 12/96			to June 26 = *1.48 NTU's	
June 26/96	0/0	74/50		GL/JP

September 04/96	0/0	74/70		GL/JP
December 11/96	0/0	74/73		GL/JP
March 05/97			to April 15 = -494 NTU's	
March 07/97			March 07-April 15 - 9998.9 NTUs	
April 15/97	0/0	74/74.2	Leaves and sand on sensor	GL
May 02/97			to May 27 = - 737 NTU's	GL
June 07/97			turbidity sensor removed from site	GL
June 07/97			to September 05 = *1.48 NTU's	
September 05/97	0/0	74/50		
October 28/97			to November 12 = * 1.09 NTU's	
November 12/97	0/0	75/69	lots of dirt around probe	GL
April 30/98			probe out since Dec /97	
July 30/98	0/0	74/76	clean - stream low	GL
December 02/98	0/10	74/72.5	Probe removed	GL

Station 5

Date	Calibration low	Calibration high	Field Notes and Corrections	Tech
March 22/94			Placement of Probe	TS
April 23/94			to June 08 = *1.61 NTU's	
June 08/94		90/56	May 02-jun14 data gaps	TS
July 05/94		84/87		TS
August 11/94		80/91		TS
September 28/94		93/90		TS
December 11/94		83/79		TS
January 17/95			to January 23 = *0.87 NTU's	
January 23/95		83/95.6	to March 04/95 = -46 NTU's	TS
March 04/95	0/2.2	83/85	leaves on Probe	TS
April 21/95		73/82	April 29- 15- no data	TS
May 16/95			slight amt of dirt	
May 16/95			sandy-repositioned	JP
June 06/95		76/77.4		JP
July 03/95	0/0	74/71.5	July06-Aug 03- no data	JP
July 31/95		76/79.9	July06-Aug 03- no data	GL/JP
August 03/95	0/0	74/77.5		GL/JP
September 13/95	0/0	74/73		GL/JP
September 15/95	0/0	74/59.7		GL/JP
September 18/95			to October 18 = *0.87 NTU's	

October 18/95		74/85	silt' on sensor	GL/JP
November 08/95			to December 12 = *1.45 NTU's	
December 12/95	0/3.9	74/51.0		GL/JP
January 31/96			to February 08 = -146 * 0.25 NTU's	
February 08/96	0/0	76/61	sand on sensor	GL/JP
March 14/96			to April 17 = *0.69 NTU's	
April 17/96	0/3.3	74/108		GL/JP
June 14/96			to June 25 = * 1.48 NTU's	
June 25/96	0/0	74/50		GL/JP
September 03/96	0/2.4	76/82.0	dirt on sensor	GL/JP
October 15/96			to December 12 = *0.86 NTU's	
December 12/96	0/0	74/86		GL/JP
April 16/97	0/3.3	74/80	Jan 07-20/97 no data	GL
September 05/97	0/0	74/70		GL
December 04/97	0/0	75/82	sediment on sensor	GL
February 24/98			to March 10 = - 698 NTU's	
March 10/98			cleaned probe - storm Feb. 22	GL
			March 30-April 29 - turb = 9998.9	
April 29/98	0/0	74/63	sand on sensor	GL
October 31/98			Oct 31 - Nov 10 - turb = 9998.9	GL
November 02/98			to November 10 = - 997 NTU's	
April 13/99	0/0.1	74/69		GL
July 10/99			to July 14 = *1.58 NTU's	
July 14/99	0/0	74/46.7		GL
October 26/99	0/1.5	74/78.3	leaves in pvc pipe	GL

Station 6

Date	Calibration low	Calibration high	Field Notes and Corrections	Tech
March 24/94			initial calibration	TS
April 12/94			April 08-12 - 9998.9 NTU	TS
April 18/94			to April 26 = - 906 NTU's	
May 21/94			to June 08 = * 1.42 (lots pollen)	
June 08/94	0/2	90/63	silt' on sensor	TS
June 28/94			to July 05 = * 0.73 NTU's	
July 05/94		84/115		TS
August 07/94			to August 11 = * 0.88 NTU's	

August 11/94		80/91		TS
September 28/94			Oct 04-15 - no data	TS
			Nov 03-16 - no data	
			Nov 19-23 - no data	
December 12/94		83/86.3		TS
January 31/95			to March 05 = - 32 NTU's	
March 31/95			to May 15 = * 1.20 NTU's	JP
April 21/95		76/78		
May 15/95				JP
June 06/95		76/78.9		AO/JP
July 01/95			to July 04 = * 0.74 NTU's	
July 04/95		76/102		JP
July 19/95			to August 03 = * 1.74 NTU's	
August 03/95		74/42.4	maybe 74/72.4	JP
September 13/95		74/70.1		JP
October 15/95			to October 18 = - 12 NTU's	
October 18/95	0/0	74/79.7	leaves on probe	JP
November 08/95			to November 16 = * 1.43 NTU's	
November 16/95		74/51.6		JP
November 29/95			to December 12 = * 0.60 NTU's	
December 12/95		74/124	Ice in turb solution	JP
January 25/96			to January 28 = -856 * 1.63 NTU's	
January 30/96			to February 08 = - 437.5 * 1.63 NTU's	
February 08/96		76/46.5	probe dirty and moved by ice	JP
April 07/96			to April 17 = * 1.32 NTU's	
April 17/96		74/55.7		JP
May 12/96			to May 13 = - 954 * NTU's	
June 20/96			to June 24 = -172 NTU's	
June 25/96		74/78		JP
September 03/96	0/0	76/84		JP
September 18/96			to September 20 = - 100 NTU's	
October 19/96			to October 21 = - 960 NTU's	
October 21/96			to December 10 = * 0.91 NTU's	
December 10/96		74/85		GL
December 20/96			to April 16 = - 0.74 NTU's	
April 16/97	0/16	74/100	probe moved with silt and leaves	GL
May 19/97			to May 27 = - 135 NTU's	

June 14/97			to June 19 = - 520 NTU's	
July 17/97			to September 03 = * 1.15 NTU's	
September 03/97	0/0	76/66		GL
November 13/97			to December 04 = * 1.12 NTU's	
December 04/97	0/0.2	75/67		GL
February 13/98			to February 18 = - 450 NTU's	
April 21/98			to April 30 * 0.80 NTU's	
April 30/98	0/0	74/86	sensor slightly dirty	GL
May 05/98			to June 12 = - 450 NTU's	
June 12/98			to June 14 = - 150 NTU's	
June 14/98			to June 22 = - 240 NTU's	
July 12/98			to July 12 = - 165 NTU's	
July 28/98			to July 29 = - 245 * 0.82 NTU's	
July 29/98	0/1.5	74/90.3	July 28-29 - missing data	GL
November 02/98			to November 10 = - 640 NTU's	
November 10/98			to December 03 = * 0.78 NTU's	
December 03/98	0/0	74/95		GL
February 10/99			to February 18 = - 84 NTU's	
February 18/99			to April 13 = * 0.84 NTU's	
April 13/99	0/0	74/88	leaf in cond sensor/sand in case	GL
April 13/99			to July 26 = * 0.87 NTU's	
July 26/99	0/5.5	74/84.7	dirt and sand on sensor	GL
August 11/99			to August 13 = - 26 NTU's	
October 18/99			to October 27 = * 0.86 NTU's	
October 27/99	0/0	74/86	leaves and dirt on sensor	GL
March 15/00	0.0/2.7	74/73.4	April 06 to April 09 = -94	GL
			April 13 to April 16 = - 561	
			April 16 to May 07 = -562	
			May 25 to June 01 = - 599	
			June 04 to June 07 = - 454	
June 08/00	0.0/10	74/92.5	June 07 to July 17 = - 106	GL
			July 17 to August 02 = - 150	
			August 06 to August 09 = -517	
			August 13 to August 16 = -561	
September 14/00	0.0/0.0	74/68.1	August 16 to Sept. 09 = - 562	GL
			Sept 27 to October 03 = -619	
			October 06 to October 09 = -454	
			October 25 to November 01 = - 501	
			Nov. 07 to Nov. 14 = - 100	
			Nov. 15 to Nov. 28 = - 93	

November 28 to December 01 = -
49

Dec. 01 to Dec. 06 = - 68

Dec. 06 to Dec. 31 = - 515

Station 9

Date	Calibration low	Calibration high	Field Notes and Corrections	Tech
April 19/95		83/72.7	Initial calibration	PD/JP
April 21/95			to April 24 = -458 NTU's	
April 24/95			to May 16 = * 1.19 NTU's	
May 16/95		76/64		PD/JP
June 08/95			to June 09/95 = *1.12 NTU's	
June 09/95		76/67.6		AO/JP
July 05/95	0/0	74/92.2		JP
August 08/95	0/0	74/67.9		JP
September 12/95	0/0	74/75.4		JP
October 16/95	0/0	74/86.1	few leaves on sensor	JP
November 20/95	0/0	74/76.2		JP
December 13/95			no calibration numbers	JP
January 25/96			to January 26 = - 700 NTU's	
January 26/96			to February 07 = - 186 NTU's	
February 07/96			cleaned probe	JP
February 08/96			to February 12 = *1.19 NTU's	
February 22/96			to March 12 = * 1.19 NTU's	
March 12/96	0/0	74/62	sediment on probe	JP
April 20/96			to May 08 = - 10 NTU's	
May 11/96			to May 13 = - 25 NTU's	
May 16/96			to May 21 = - 60 NTU's	
June 27/96			to July 04 = * 1.25 NTU's	
July 04/96	0/2.2	74/59	may not have been calibrated	GL/JP
July 28/96			to September 03 = *1.03 NTU's	
September 03/96	0/2.1	74/71.3		GL/JP
October 14/96			to October 22 = - 40 NTU's	
December 09/96			to December 09 = -20 *0.83 NTU's	
December 11/96	0/5.6	74/89.2		GL/JP
April 07/97			to April 14 = - 280 * 0.87 NTU's	
April 14/97	0/0	74/85.3	June 14-July 24 - no data	GL
May 11/97			to May 27 = -70 NTU's	
September 03/97			to September 05 = * 1.27 NTU's	

September 05/97	0/2.5	75/59	Dec 13/97-Jan 21/98 - no data	GL
November 10/97			to December 04 = *0.74 NTU's	
December 04/97	0/0	75/101	Probe under ice	GL
May 04/98	0/0	74/70.5	minor dirt	
November 08/98			to November 10 = -130 NTU's	
December 02/98	0/4.0	74/83.5		GL
February 14/99			S4 probes replaced in s9 ***	
March 25/99			to February 18 = - 360 NTU's	
April 14/99	0/0	74/74	to April 14 = - 460 NTU's	
July 16/99	0/2.4	74/75	High turb - log on casing- dirty	GL
September 25/99			dirt-silt-algae	GL
			to October 26 = - 85 NTU's	
		74/94	silt and dirt	GL
October 26/99				
March 15/00	0.0/2.7	74/73.4	Lis pH sensors replace in s9 probes	
			January 01/00 to Mar 15 = -5.0	GL
			Mar. 15 /00 to Mar. 29/00 missing data	
			March 29 to 30 = -9990	
			March 30 to May 04 = -5.0	
June 08/00	0/0	74/96	June 04 to June 08 = - 94	GL
September 12/00	0/0	74/29.3		GL
			November 19 to Nov. 30 = -95	
			November 30 to Dec.06= -560	

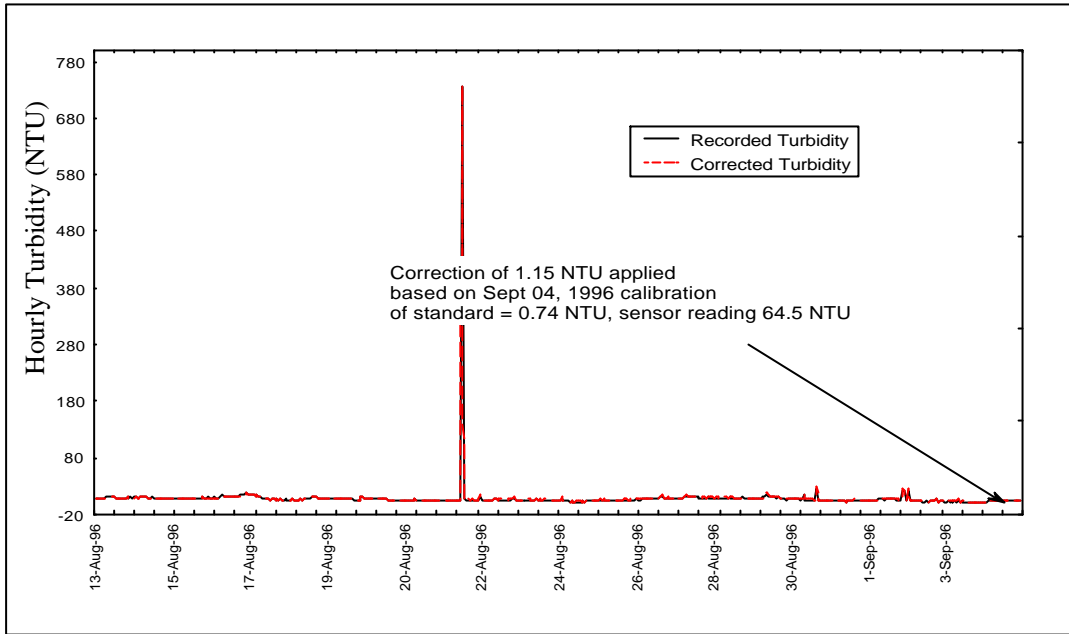


Fig. A1.1. Examples of corrections applied to hourly turbidity (NTU) as a result of information gathered from September 03, 1996 calibration sheet.

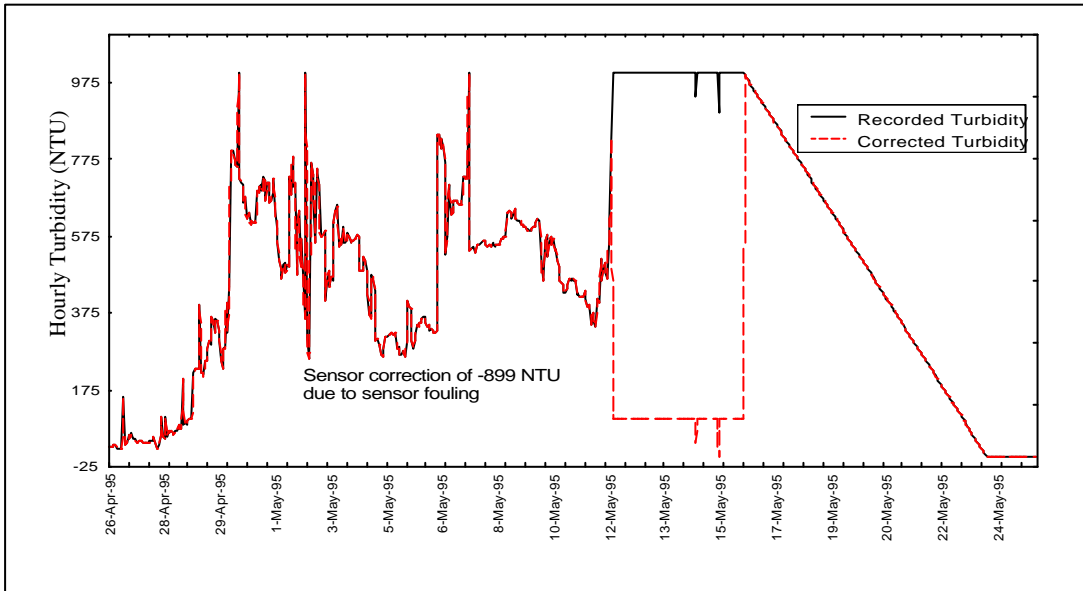


Fig. A1.2. Examples of corrections applied to turbidity events in the Hayward Brook watershed Study.

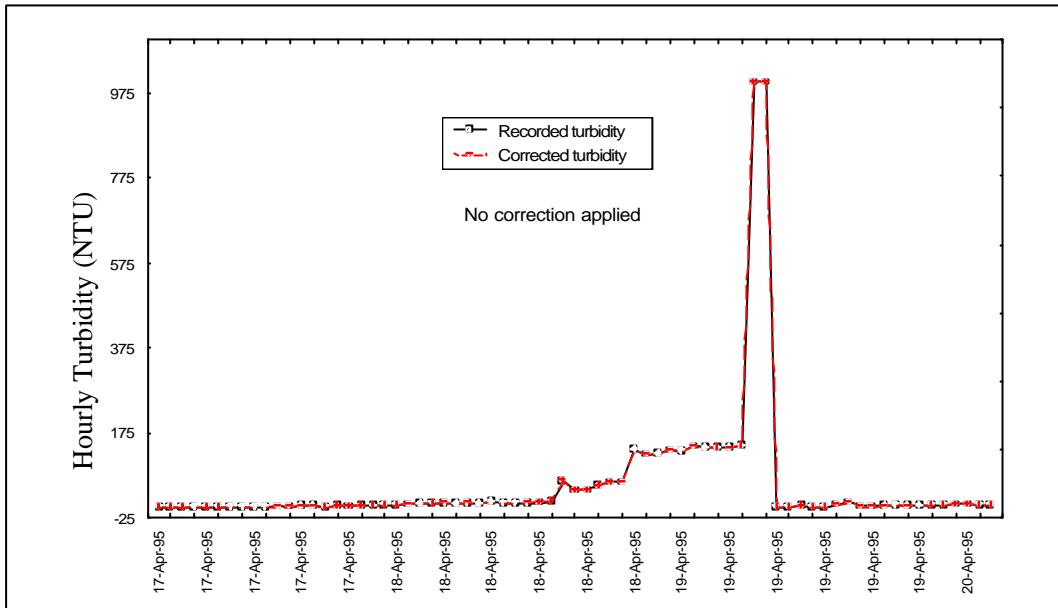


Fig. A1.3. No corrections applied to turbidity events in the Hayward Brook Watershed Study.

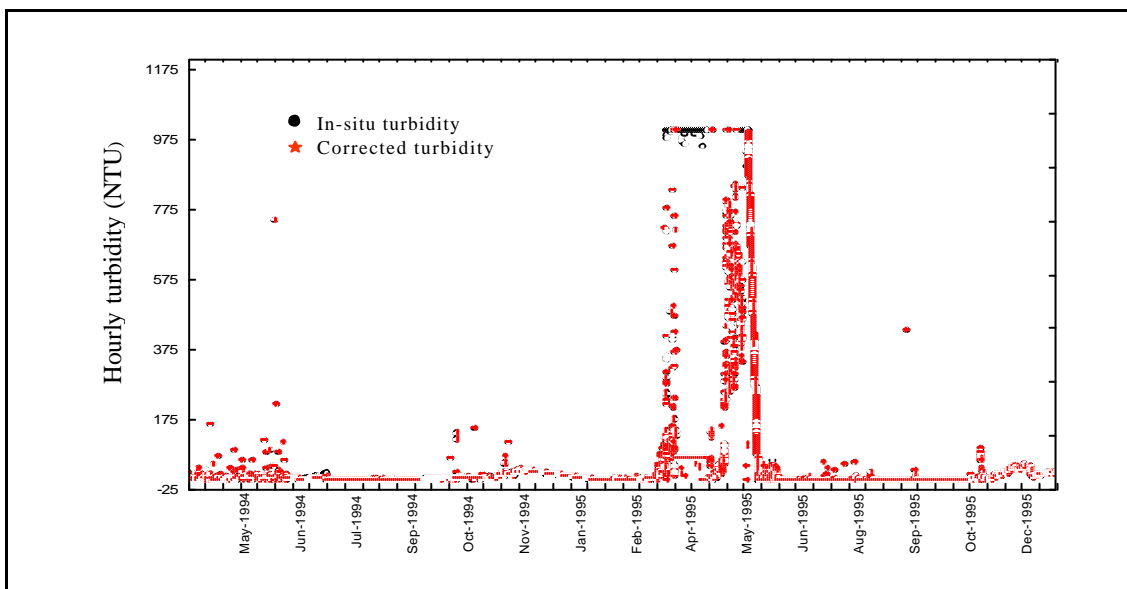


Fig. A1.4. An example of the hourly in-situ data (NTU o) and corrected turbidity data (*) for Stream 1 of Hayward Brook during April 1994 to December 1995.

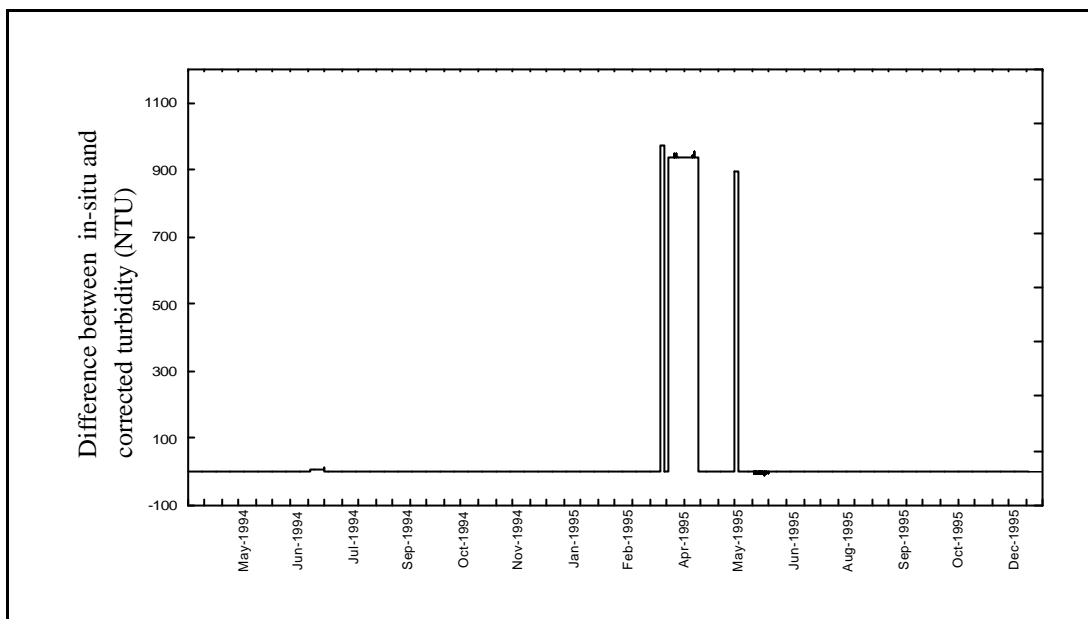


Fig. A1.5. Difference between in-situ data (NTU o) and corrected turbidity data (*) for Stream 1 of Hayward Brook during April 1994 to December 1995.

APPENDIX 2

RANDOM PULSE TURBIDITY MODEL LISTING

$\text{cumulative_sediment_load}(t) = \text{cumulative_sediment_load}(t - dt) + (\text{sed_cum}) * dt$

INIT cumulative_sediment_load = 0

INFLOWS:

$\text{sed_cum} = (2.79 * \text{turbidity_peak} * (1 - \exp(-0.0069 * \text{turbidity_peak})) * \text{annual_daily_discharge} / 10^6)$

$\text{cumulative_turbidity}(t) = \text{cumulative_turbidity}(t - dt) + (\text{turb_cum}) * dt$

INIT cumulative_turbidity = 0

INFLOWS:

$\text{turb_cum} = \text{turbidity_peak}$

$\text{cum_peak_signal_count}(t) = \text{cum_peak_signal_count}(t - dt) + (\text{peak_signal_counter}) * dt$

INIT cum_peak_signal_count = 0

INFLOWS:

$\text{peak_signal_counter} = \text{if peak_signal}=0 \text{ then } 1/dt \text{ else } 0$

$\text{max_peak_height}(t) = \text{max_peak_height}(t - dt) + (\text{max_peak_height_initiator} - \text{max_peak_height_reset}) * dt$

INIT max_peak_height = $-(1/'b'_constant) * \text{LOGN}(1 - \text{random_number}^{(1/0.35)}) / dt$

INFLOWS:

$\text{max_peak_height_initiator} = \text{if } \text{peak_signal_counter} > 0 \text{ then } -(1/'b'_constant) * \text{LOGN}(1 - \text{random_number}^{(1/0.35)}) / dt \text{ else } 0$

OUTFLOWS:

$\text{max_peak_height_reset} = \text{if } \text{peak_signal_counter} > 0 \text{ then } \text{max_peak_height} / dt \text{ else } 0$

$\text{peak_signal}(t) = \text{peak_signal}(t - dt) + (\text{peak_to_peak_interval_generator} - \text{peak_signal_reset}) * dt$

$\text{INIT peak_signal} = -(1/'c'_constant) * \text{LOGN}(1 - (\text{RANDOM}(0,1)^{(1/0.32)}))$

INFLOWS:

$\text{peak_to_peak_interval_generator} = \text{if } \text{peak_signal} > 0 \text{ then } 0 \text{ else } -(1/'c'_constant) * \text{LOGN}(1 - (\text{RANDOM}(0,1)^{(1/0.32)})) / dt$

OUTFLOWS:

$\text{peak_signal_reset} = \text{if } \text{peak_signal} > 0 \text{ then } 1 \text{ else } 0$

$\text{time_during_peak}(t) = \text{time_during_peak}(t - dt) + (\text{peak_intitiator} - \text{peak_terminator}) * dt$

$\text{INIT time_during_peak} = 0$

INFLOWS:

$\text{peak_intitiator} = \text{if } \text{peak_signal} > 0 \text{ then } 1 \text{ else } 0$

OUTFLOWS:

$\text{peak_terminator} = \text{if } \text{peak_signal} = 0 \text{ then } \text{time_during_peak} / dt \text{ else } 0$

$\text{turbidity_peak}(t) = \text{turbidity_peak}(t - dt) + (\text{turbidity_intitiator} - \text{turbidity_terminator}) * dt$

INIT turbidity_peak = 0

INFLOWS:

turbidity_initiator = 'a'_constant*max_peak_height*time_during_peak*exp(-0.72*('a'_constant^0.5)*time_during_peak)/dt

OUTFLOWS:

turbidity_terminator = turbidity_peak*envelop_adjuster

'a'_constant = 13.2

'b'_constant = 0.0067

'c'_constant = 0.0307

annual_daily_discharge = 7499

peak_decay_adjuster = 0.15

random_number = random(0,1)

APPENDIX 3

FRESH WATER CREEK TURBIDITY AND SUSPENDED SEDIMENT DATA

Date	Time	Stage (m)	Discharge (m ³ sec ⁻¹)	Turbidity (NTU)	Suspended sediment Concentrations (mg l ⁻¹)
11/16/1999	10:15	0.442	17.38	20	32.8
11/16/1999	13:15	0.609	29.75	37	23.1
11/16/1999	15:00	1.177	89.83	88	146.5
11/21/1999	13:00	0.743	41.53	20	6.6
11/29/1999	20:15	1.91	202.3	240	518
11/29/1999	21:15	2.038	225.6	224	444.1
11/29/1999	23:00	1.974	213.8	155	255.6
11/30/1999	8:15	1.489	133.3	58	68.3
11/30/1999	15:30	1.429	124.4	93	115.5
11/30/1999	17:45	2.145	245.8	150	262.9
12/2/1999	9:15	0.944	62.1	28	30.4
12/6/1999	20:00	0.489	20.59	20	2.7
12/7/1999	9:30	0.97	58.14	21	17.4
12/8/1999	7:15	1.059	75.22	30	13.6
12/9/1999	4:15	1.802	183.5	94	189.8
12/9/1999	6:30	1.809	184.6	97	198.9
12/9/1999	9:00	1.75	174.7	70	82
12/9/1999	12:30	2.018	221.8	78	108.5
12/9/1999	19:30	2.017	221.7	61	71.3
12/10/1999	19:45	1.096	79.76	30	16.4
12/12/1999	22:45	1.219	95.24	100	127.3
12/13/1999	1:30	1.91	202.2	99	128.4
12/13/1999	6:00	1.669	161.4	60	62
12/13/1999	9:15	1.489	133.2	44	32
12/13/1999	22:00	1.121	82.84	29	11.6
12/18/1999	15:00	0.688	36.54	20	4.9
12/19/1999	17:30	0.593	28.46	17	3.4
12/19/1999	18:15	0.589	28.14	16	2.2
12/31/1999	14:00	0.351	11.81	3	0.4
1/4/2000	6:30	0.448	17.78	30	13.9
1/4/2000	9:15	0.46	18.59	23	4.3
1/4/2000	11:15	0.466	18.99	20	2.8
1/4/2000	14:15	0.564	26.16	24	7
1/4/2000	21:45	0.619	30.58	22	4.1
1/10/2000	17:45	0.6	29.03	13	7.6
1/10/2000	18:45	0.676	35.43	22	17.4
1/10/2000	22:15	1.168	88.68	94	150.4
1/10/2000	23:30	1.987	216.1	213	489.4
1/11/2000	0:15	2.703	362.2	388	1172
1/11/2000	0:45	3.177	475	535	1620
1/11/2000	2:15	4.265	778.4	696	2156
1/11/2000	5:15	4.651	900	593	1797
1/11/2000	6:15	4.315	793.6	527	1512
1/11/2000	6:45	4.144	741.6	500	850.3

Date Time Stage Discharge Turbidity Suspended sediment

		(m)	(m ³ sec ⁻¹)	(NTU)	Concentrations (mg l ⁻¹)
1/11/2000	7:15	3.921	675.7	473	1232
1/11/2000	8:15	3.498	558.2	418	1030
1/11/2000	9:15	3.134	464.2	364	823.1
1/11/2000	10:00	2.939	416.8	290	729.5
1/11/2000	12:30	2.439	304.9	211	548.2
1/11/2000	19:30	1.85	191.8	125	212.5
1/11/2000	19:45	1.836	189.4	126	219.3
1/11/2000	21:45	1.739	172.8	117	179.4
1/12/2000	0:30	1.626	154.5	103	135.5
1/12/2000	14:15	1.245	98.67	58	67.4
1/12/2000	14:30	1.241	98.23	55	51.5
1/12/2000	22:30	1.074	77.01	46	37.8
1/14/2000	1:30	1.483	132.4	87	220.6
1/14/2000	4:00	2.1	237.3	193	638.9
1/14/2000	6:15	3.032	439.1	321	1084
1/14/2000	8:00	3.939	681.1	508	1669
1/14/2000	10:15	4.532	861.5	494	1626
1/14/2000	10:45	4.42	826.3	443	1422
1/14/2000	11:00	4.416	824.9	417	1261
1/14/2000	11:45	4.168	748.8	364	1127
1/14/2000	13:30	3.665	603.5	298	810.1
1/14/2000	16:15	3.031	438.9	224	594.5
1/14/2000	22:30	2.177	252	131	245.9
1/15/2000	9:00	1.599	150.2	76	129.6
1/15/2000	22:00	1.544	141.6	56	54.8
1/16/2000	0:30	1.79	181.4	82	176.4
1/16/2000	2:00	2.528	323.7	227	735.7
1/16/2000	3:45	2.863	398.9	257	795.4
1/16/2000	4:45	2.748	372.3	198	560.2
1/16/2000	6:15	2.48	313.5	149	387.2
1/16/2000	10:00	2.138	244.4	101	236.1
1/16/2000	19:45	1.648	157.9	61	34
1/17/2000	10:30	1.235	97.38	39	47
1/18/2000	7:30	0.943	61.91	30	24.6
1/19/2000	16:00	1.585	148	86	217.7
1/19/2000	19:30	2.064	230.3	142	276.5
1/19/2000	22:00	1.978	214.5	98	163.8
1/20/2000	4:00	1.631	155.3	60	86.2
1/21/2000	7:45	1.005	68.97	30	20.9
1/21/2000	8:30	1.007	69.21	30	17.4
1/21/2000	9:45	0.99	67.16	30	12.3
1/21/2000	10:15	0.981	66.14	30	15.3
1/21/2000	11:45	0.965	64.36	30	16.8
1/22/2000	16:30	0.886	55.78	26	8
1/24/2000	11:30	0.673	35.19	35	27.9
1/24/2000	12:15	0.671	35	21	6.4
1/25/2000	14:45	0.86	53.06	23	15.7
1/26/2000	14:45	0.948	62.54	29	11.9
1/27/2000	18:00	0.733	40.61	21	7.9

Date Time Stage Discharge Turbidity Suspended sediment

		(m)	(m ³ sec ⁻¹)	(NTU)	Concentrations (mg l ⁻¹)
1/30/2000	5:45	0.553	25.33	24	23.4
1/30/2000	7:30	0.581	27.49	26	16.4
1/30/2000	22:45	1.288	104.5	59	60.7
1/31/2000	16:15	1.073	76.92	37	16.9
2/1/2000	7:45	0.921	59.5	30	7.7
2/3/2000	20:00	0.589	28.11	16	4.9
2/4/2000	2:45	0.567	26.4	16	7.9
2/4/2000	10:45	0.545	24.73	15	2.5
2/4/2000	13:30	0.539	24.26	15	2.5
2/4/2000	14:00	0.54	24.33	15	10.4
2/4/2000	14:30	0.538	24.18	15	1.5
2/5/2000	10:00	0.547	24.88	22	8.9
2/5/2000	14:00	0.634	31.84	23	12.9
2/5/2000	15:15	0.69	36.69	20	17.6
2/6/2000	13:15	0.769	43.99	30	6.3
2/12/2000	6:15	0.532	23.71	47	54
2/12/2000	7:30	0.542	24.45	51	43.3
2/12/2000	9:45	0.583	27.68	30	18
2/12/2000	13:00	0.832	50.21	29	27.3
2/14/2000	1:15	1.188	91.3	94	151.6
2/14/2000	2:30	1.782	180	206	533.6
2/14/2000	4:00	2.639	347.9	343	1108
2/14/2000	6:30	3.074	449.4	349	930.1
2/14/2000	7:15	2.915	411.2	282	696.5
2/14/2000	8:30	2.79	382	214	567.1
2/14/2000	11:15	3.259	495.7	217	592.2
2/14/2000	12:00	3.98	693	417	1491
2/14/2000	12:30	4.346	803.2	565	2056
2/14/2000	12:45	4.369	810.3	596	2024
2/14/2000	13:30	4.345	802.9	525	1452
2/14/2000	13:45	4.265	778.2	492	1296
2/14/2000	14:15	4.172	750	414	816.1
2/14/2000	14:45	4.111	731.7	357	988.1
2/14/2000	15:00	4.107	730.5	342	1007
2/14/2000	16:45	4.086	724.3	293	690
2/14/2000	17:00	3.961	687.4	287	681.6
2/14/2000	17:45	3.795	639.9	286	605.8
2/14/2000	20:00	3.274	499.6	215	425.5
2/14/2000	21:15	3.12	460.7	188	399.1
2/14/2000	21:45	3.02	436.2	178	341.3
2/14/2000	22:15	2.921	412.6	167	497.5
2/14/2000	22:45	2.86	398.2	158	321.2
2/14/2000	23:30	2.779	379.5	150	311
2/15/2000	4:15	2.411	298.9	101	190.4
2/15/2000	13:30	1.885	197.9	62	97.5
2/17/2000	11:30	1.128	83.69	30	23.1
2/22/2000	9:15	0.529	23.49	21	17.9
2/22/2000	14:15	1.033	72.13	54	172.6

Date	Time	Stage (m)	Turbidity (NTU)	Suspended sediment Concentrations (mg l ⁻¹)	
2/22/2000	16:45	1.246	98.83	86	114.3

2/23/2000	4:00	1.383	117.7	60	58
2/24/2000	22:45	1.013	69.85	30	19.1
2/26/2000	19:30	0.969	64.83	52	50.2
2/26/2000	22:00	1.543	141.5	95	177.6
2/27/2000	1:15	1.61	151.9	105	148.7
2/27/2000	6:15	1.528	139.2	62	58.2
2/27/2000	13:45	1.631	155.2	61	81.4
2/27/2000	16:15	1.868	194.9	84	167.8
2/27/2000	22:45	2.479	313.3	179	444.9
2/28/2000	5:30	2.704	362.4	142	307.5
2/28/2000	9:30	2.342	284.8	100	185.5
2/28/2000	10:15	2.26	268.3	95	244
2/28/2000	17:45	1.819	186.4	61	97.7
2/28/2000	20:30	1.715	168.9	57	71.6
2/29/2000	6:30	2.085	234.4	82	118.7
2/29/2000	18:30	2.042	226.3	60	97
3/2/2000	10:15	1.156	87.16	30	19.8
3/4/2000	6:15	0.877	54.85	26	10.7
3/4/2000	19:00	1.544	141.6	81	133.7
3/5/2000	0:15	1.596	149.7	60	78.2
3/6/2000	1:00	1.106	80.93	30	12.7
3/9/2000	17:30	0.827	49.7	23	14.5
3/11/2000	17:15	0.851	52.15	27	10.7
3/16/2000	5:45	0.8	47.01	88	87
3/16/2000	7:15	0.883	55.48	61	34.9
3/16/2000	11:00	1.44	126	88	120.2
3/16/2000	16:00	1.326	109.7	62	45.1
3/19/2000	3:30	0.837	50.72	60	15.1
3/19/2000	17:00	0.9	57.28	26	7.3
3/24/2000	19:00	0.549	25	22	5.7
3/25/2000	11:45	0.533	23.79	28	9.4
3/26/2000	2:00	0.535	23.98	27	3.2
4/15/2000	15:30	0.38	13.49	13	15.9
4/15/2000	16:30	0.38	13.49	12	13.7
4/16/2000	19:30	0.448	17.78	16	6.9
4/16/2000	22:45	0.529	23.5	21	15.5
4/17/2000	9:30	1.148	86.21	77	81
4/17/2000	16:30	1.264	101.2	83	92
4/17/2000	23:15	1.596	149.7	103	110.2
4/18/2000	7:30	1.191	91.66	62	67.7
4/20/2000	2:00	0.624	30.97	30	7.4
4/22/2000	17:00	0.684	36.13	21	12.5
4/23/2000	3:15	0.648	33	26	13.7
4/24/2000	0:15	0.564	26.13	20	4.9
4/24/2000	1:15	0.563	26.05	19	1.6
4/27/2000	13:45	0.47	19.27	21	9.3
4/27/2000	22:00	0.78	45.05	23	10.6
4/28/2000	19:30	0.682	35.95	30	4.9
4/30/2000	12:30	0.522	23.01	26	10.6

Date	Time	Stage (m)	Discharge (m ³ sec ⁻¹)	Turbidity (NTU)	Suspended sediment Concentrations (mg l ⁻¹)
5/1/2000	22:15	0.479	19.9	26	3.7

5/2/2000	22:15	0.463	18.79	22	6.4
5/8/2000	13:30	0.519	22.76	21	7.1
5/10/2000	0:30	0.657	33.77	23	12.8
5/10/2000	2:15	0.736	40.85	51	46.7
5/10/2000	4:15	0.884	55.55	77	87
5/10/2000	5:45	1.289	104.6	82	119.2
5/10/2000	10:15	1.507	135.9	102	132.8
5/10/2000	18:30	1.359	114.3	61	48.6
5/11/2000	23:15	1.069	76.48	45	13
5/11/2000	1	1.062	75.64	44	13.6
5/13/2000	9:45	0.729	40.24	23	5.4
5/13/2000	16:30	0.694	37.05	20	2.8
5/13/2000	20:00	0.671	34.98	27	3.2
5/14/2000	0:15	0.652	33.39	28	5.5
5/14/2000	1:45	0.646	32.81	27	4.4
5/14/2000	7:45	0.628	31.29	24	3.4
5/14/2000	10:30	0.623	30.91	18	2.6
5/14/2000	16:15	0.605	29.42	18	2
5/14/2000	17:30	0.603	29.27	16	2.2
5/15/2000	14:00	0.569	26.56	20	4.9