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# Spatial and temporal patterns of fluvial suspended sediment yield from eastern North America

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# SPATIAL AND TEMPORAL PATTERNS OF FLUVIAL SUSPENDED SEDIMENT YIELD FROM EASTERN NORTH AMERICA

by

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# ABSTRACT

A knowledge of spatial and temporal patterns of sediment yields and an understanding of the factors that determine those patterns have theoretical, environmental and socio-economic significance. To assess the change in sediment yields (in both space and time) a data base of 193 river gauging sites spanning the eastern provinces of Canada and eastern United States was compiled. The original source of the data was the United States Geological Survey data base (obtained from a Hydrosphere Data Inc. cd-rom) and Environment Canada (HYDAT) data base, which included stream discharge, sediment loads and basin areas, with record lengths of one year through 42 years. The results indicate non-stationarity in spatial patterns of yields and oscillations in the time series(for stations with at least 15 years of record length). The temporal trend spans eastern North America, indicating the significance of climatological conditions (wetter or dryer than normal weather conditions). The shifting spatial patterns can additionally be attributed to changes in land use and land disturbance. The magnitude differences between sediment yields across the study area (with a general inverse relationship of increasing sediment yield with decreasing latitude) are also attributed to availability of erodible material.

Since the 1970s, many of the gauging stations have been closed, making long-term time series analysis difficult. As time goes on, the availability of basic hydrologic data and subsequent analysis become even more important in furthering our theoretical knowledge of global environmental change, and in planning and design of reservoirs and dams.

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I am here, completing this thesis because of my family. This thesis is for all of them. The return trips back home supplied replenishing breaths of fresh air time and again.Thank you mom and dad for giving me that atlas in grade three and for raising me to be the person that I am today. Thank you to my husband and best friend Scott, for all the support and understanding and for helping me to see this through to the end. Here's to the beginning of the next stage of our life together.

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# INTRODUCTION

## 1.1 Aims and Purpose of the Research

Geomorphology: "...the core of the subject is the comprehension of the form of the ground surface and the processes that mould it" (Goudie, 1994, p.228). The form of the ground surface is modified by both mechanisms of uplift and land surface degradation. It is a goal for the geomorphologist to understand the relationship between uplift and erosion in order to further comprehend the form of the ground surface. Is a landscape in decay, or are forces of uplift outweighing erosion? Attempts to assess the different rates of denudation and uplift have certainly been made (Schumm, 1963; Ahnert, 1970; Yoshikawa, 1985). And yet, although researchers have long known that erosion and tectonics continuously shape Earth's surface, our understanding of the innumerable associated processes remains inadequate (Stallard, 1995).

A range of approaches (e.g. thermochronology and calculations of offshore sediment volumes) can provide estimates of longer-term denudation rates. However, it is generally accepted that data for contemporary rates derived from sediment and solute discharges of rivers generally provide one of the most valuable sources of denudation estimates, especially for linking variations in denudation rates to controlling variables (Summerfield & Hulton, 1994). Sediment and solute yields ( $t\ km^{-2}\ a^{-1}$ ) may be converted into volumes of material removed ($m^3\ km^{-2}\ a^{-1}$ ) and subsequently into depths of material removed (i.e. mm $ka^{-1}$). It is usual to then convert the stream load to an equivalent volume of solid rock by assuming a mean rock density (bulk density: which is generally given as 2.65 Mg $m^{-3}$) (Gregory & Walling, 1973). When the accuracy of sediment yields are questioned, this will inevitably affect the reliability of estimates of denudation. If denudation rates are extrapolated backwards in time to obtain estimates of landscape development, an understanding of the temporal patterns of fluvial sediment loads is imperative. Our understanding of the spatial and temporal characteristics of sediment loads remains vague, and yet studies of denudation continue to rely on sediment yield values. Sufficient data are now available for regions of the globe to undertake more thorough considerations of the patterns of yields through time and space.

The purpose of this thesis is to study fluvial suspended sediment yields through the investigation of:

- spatial sediment yield patterns from eastern North America
- temporal sediment yield patterns from eastern North America
- factors which may explain the spatial and temporal variations

The consequence of this study will be a better understanding of the spatial and temporal patterns of sediment yields at a regional scale.

## 1.2 Importance of the Research

A knowledge of sediment yield patterns and an understanding of the factors that determine those patterns are important for a number of reasons. The following sections will describe the *theoretical*, *environmental* and *socio-economic* significance of patterns of sediment yields.

### 1.2.1 Theoretical Implications

Fournier (1960) emphasized that sediment yield data for the world's rivers provide a valuable means of studying the global denudation system. Many researchers have estimated denudation using suspended sediment yield as their indicator of surface lowering (Dole and Stabler 1909; Fournier 1960; Schumm 1963; Judson and Ritter 1964; Ahnert 1970; Yoshikawa 1985; Bartolini et al. 1996). Denudation, the laying bare of underlying rocks or strata by the removal of overlying material, is dependent upon two things: the intensity with which the different agents operate, singly or collectively; and the ability of the ground surface and the underlying materials to withstand the stresses generated (Ollier, 1981). The intimate connection between the nature of the applied force and the actual resistance of earth materials makes it difficult to produce realistic generalizations about denudation rates. Quantitative models of landscape evolution depend on estimates of the rates at which landscape change occurs (Summerfield & Hulton, 1994). The accuracy of these models depends on realistic estimates of sediment yields, which are utilized to estimate denudation rates. The importance of understanding sediment yield patterns goes beyond estimating rates of erosion and denudation. There has also been an increasing awareness of the significance of determining sediment loads of rivers for the purpose of assessing material transport to the world's oceans (Curtis et al.,1973; Milliman & Meade, 1983), geochemical cycling (Walling & Webb, 1987), and the supply of material to the coastal environment (Meybeck, 1997). Recent interest in the broader context of global environmental change promoted by the International Geosphere Biosphere Programme (IGBP) has also directed attention to the potential relationship between climate change and sediment fluxes (Walling, 1997b). Sufficient data has now been collected in order to estimate better the temporal and spatial variation of sediment yields. An increased understanding of patterns of yields can then be used with more confidence for theoretical applications.

### 1.2.2 Environmental Implications

It has been said that streams are the gutters down which flow the ruins of the continents (Leopold et al., 1964). The visible signs are obvious: muddy water, choked ditches, silted streams. The downstream result of soil erosion and increased sediment loads of rivers is water pollution. Eckholm (1976) contended that "...excess sediment is the major form of human-induced water pollution in the world today" (p.128). Sediment is estimated to be the largest single water pollutant by volume - at least 700 times that of sewage (N.S. Department of the Environment, 1988, p.7b). Increases in sediment loads can result in degradation or destruction of fish and wildlife habitat. Subsequent sedimentation of lakes reduces mean depth and volume and provides substrates for nuisance aquatic plants. Increased sediment yields from river basins as a consequence of accelerated erosion caused by vegetation clearance, land use change, and other forms of catchment disturbance have been increasingly recognized as a major environmental problem in many areas of the world (Walling, 1997b).

### 1.2.3 Socio-Economic Implications

Sediment transport by rivers has an important social and economic dimension that adds to the importance of this study. Turbidity caused by excess sediment in water destroys the aesthetic attraction of lakes and streams, thereby spoiling recreational activities such as swimming and fishing. Deterioration of the quality of municipal water supply for extended periods eventually results in the necessary implementation of sophisticated and expensive water purification treatments (Walling & Webb, 1996b). Increasing sediment loads in rivers can cause sedimentation of reservoirs and navigation channels and impairment of irrigation techniques. Mahmood (1987) estimated that major reservoirs of the world are losing their storage capacity at the rate of 1% or 50 $km^3$ per year ($6 billion annual economic loss) as a result of sedimentation.

Against this background, the theoretical and applied importance of this research can be placed into context, given that the following questions remain unanswered:

(1) How different were sediment yields in the past (from those calculated at present)?

(2) How different are they today (from those calculated for the past)?

(3) How might they change in the future? (Walling, April 28, 1997a)

## 1.3 Previous Suspended Sediment Load Research

### 1.3.1 The Global Scale

Global database compilations of suspended sediment have been undertaken by a number of researchers (e.g. those listed in Table 1.1) for a variety of purposes, such as estimating denudation, determining the sediment discharge to the oceans and mapping global patterns of sediment yields. These databases have been lacking in their geographical coverage. Of the 193 locations from eastern North America utilized in the analysis for this research, Table 1.1 includes the number of those locations included by each of the noted authors. Some of the authors listed in Table 1.1 (e.g. Milliman & Meade, 1983; Meade et al., 1990) were conducting regional analyses, which one would expect to include more detailed data coverage, although this is not the case. An example of the global database coverage in such studies (Table 1.2) includes the names of rivers used in two global studies of sediment yields (Fournier, 1960; Holeman, 1967). The rivers used in this thesis are noted in bold lettering. Drainage basin area and period of record, if noted by the author, are included in addition to the estimates of sediment yield for both authors. Additional authors could not be included in this table for the

| AUTHOR | # of rivers from eastern N.A. in study |
|---|---|
| Dole & Stabler (1909) | 16 |
| Judson & Ritter (1964) | 9 |
| Holeman (1967) | 2 |
| Curtis et al. (1973) | 5 |
| Meade (1982) | 9 |
| Milliman & Meade (1983) | 1 |
| Dedkov & Mozzherin (1984) | ca. 12 (U.S. and Canada) |
| Jansson (1988) | 13 (4 of these in eastern Canada) |
| Meade et al. (1990) | 4 |
| Milliman & Syvitski (1992) | 9 |

Table 1.1: Global and regional studies utilizing sediment load data and the corresponding number of locations from this research included in those studies. (All locations are in the United States portion of the study area with the two noted exceptions.)

following reasons:

- raw data were not included in their study
- drainage area was not included, from which to determine sediment yield
- sediment yield was recorded in imperial units, without the raw data from which to convert to metric units (without tonnage of sediment or basin area included).

The table is organized according to increasing sediment yields based on Fournier's database (these locations were not utilized by Holeman) and then in increasing sediment yield for both Holeman and Fournier. Several comments can be made about Tables 1.1 and 1.2. A notable observation is the lack of coverage from eastern North America. Although much of the data had been available, only a small

| NAME | LOCATION | DRAINAGE AREA* | Sediment Yield FOURNIER, 1960 | PERIOD OF RECORD | Sediment Yield HOLEMAN,1967 | PERIOD OF RECORD |
|---|---|---|---|---|---|---|
| Sainte-Croix R. | USA | 19 | 1 | 1932-1933 | | |
| **Merrimac R.** | **USA** | **13** | **2.4** | **n/a** | | |
| Kennebec R. | USA | 15 | 2.4 | n/a | | |
| Saint-Johns R. | Canada | 19 | 2.5 | n/a | | |
| Penobscot R. | USA | 22 | 2.8 | n/a | | |
| Connecticut R. | USA | 29 | 2.8 | n/a | | |
| **Hudson R.** | **USA** | **36** | **10** | **n/a** | | |
| Minnesota R. | USA | 41 | 10 | 1932-1933 | | |
| **Susquehanna R.** | **USA** | **71** | **12** | **n/a** | | |
| Marias R. | USA | 24 | 14.3 | 1929-1930 | | |
| Allegheny R. | USA | 29 | 23 | n/a | | |
| Saline R. | USA | 7 | 23 | 1929-1930 | | |
| **Raritan R.** | **USA** | **3** | **25** | **n/a** | | |
| Iowa R. | USA | 8 | 26 | n/a | | |
| Scioto R. | USA | 17 | 26 | n/a | | |
| **Passaic R.** | **USA** | **2** | **26** | **n/a** | | |
| Niobra R. | USA | 32 | 27 | 1929-1930 | | |
| Chippewa R. | USA | 23 | 27 | 1932-1933 | | |
| **James R.** | **USA** | **27** | **33** | **n/a** | | |
| Little Sioux R. | USA | 11 | 36 | 1929-1930 | | |
| James R. | USA | 56 | 41 | 1929-1930 | | |
| Illinois R. | USA | 69 | 45 | n/a | | |
| Neches R. | USA | 9 | 46 | 1930-1950 | | |
| Grand R. | USA | 14 | 50 | 1929-1930 | | |
| Smoky Hill R. | USA | 50 | 50 | 1929-1930 | | |
| Mobile R. | USA | 109 | 52.8 | n/a | | |
| Solomon R. | USA | 18 | 55 | 1929-1930 | | |
| Apalachicola R. | USA | 48 | 55.6 | n/a | | |
| Black R. | USA | 5 | 56.2 | 1932-1933 | | |
| Kanawha R. | USA | 28 | 70 | n/a | | |
| Cannonbal R. | USA | 9 | 73 | 1929-1930 | | |
| Altamaha R. | USA | 36 | 75 | n/a | | |
| Republican R. | USA | 66 | 76 | 1929-1930 | | |
| Big Sandy R. | USA | 10 | 77 | n/a | | |
| Monongahela R. | USA | 20 | 78 | n/a | | |
| Savanna R. | USA | 29 | 81 | n/a | | |

| NAME | LOCATION | DRAINAGE AREA* | Sediment Yield FOURNIER, 1960 | PERIOD OF RECORD | Sediment Yield HOLEMAN,1967 | PERIOD OF RECORD |
|---|---|---|---|---|---|---|
| Linking R. | USA | 8 | 85 | n/a | | |
| Kentucky R. | USA | 20 | 85 | n/a | | |
| Cimarron R. | USA | 41 | 127 | 1930-1931 | | |
| Yellowstone R. | USA | 173 | 130 | 1929-1930 | | |
| Youghiogeny R. | USA | 4 | 142 | n/a | | |
| Adige R. | Italy | 10 | 160 | 1932-1935 | | |
| Elkorn R. | USA | 17 | 177 | 1929-1930 | | |
| Loup R. | USA | 35 | 200 | 1929-1930 | | |
| Big Blue R. | USA | 24 | 216 | 1929-1930 | | |
| Green R. | USA | 105 | 243 | 1930-1941 | | |
| Root R. | USA | 3 | 249.5 | 1932-1933 | | |
| Garonne R. | France | 10 | 250 | 1839-1846 | | |
| Upper Iowa R. | USA | 3 | 329 | 1932-1933 | | |
| Grand R. | USA | 6 | 508 | 1929-1930 | | |
| Isere R. | France | 5 | 615 | 1839-1846 | | |
| Si-kiang R. | China | 400 | 660 | n/a | | |
| Drac R. | France | 4 | 780 | 1839-1846 | | |
| Rhone R. | Switzerland | 5 | 853 | 1904-1905 | | |
| Thompson R. | USA | 4 | 907 | 1929-1930 | | |
| Whei R. | China | 145 | 3369 | 1935 | | |
| Oder R. | Poland | 109 | | | | |
| Dnepr R. | USSR | 434 | | | 1.22 | 1961-64 |
| St. Lawrence R. | Canada | 1290 | | | 2.52 | 1938-39 |
| Rhine R. | Holland | 145 | | | 2.8 | n/a |
| Loire R. | France | 121 | | | 3.15 | n/a |
| Niger R. | Nigeria | 1114 | | | 3.5 | n/a |
| Yenesei R. | USSR | 2471 | | | 4 | n/a |
| Red R. | Canada | 287 | | | 4.25 | 1942,43 |
| Colorado R. | Argentina | 9895 | | | 5.6 | 1956-58;61-64 |
| Vistula R. | Poland | 193 | | | 5.6 | 1938-64 |
| Ural R. | USSR | 194 | | | 7.9 | 1946-53 |
| San Joaquin R. | USA | 36 | | | 8 | 1936-41,47 |
| Don R. | USSR | 378 | | | 8.74 | 10/56-9/60 |
| Saskatchewan R. | Canada | 324 | | | 12.86 | 1932-40,46,47 |
| Volga R. | USSR | 1350 | | | 12.88 | 1954-60;62-64 |
| Negro R. | Argentina | 95 | | | 14 | 1934,35,38-40 |
| | | | | | 14 | n/a |

| NAME | LOCATION | DRAINAGE AREA* | Sediment Yield FOURNIER, 1960 | PERIOD OF RECORD | Sediment Yield HOLEMAN,1967 | PERIOD OF RECORD |
|---|---|---|---|---|---|---|
| Congo R. | mouth, Congo | 4015 | | | 16 | n/a |
| Danube R. | USSR | 816 | | | 23.8 | n/a |
| Medjerdah R. | Tunisia | 8150 | | | 24 | 5 years |
| Seine R. | France | 44 | 17 | 1863-1866 | 25 | pre 1865 |
| Murray-Darling R. | Australia | 1072 | | | 30 | n/a |
| Alabama R. | USA | 57 | | | 33.89 | 10/52-9/60 |
| Parana R. | Argentina | 2305 | | | 35 | n/a |
| Uruguay R. | Argentina | 389 | | | 35 | n/a |
| Columbia R. | USA | 266 | | | 35.12 | 6/50-7/52 |
| Euphrates | Syria | 121 | | | 35.6 | 1962-64 |
| Nile R. | Egypt | 2979 | | | 37 | |
| Snake R. | USA | 268 | | | 44.33 | 4/50-7/52 |
| **Delaware R.** | **USA** | **18** | **19** | **n/a** | **50** | **10/49-9/57** |
| Sabine R. | USA | 13 | 52.6 | 1932-1950 | 51 | 1932-1950 |
| Ob R. | USSR | 2448 | | | 58 | 1938-44 |
| **Potomac R.** | **USA** | **38** | **33** | **n/a** | **59.67** | **n/a** |
| Amazon R. | Brazil | 5777 | | | 63 | n/a |
| Tisza R. | Hungary | 156 | 64 | n/a | 64 | n/a |
| Ohio R. | USA | 198 | | | 68.71 | 10/41-9/42 |
| Pearl-West R. | China | 312 | | | 89.5 | n/a |
| Orinoco R. | Venezuela | 950 | | | 91 | n/a |
| Mississippi R. | USA | 3223 | | | 97 | 10/51-9/65 |
| Chao Phya R. | Thailand | 106 | | | 107 | 1956-63 |
| Rio Grande R. | USA | 69 | 293 | 1897-1941 | 123.83 | 10/47-9/56 |
| Ishikari R. | Japan | 13 | | | 134 | 1960 |
| Cheliff R. | Algeria | 22 | | | 140 | 16 years |
| Rio San Juan | Mexico | 31 | 156 | 1934-1941 | 156 | 1934-41 |
| Yellowstone R. | USA | 173 | | | 158.86 | 1929-31 |
| Missouri R. | USA | 1370 | | | 159 | 1949-54 |
| Colorado R. | USA | 637 | 85 | 1930-1950 | 212 | 10/25-9/57 |
| Mekong R. | Thailand | 795 | | | 213 | n/a |
| Tone R. | Japan | 12 | | | 239 | 1951 |
| Pecos R. | USA | 10 | | | 246.7 | 10/48-9/57 |
| Garonne R. | France | 10 | | | 250 | 1839-46 |
| Yangtze R. | China | 1943 | 420 | 1912-1922 | 256 | n/a |
| Kabul R. | Pakistan | 90 | | | 262 | 1961,1962 |
| Arno R. | Italy | 8 | | | 275.5 | 1936-42; 54-64 |

| NAME | LOCATION | DRAINAGE AREA* | Sediment Yield FOURNIER, 1960 | PERIOD OF RECORD | Sediment Yield HOLEMAN,1967 | PERIOD OF RECORD |
|---|---|---|---|---|---|---|
| Kosi R. | India | 62 | | | 278 | n/a |
| Inn R. | Germany | 10 | | | 319 | 1953-1960 |
| Tiber R. | Italy | 17 | 473 | 1930-1935 | 342.5 | 1933-46,49-63 |
| Brazos R. | USA | 90 | 350 | 1924-50 | 350.7 | 1924-50 |
| Indus R. | West Pakistan | 969 | 455 | 1902-1925 | 449 | 1902-25 |
| Mahanadi R. | India | 132 | | | 465.8 | n/a |
| Caroni R. | Venezuela | 91 | | | 523 | 1935-65 |
| Tigris R. | Irac | 80 | 654 | 1918-1919 | 653 | 1918,1919 |
| **Irrawaddy R.** | **Burma** | **430** | **700** | **1869-1879** | **696** | **n/a** |
| **Rhine R.** | **Switzerland** | **12** | **843** | **1893-1912** | **728** | **n/a** |
| **Red R.** | **North Vietnam** | **119** | | | **1089** | **n/a** |
| **Bramaputra R.** | **East Pakistan** | **665** | | | **1091** | **n/a** |
| **Drin R.** | **Albania** | **12** | | | **1226** | **1960-63** |
| **Damodar R.** | **India** | **20** | | | **1419** | **n/a** |
| **Chenab R.** | **Pakistan** | **33** | | | **1511.7** | **1961,1962** |
| **Ganges R.** | **India** | **956** | **1400** | **1874-1879** | **1518** | **1874-1879** |
| **Simento R.** | **Sicily** | **1.8** | | | **1995** | **1936-42;57-63** |
| **Eel R. (Scotia, Cal.)** | **USA** | **8** | | | **2063** | **10/57-9/60** |
| **Po R.** | **Italy** | **54** | **300** | **1928-1935** | **2281.7** | **1956-62** |
| **Kosi (Ganges Trib.)** | **India** | **62** | | | **2780** | |
| **Yellow R.** | **China** | **674** | **2490** | **1934** | **2799** | **1934-42** |
| **Semani R.** | **Albania** | **5** | | | **4140** | **1961-63** |
| **Waipaoa R.** | **New Zealand** | **1.6** | | | **6893.2** | **1960-64** |
| **Ching (Yellow Trib.)** | **China** | **57** | | | **7160** | **1932-45** |
| **Lo (Yellow Trib.)** | **China** | **26** | **1127** | **1934** | **7325** | **1934-45** |

Table 1.2: Locations of rivers in selected global sediment yield analyses (Fournier, 1960; Holeman, 1967). Rivers in this study are bolded.

*Drainage area is in thousands of square kilometers and sediment yields are in tonnes per square kilometer per year.

number of the 193 sites with sediment load data included in this study have been used. Of those that have been included by previous authors, many of the locations are found on large rivers, with a general lack of coverage for smaller rivers . So few locations from eastern North America (not to mention much of the globe) have been included in global evaluations of sediment yield patterns that over-generalization has been conducted at the largest scale. Nine locations spanning all of continental eastern North America do not account for all climatic regimes, types of geologic material and terrain. Since fluvial sediment loads are influenced by numerous factors, these among them, the few locations which have continually been used in such studies do not represent the complete picture of global patterns of sediment yields.

Almost forty years ago, Fournier had access to a limited data set (96 rivers). Most of these were from North America, no data were available for Africa, South America or Australasia and data for Asia mostly included rivers from the Yellow River basin which has very high sediment loads (Walling & Webb, 1996b). Subsequent analyses have used more extensive databases (Walling & Webb, 1983; Dedkov & Mozzherin, 1984; Jansson, 1988) resulting in more meaningful maps of global suspended sediment yield patterns. Despite this major expansion, the existing global data-base still possesses many limitations in terms of providing a comprehensive and reliable basis for investigating the global denudation system (Walling & Webb, 1996b). Data collection in many parts of the world either does not exist or is inadequate. The reliability of the data that are collected in many regions may also be questioned. Variations in the application of load calculation procedures has also been a problem, resulting in significantly different estimates of sediment yield (Walling, 1984; Walling & Webb, 1981, 1985, 1988). Broad trends have been explained based primarily on variations in precipitation and runoff (Langbein & Schumm, 1958; Fournier, 1960; Douglas, 1967; Jansson, 1988). More recently, the importance of relief influencing sediment yields has been reported (Pinet & Souriau, 1988; Milliman & Syvitski, 1992; Summerfield & Hulton, 1994). These results are highly generalized and more work is required to clarify the relative importance of relief, climatic and other factors that account for variations in sediment yields.

### 1.3.2 The Regional Scale

Some researchers have investigated suspended sediment yields in specific regions across the globe. Meade (1982) studied the sediment loads of rivers in the Atlantic drainage of the United States, emphasizing the sources, storage and sinks of the material, rather than the temporal and specific spatial nature of the data collected in this region. Milliman *et al.* (1987) investigated the changes in sediment loads of the Yellow River in China. Ashmore & Day (1988) and Church *et al.* (1989) considered sediment loads for basins in western Canada. Abernethy (1990) assembled data for a number of small catchments in Southeast Asia. Alford (1992) reported on the Chao Phraya river basin of northern Thailand. Stone & Saunderson (1996) detailed the patterns of sediment yields in southern Ontario. And yet, a clear understanding of the temporal and spatial patterns of sediment yields continues to elude us. There remains a need to undertake a comprehensive review and synthesis of the available data for *regions* throughout the world. The present availability of a spatially and temporally detailed regional database allows for the re-evaluation and revision of our understanding of sediment yields for one particular region (which is discussed in Chapter 2).

### 1.3.3 Sources of Error in Estimates of Sediment Yields

Sources of error in studies of sediment yields range in scale and magnitude. This research addresses some of the problems encountered in earlier suspended sediment yield studies. Errors which can not be eliminated and are inherent in such research will be addressed.

#### 1.3.3.1 Errors in Previous Studies

Some of the early global sediment yield estimates were based on limited databases (i.e. Fournier, 1960). The expectation might be that the spatial and temporal coverage since that time has become more detailed and databases are now significantly larger than those available to earlier researchers. Despite a major expansion in the availability of sediment load data as a result of the implementation of the IGBP programme, the existing global database still possesses many limitations in terms of providing a comprehensive and reliable basis for investigating sediment yield patterns across the globe (Walling & Webb, 1996b). Under-representation and lack of detail in many studies have resulted in large-scale generalization. Although more recent studies (e.g. Dedkov & Mozzherin, 1992) have resulted in improved representations of the generalized *global* pattern of suspended sediment yield, considerable scope now exists to refine these representations and estimates. The possibility to undertake a detailed study of *regional* patterns of yields is also much improved. Previous researchers did not have access to the length of record that has now been collected and compiled. In addition to mapping general patterns of sediment yields and determining denudation rates and fluxes of sediment to the world's oceans, such studies also strove to account for influencing factors such as relief, climate, geology and tectonic stability (Langbein & Schumm, 1958; Fournier, 1960; Strakhov, 1967) . Given the complexity of the controls involved, and the under-representation of many regions of the globe, clear relationships between the myriad factors have not been established. Changes and influences of human land uses and activities on sediment yields have also been lacking in previous studies. There is a gap in the present state of knowledge regarding the degree to which sediment loads of the world's rivers have changed within the recent past in response to the impact of both human activity and other aspects of environmental change (Walling, 1997b).

In addition to these limitations in the earlier research, the accuracy and reliability of the sediment load data itself have been questioned (Walling & Webb, 1981; Milliman & Meade, 1983; Walling, 1984). The admittedly variable quality of the data in global studies of sediment yields is often a result of differences in measurement techniques and in sampling procedures. The data in this thesis have been collected according to standard federal techniques and methods across state and provincial boundaries (U.S. DH-48, U.S. DH-42 or U.S. D-49 sediment samplers). However, data for global studies require rivers from developing countries which often have had questionable accuracy. Compounding the problem in global studies still further is the inability to gain access to original data; quoting published reports has resulted in the utilization of recycled data (Milliman & Meade, 1983). All data used in this study are original.

#### 1.3.3.2 Limitations in the Present Research

There are several limitations to conducting a large-scale research project such as this. The spatial coverage of the gauging stations is not even across the region. Even though all stations which were available were utilized, large areas of spatial interpolation exist. There are more gauging stations with sediment load information in some states (e.g. Pennsylvania) than others (e.g. Delaware, Massachusetts). This may partially be attributed to the relative size of those states. The differing spatial coverage of the gauging sites can also be a result of differing state jurisdictions and mandates for collecting this specific information. The gauging stations also have differing record lengths. Not all of the 193 gauging locations have overlapping coverage. The number of gauging stations with sediment load data is not constant through the duration of coverage in the study area (1930 - 1993). Coverage ranges from a high of 58 locations in 1974 to a low of 1 station in

1930-33 and 1944-47 (Figure 1.1). Suspended sediment load data collection peaked (globally) through the 1970s followed by a subsequent decline into the 1990s. The reason for the drop in data collection was a belief that the "general picture" (Grabs, 1999) was known, and that knowledge could simply be extrapolated into the future.

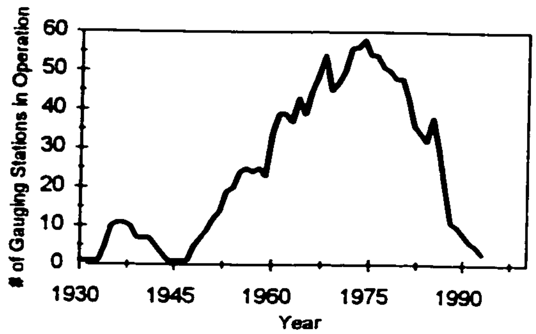



Figure 1.1: Number of gauging stations with sediment load data for each of the years of record in this study (1930-1993).

As of 1993 (the most recent year in the data set) there were only three stations collecting suspended sediment load data.

There remain issues which have been addressed by other authors (i.e. Walling, 1983; Walling & Webb, 1987) that are inherent in this study as well. If sediment loads are to ultimately be used as indicators of rates of erosion and soil loss, improved knowledge of the processes of sediment delivery is required to understand the lag between on-site erosion and the sediment yield at the outlet of the drainage basin. It is also important to stress that this study, in considering *suspended* sediment loads, does not attempt to make estimates of regional denudation since *bedloads* and *dissolved* loads are not included in the dataset. The bedload and dissolved loads transported by the rivers in the study area have not been included primarily because they have not been measured or even estimated for most sites. Infrequent samples would be unlikely to provide a meaningful representation of the pattern of variation. In addition to this, there remain questions regarding the source of the dissolved constituents of river water. Sources of solutes include rock weathering, atmospheric fallout of material of both oceanic and terrestrial origin, atmospheric gases, and decomposition and mineralization of organic material (Walling & Webb, 1986). Suspended loads in rivers may be anthropogenically-induced, but the source of the sediment is earth material. When the solutes are anthropogenic, these are entirely new inputs to the system and therefore additional care would be required in eventual estimates of denudation.

Limitations due to computational errors are also inherent in the mapping methodology. The technique employed in the production of surface maps of sediment yields (multiquadric interpolation, which is discussed in detail in Chapter 2) provides an exact surface, yet there remain errors between points. Among the various interpolation techniques that are available, the technique utilized in this analysis is believed to be most accurate (Chapter 2).

### 1.4 Summary

This thesis is an investigation of a regional dataset of suspended sediment yields. The reliability of studies which use sediment yield data is critical, since this information can ultimately form a basis for theories of landscape evolution as well as the effects of human activities on the land surface. In addition, sediment transport by rivers has an important social and economic dimension related to problems such as reservoir siltation as well as wide-ranging environmental implications, which underscores the importance of this study. Important uncertainties regarding the reliability of suspended sediment data exist because of differing periods of record, non-stationary river behaviour, and data reliability (Walling & Webb, 1996b).

The structure and organization of the thesis is as follows: Temporal and spatial patterns of sediment yields are presented at the regional-scale across eastern North America (Chapters Three through Seven). The stationarity of the data is explored (Chapter Four) and conclusions regarding the characteristics of the data will be made (Chapter Three). Explanations for the *temporal* variability of the data are suggested based on factors such as discharge and precipitation (Chapter Seven). Explanations for the *spatial* variability of the data are explored based on factors such as the human use of the land. This human influence may manifest itself in different ways, as is illustrated in Chapters Five (urbanization) and Six (agriculture). This unique mix of environmental and anthropogenic forces is explored through-out the thesis.

# CHAPTER TWO

# THE STUDY AREA

## 2.1 Choice of Area

The area under investigation covers provinces and states from eastern North America, including the provinces of Newfoundland, New Brunswick, Prince Edward Island and Nova Scotia and the states of Georgia, South Carolina, North Carolina, Virginia, Delaware, New Jersey, New York, Maryland, Maine, Massachusetts, Connecticut, and Pennsylvania. This region was selected for a number of reasons. Foremost, data was available for most states and all provinces in eastern North America, spanning a 42-year period in some locations. Few studies (as noted in Chapter One) had undertaken to investigate sediment yield in the eastern United States, and even fewer in the Canadian provinces. In compiling the datasets of the eastern U.S. and Canada, the purpose was to investigate the regional patterns of yields within this study area. In addition, the eastern region of North America held particular interest to the author, having lived in Nova Scotia for an extended period of time.

## 2.2 Availability of Eastern North American Suspended Sediment Load Data

The original sources of the daily suspended sediment load data were the United States Geological Survey (USGS WATSTORE database) and Environment

Canada (Surface Water and Sediment Data from the Water Survey of Canada). The data were available in compiled spreadsheet form in cd-rom format from private firms. The data for the eastern United States, which included all of the gauging sites in the eastern United States (up to and including 1992), were acquired from Hydrosphere Data Products Inc., based out of Boulder Colorado. After having been initially dismayed at the prospect of accessing and retrieving digital data from several states and databases, or retrieving the data from the USGS WATSTORE database, a time-intensive and often cumbersome task, this source was most useful. Similarly, the Canadian data (up to and including 1994) were retrieved from Greenland Engineering Group, based out of Toronto, Ontario. The original source for this database was Environment Canada's Water Resource Branch HYDAT files. All stream gauging sites in Canada are compiled on this cd. Both databases included all stream gauging locations and were searched for the locations with suspended sediment load data that had been collected continuously (at most locations twice daily) for at least one full year. Absent from the data set were the states of Maine, New Hampshire, Rhode Island, Vermont and Florida. Alternate sources of data were sought for these states. However, the sediment load information has either not been collected (e.g. Florida) or is in limited supply. Maine, for example, has only two stations which have collected sediment load data, and these were discontinued after one year of data collection (Nielson, 1996). Many of the states had numerous gauging stations, but only a few (2.47%) collected or had collected sediment data (Table 2.1). Scattered sites had samples of solute and bedload, but these were infrequent and insufficient to undertake any detailed investigation.

| State | Total # of Stations | Stations with Sed. Data |
|---|---|---|
| Connecticut | 255 | 7 |
| Delaware | 116 | 2 |
| Georgia | 775 | 13 |
| Maine | 203 | 2 |
| Maryland | 610 | 13 |
| Massachusetts | 306 | 2 |
| New Jersey | 596 | 15 |
| New York | 890 | 20 |
| North Carolina | 855 | 10 |
| Pennsylvania | 925 | 60 |
| South Carolina | 596 | 4 |
| Virginia | 626 | 16 |
| **Total** | 6753 | 167 |

**Table 2.1:** Total number of USGS gauging stations in the States investigated in this study, and the number of stations in each of those States with sediment load data.

Figures 2.1 and 2.2 show the locations of the gauging stations which were used in this study.

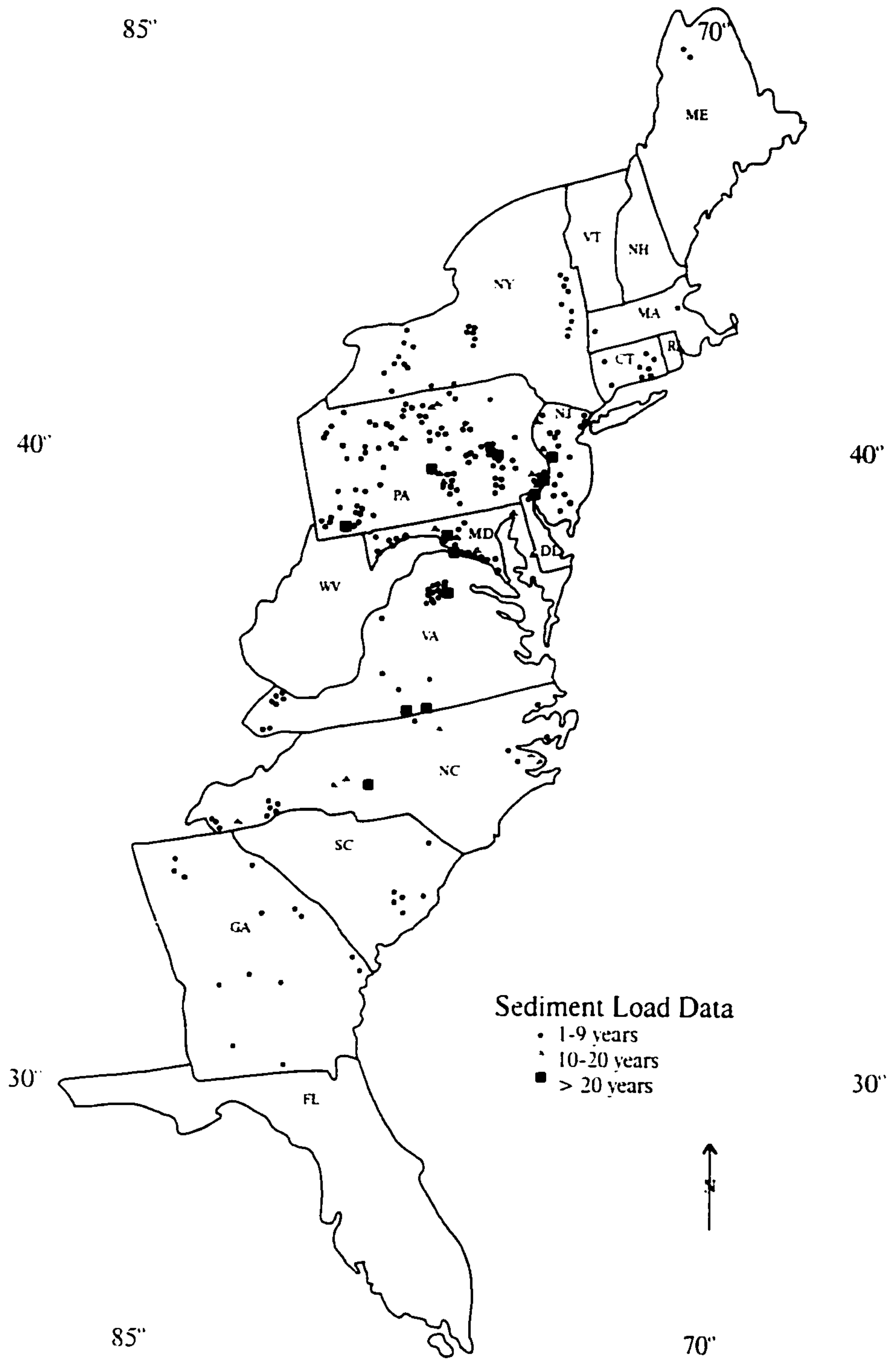



Figure 2.1: Location of Gauging Stations in the Eastern United States with 1-9 years, 10-20 years and >20 years of Continuous Sediment Load Data

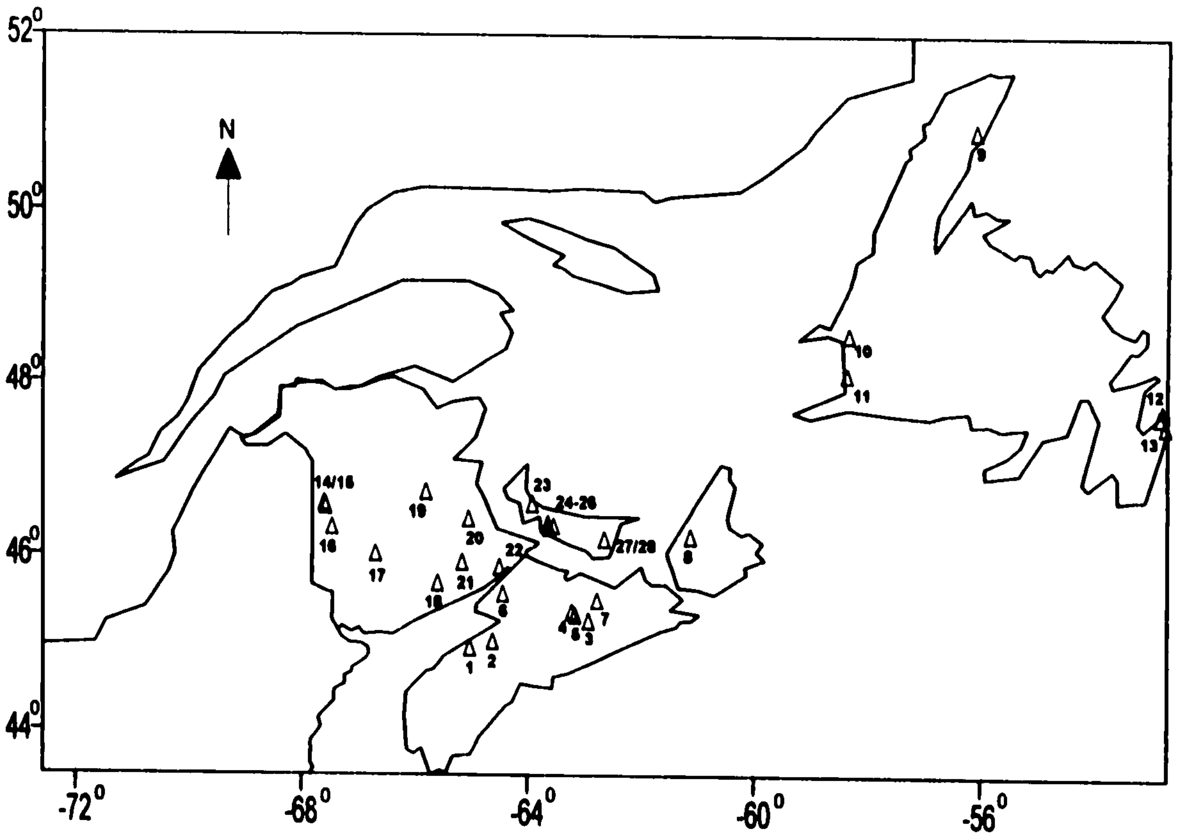



Figure 2.2: Location of Gauging Stations in the Eastern Canadian provinces. (The reference numbers next to the sites relate to the organization of the data for this section of the study area, which is further discussed in Chapter Six)

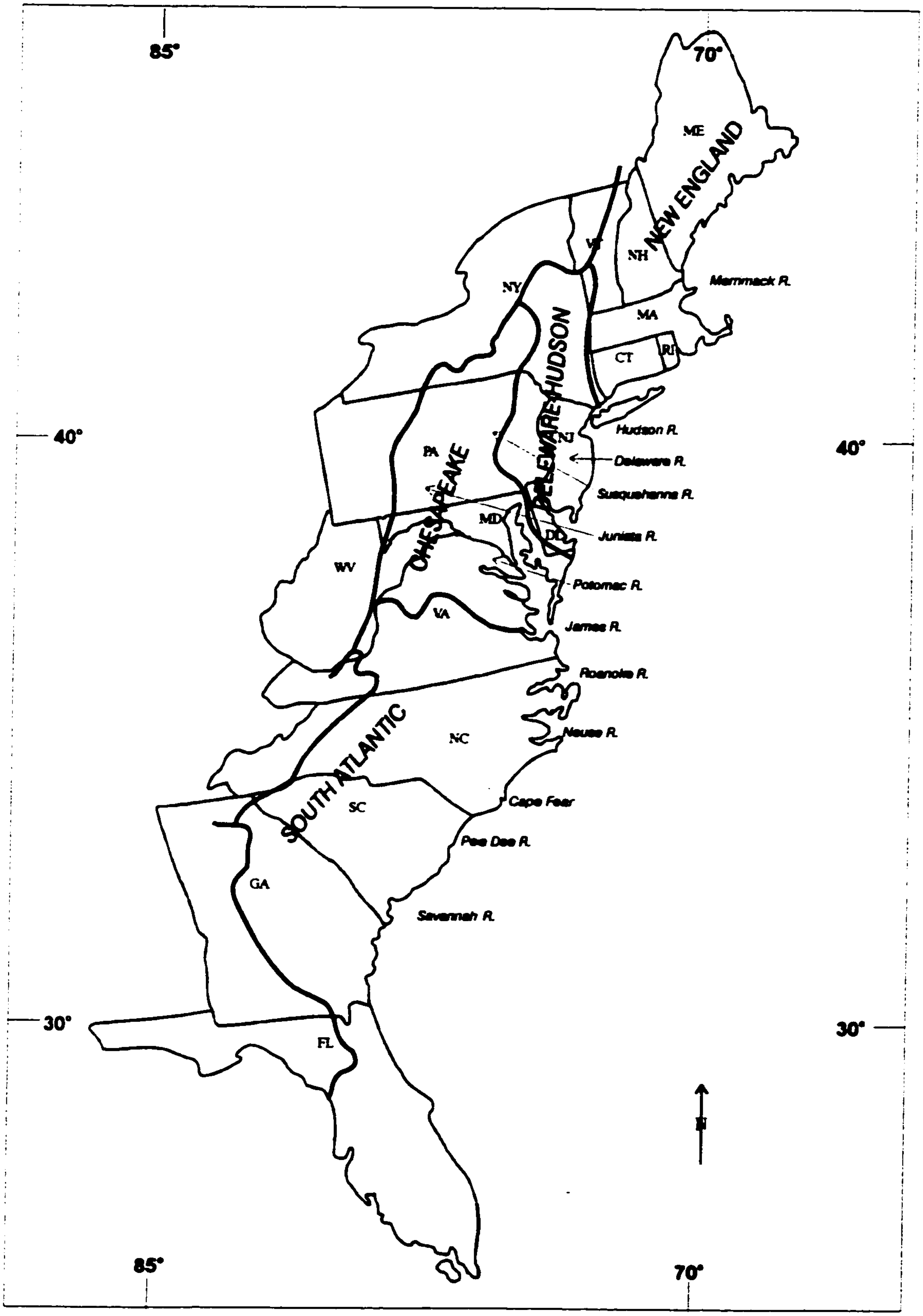


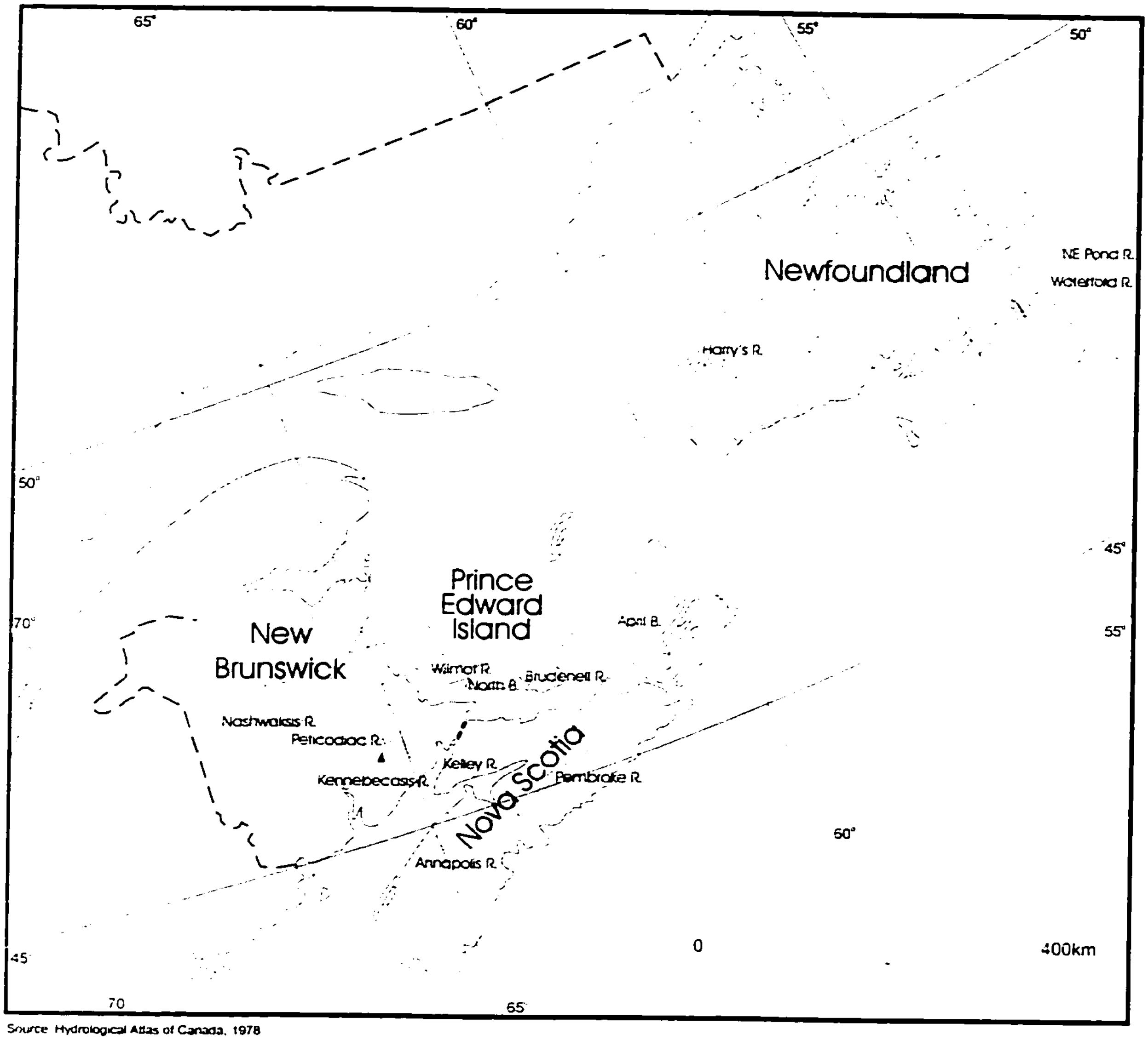

Figure 2.3: The Hydrology of the Eastern United States: Major Drainage Basins

## 2.3 Characteristics of the Region

### 2.3.1 Hydrography of eastern North America

The eastern United States can be divided into four major hydrographic regions (Figure 2.3). The New England region, approximately 153 000 km$^2$, extends through Maine, New Hampshire, Massachusetts, Rhode Island and Connecticut. Eleven of the total 193 gauging sites are situated within this region, primarily along tributaries to the Merrimack and Hudson Rivers. The Delaware-Hudson region, approximately 80 000 km$^2$, extends through eastern New York, Pennsylvania, New Jersey and Delaware. Approximately 58 of the gauging sites are located in this region, primarily on tributaries to, and main channels of the Hudson and Delaware Rivers. The Chesapeake region covers 148 000 km$^2$ including south-central New York, central Pennsylvania, Maryland and northern Virginia, with a total of approximately 70 gauging sites. The sites in this region are mostly located on the tributaries to, and main channels of the Susquehanna, Juniata and Potomac Rivers. The South Atlantic region is 440 000 km$^2$, stretching from southern Virginia through North and South Carolina, Georgia and Florida. Approximately 30 gauging sites are located within this area, primarily along the James, Roanoke, Neuse, Pee Dee and Savannah Rivers.

Figure 2.4 shows the major drainage patterns of the Atlantic provinces and locations of rivers with gauging stations situated on them. The drainage divides generally trend through the centre of New Brunswick, with channels flowing either to the Bay of Fundy or Gulf of St. Lawrence, and through the centre of Nova Scotia,



Source: Hydrological Atlas of Canada, 1978

Figure 2.4: Hydrology of Eastern Canada

dividing the channels flowing to the Bay and those flowing to the Atlantic Ocean. In Newfoundland the channels in the west flow to the Gulf of St. Lawrence, the rivers traversing the central lowlands and northeast coast flow to the north Atlantic and the rivers flowing down from the western mountains to the Avalon reach the Atlantic Ocean.

Throughout the eastern states and provinces mean annual precipitation typically varies from 1200 to 1600 mm $a^{-1}$ (Lins, 1990), although local lows can reach 900 mm $a^{-1}$.The *form* of precipitation varies considerably. Regions north of approximately 35° N latitude experience extended periods of subzero temperatures (with higher latitudes having the most extended periods). The major impact of temperature on the hydrology of any region is a change in runoff, as water is temporarily stored as snow and ice. When precipitation occurs as snow, ice forms on stream channels, lakes and ponds, and to a certain extent in the soil. The flow regimes of streams result in low runoffs during winter and major runoffs in spring or early summer when the snow and ice melt (Riggs, 1990). The mean annual discharge does not vary according to latitude, however the annual, seasonal pattern does differ as a direct result of the presence (at higher latitudes) or absence (at lower latitudes) of spring thaw. Figure 2.5 illustrates the difference between the hydrographs of a relatively high latitude basin and a relatively lower latitude basin. In environments with a clear seasonal variation in precipitation or temperature, stream flow (and consequently sediment yield) will be expected to vary fairly systematically throughout the year, being highest during the wet season or during the period when lower temperatures reduce water losses through evapotranspiration (Summerfield, 1991).

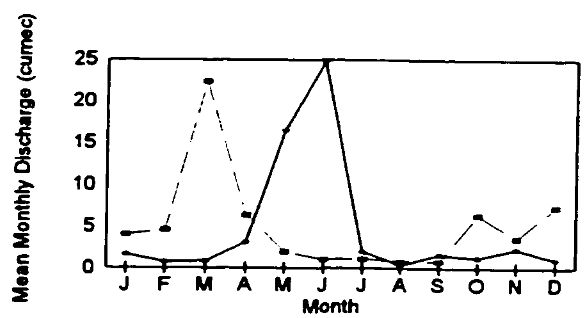



Figure 2.5: Mean monthly discharge for Northeast Brook, Newfoundland (Latitude: 505544 N), shown with a solid bold line, and for the Little River, Georgia (Latitude: 333646 N), shown with a dashed line.

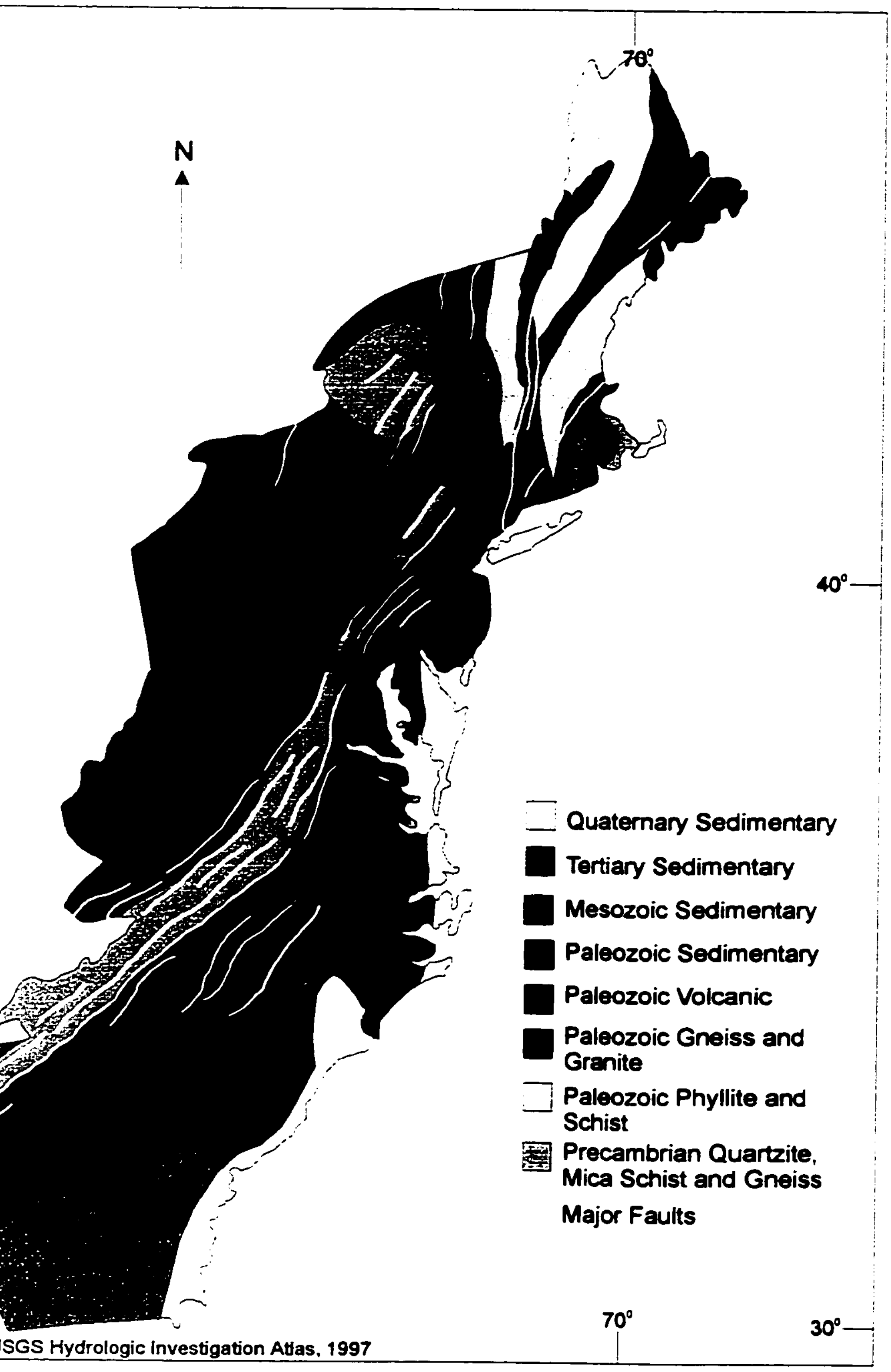
### 2.3.2 Surficial Hydrogeology and Aquifers of eastern North America

Depths of unconsolidated sediments tend to decrease with increasing latitude, as a result of the Pleistocene ice sheets which occupied much of the higher latitudes of eastern North America. In the Maritime provinces, surficial bedrock outcrops fringe the entire province of Newfoundland and the Highlands of Cape Breton and intermittent outcrops extend through eastern sections of Nova Scotia. Unconsolidated material is found through central Newfoundland, most of Nova Scotia and New Brunswick and all of Prince Edward Island, although the depth is limited in many areas. Surficial deposits are primarily sands and gravels of glacial origin, but are generally small in size and of limited distribution, being confined to valleys. The thin layer of till that covers most of the Maritimes is a relatively poor aquifer (Fisheries and Environment Canada, 1978). In the New England states (Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Vermont and New York) the surficial aquifer system also consists primarily of glacial deposits. Coarse-grained outwash and ice-contact deposits partially fill deeply incised bedrock valleys throughout the region. Reworked outwash partially fills valleys south of the glacial limit in western New York. Depth of unconsolidated material ranges from approximately 3 to 330 m (USGS, 1995). The unconsolidated deposits of Quaternary age are also located in the northern and western sections of the middle, eastern states (Pennsylvania, New Jersey, Delaware, Maryland, Virginia and North Carolina). There is a large range in depth of unconsolidated materials throughout this region. The aquifer system is thinner where parts of the underlying crystalline rock surface have been upwarped (e.g. Cape Fear Arch in North Carolina) and thicker where the crystalline rocks have been downwarped (e.g. Salisbury Embayment in Maryland/Delaware). Depths of unconsolidated material in this region range from approximately 390 to 1050 m, also tending to thicken towards the coast (USGS, 1997). The mountainous regions, however, have small surficial bedrock outcrops and thinner aquifers beneath ridges and hilltops, whereas thickest sequences tend to be located in valleys. In the southernmost section of the study area, in South Carolina and Georgia, greatest depths of unconsolidated material extend to 1500 m on the coastal plain (USGS, 1996).

### 2.3.3 Geology of eastern North America

The Appalachian Mountains form the dominant topographic feature of the region, lying between the interior of North America to the west, and the Coastal Plain to the east. The southern segment of the Appalachian Mountains can be divided into four geologic provinces. The Appalachian Plateau in the west is comprised predominantly of Paleozoic sedimentary rocks. The Ridge and Valley province and the Blue Ridge province, to the east of the Appalachian Plateau, are predominantly igneous, Paleozoic rocks, and the Piedmont province is made up of metamorphosed Paleozoic and Precambrian rocks. The northern segment of the Appalachians cannot be readily divided into subdivisions, ranging from sedimentary rocks in the west to igneous, metamorphic, and sedimentary rocks in the east (Fig. 2.6 and 2.7). The rocks in this region range in age from Precambrian to early Mesozoic, but those of Cambrian through Devonian age are the most widespread. Precambrian through Triassic age bedrock extends throughout the eastern Canadian provinces. Igneous and metamorphic rocks dominate the southern and eastern regions of Nova Scotia, while sedimentary rocks dominate Prince Edward Island, and New Brunswick. The oldest rocks in the Atlantic Provinces are found in southern New Brunswick, small outcrops in northern Nova Scotia and Cape Breton and the west and east coasts of Newfoundland (Gardner & Sevon,1989). Figure 2.8 indicates the locations of the major geologic divisions along eastern North America, which have been classified based on the geologic maps discussed.

The Pleistocene continental ice sheet covered the entire northern segment




ıre 2.6: Simplified Geologic Map of the Eastern United States:
jor Rock Units and Faults.

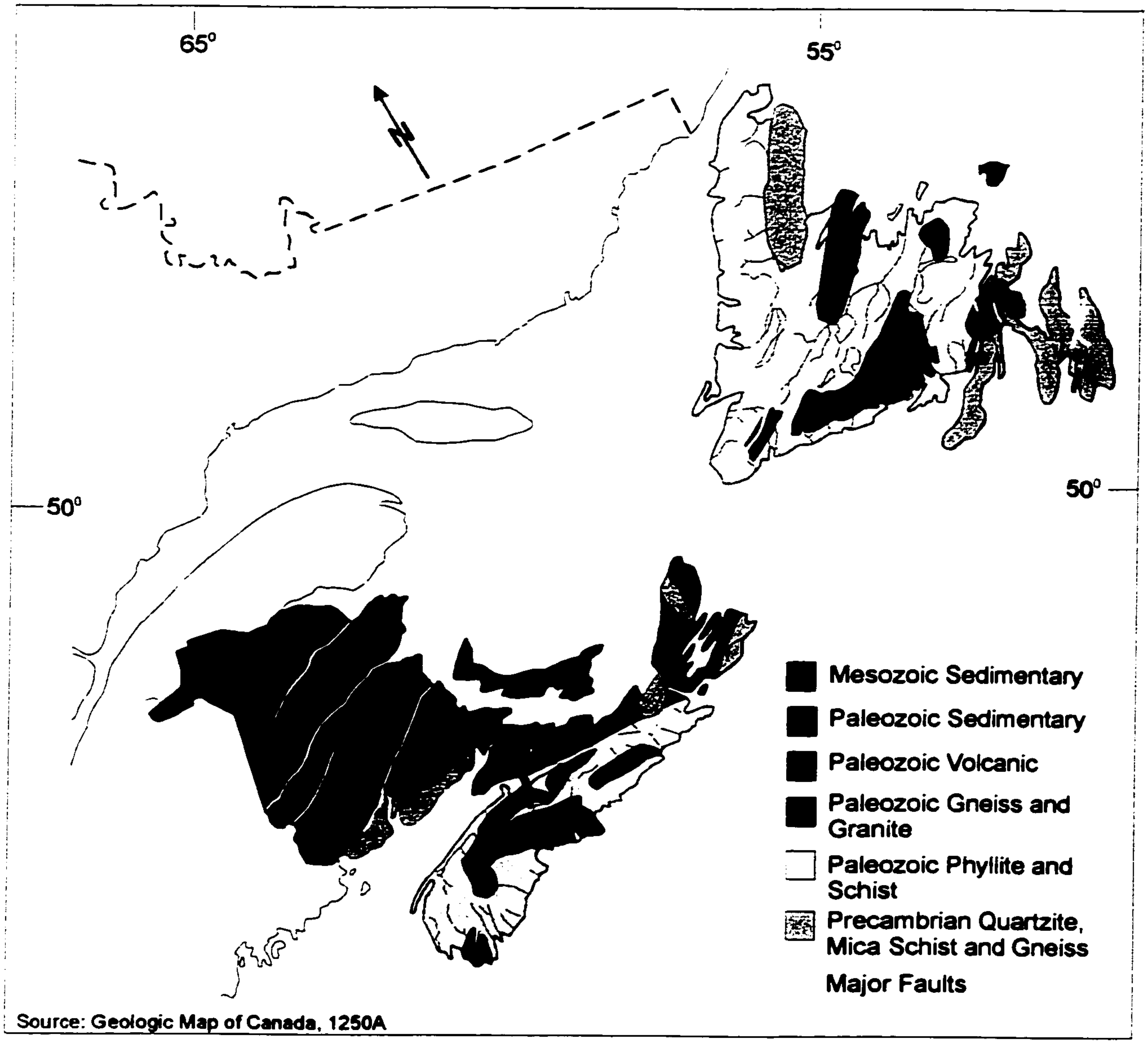



Figure 2.7: Simplified Geologic Map of Eastern Canada: Major Rock Units and Faults

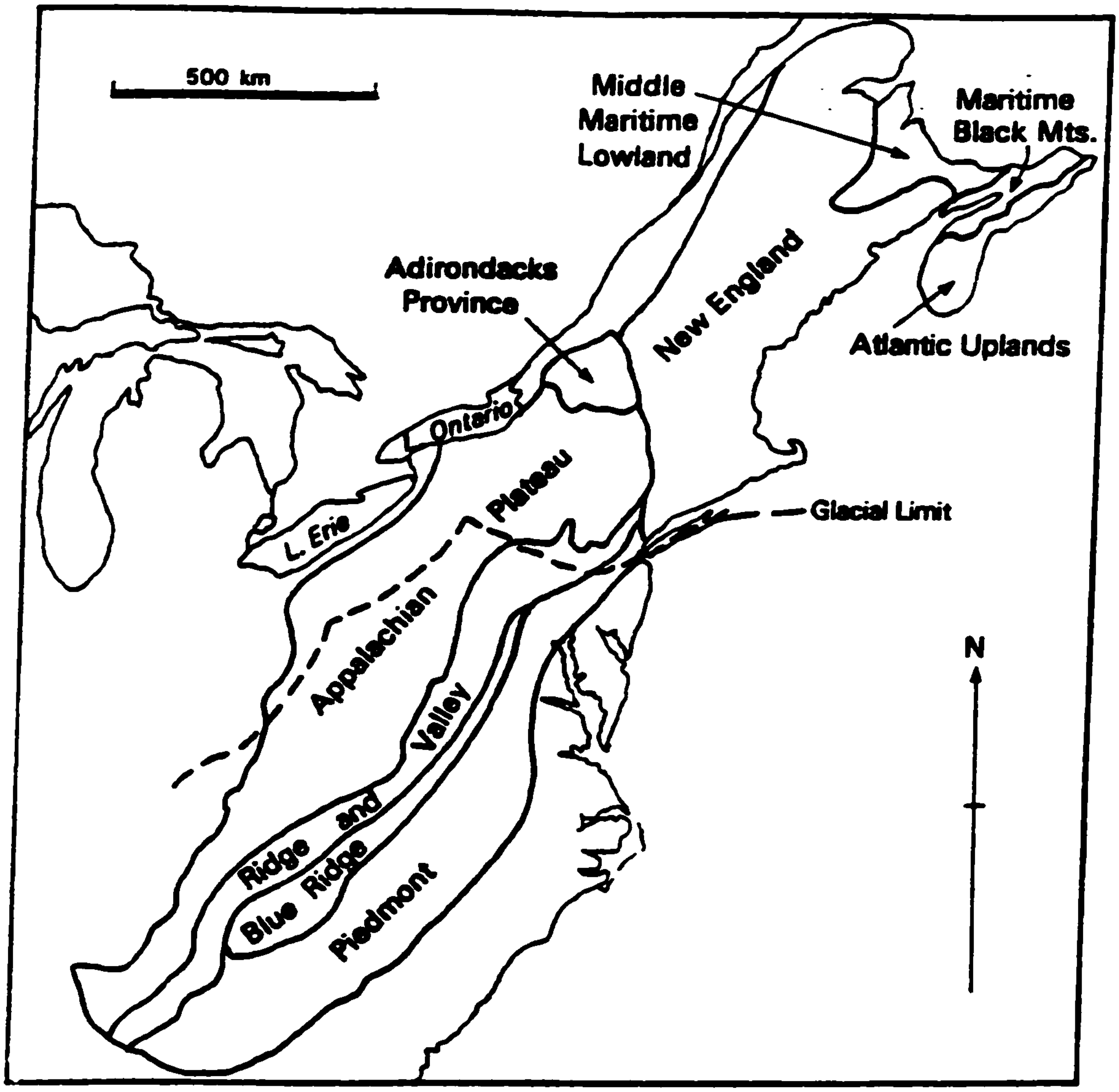



Figure 2.8: Major Geologic Divisions Along Eastern North America
(Source: Gardner and Sevon, 1989)

of the Appalachians, and extended approximately as far as latitude 38° N. As a result, continental glaciers planed off soil, weathered bedrock and redeposited these materials as a thin mantle of glacial debris over the bedrock surface. Sheetlike Quaternary glacial outwash deposits mantle Cape Cod and overlie Cretaceous Northern Atlantic Coastal Plain sediments on Long Island, Block Island, Martha's Vineyard, and Nantucket Island. Quaternary age material extending through Delaware, eastern Virginia, North and South Carolina and Georgia was primarily deposited in shallow marine environments when sea level was higher relative to the land surface than at present, or in the floodplains and deltas of the rivers that drained this portion of the landmass (Rodgers, 1970; USGS, 1997).

### 2.3.4 History of European Settlement

> "...the...plantation harbors often silted full and became land themselves, so that at a place like Port Tobacco, you can walk through fields where once the little ships sailed in and out fetching hogsheads of cured brown weed for the pipes and snuff boxes of Europe" (Graves, 1966).

It is also important to have a brief understanding of the history of European settlement in the region under investigation in order to account for the potential human influence on otherwise natural loads of fluvial sediment. Many of the rivers flowing to the Atlantic have a long history of use and abuse. The earliest settlers arriving in the 18th century moved to various locations along the east coast: Acadia and Louisbourg in Nova Scotia and Boston and New York City. As a result, the population of eastern North America continued to grow and ultimately placed pressure on the natural environment. The eventual growth of cities and industries has caused an alarming encroachment upon, and destruction of much of the natural world. In 1790, only 5% of the United States population lived in urban areas; in 1920, more than half lived in urban areas, but by 1990, 75% of the American population lived in areas classified as urban (Johnson, 1997). The population of the eastern United States has exploded far more than that of Atlantic Canada (Table 2.2), with stresses to the natural systems of those states associated with that explosion.

| | POP. BY YEAR (1000s) | | | | |
|---|---|---|---|---|---|
| **STATE/PROVINCE** | **1790** | **1850** | **1900** | **1950** | **1990** |
| Delaware | 60 | n/a | 180 | 320 | 670 |
| Maryland | 320 | n/a | 1190 | 2340 | 4780 |
| Pennsylvania | 430 | n/a | 6300 | 10500 | 11880 |
| Washington, D.C.* | n/a | n/a | 280 | 800 | 610 |
| Nova Scotia | n/a | 280 | 460 | 640 | 900 |
| New Brunswick | n/a | 190 | 330 | 500 | 720 |
| Newfoundland | n/a | n/a | n/a | 360 | 570 |
| Prince Edward Isle. | n/a | 60 | 100 | 100 | 130 |

Table 2.2: Changes in population since colonial times in selected States and the Eastern Canadian Provinces (*National Capital).
(Leacy, 1983; Johnson, 1997).

Figure 2.9: Alexander Wyant's (Hudson River School) "Tennessee" (1866), from the Cumberland Plateau (Howat, 1987).

Figure 2.10: A Series of Four Engravings made in 1850 Chronicle Changes in Land Use and Vegetation on one New York Farmstead (Thomas, 1956).

The population of Washington D.C. alone has been larger than each of the Maritime provinces, with the exception of a decline in the population in Washington D.C. from 1950 to 1990. This resulted from individuals moving out of the city limits, but continuing to work in the city itself. The population of Maryland, on the other hand, had increased two-fold within the same period of time.

America's natural environment inspired artists of the Hudson River School in the mid-1800s (Figure 2.10) in addition to the settlers converging on eastern North America. Within a century, however, land clearance (Figure 2.11) and strip mining of coal changed the landscape, causing "soil erosion, stream pollution, the accumulation of stagnant water and the seepage of contaminated water, [increasing] the likelihood of floods, [destroying] the value of land..." (Howat, 1987). It was the fertility of the soil itself that drew the English and Scottish to the Piedmont region. They later spread out across the Blue Ridge into the wide, rich trough of the Ridge and Valley, where they eventually met German settlers moving down from Pennsylvania (Graves, 1966). While inland the settlers shared in the prosperity of the fertile land, the inhabitants of the Coastal Plain were profiting from the tobacco boom. Towards the middle of the 19th century, the shift away from agriculture in many areas of the eastern United States had already begun. The industrial revolution was taking place in the New, as well as the Old World. This "New World" was now one of industries and conquests, factories and frontiers. The urban sprawl of American cities had begun, while the eastern provinces of Canada did not share in this population revolution (Graves, 1966).

### 2.3.5 Suspended Sediment Yield

Sediment loads were obtained from the United States Geological Survey (USGS) and Environment Canada. In both the United States and Canada, most suspended sediment samples were collected with the U.S. DH-48, U.S. D-43, or U.S. D-49 sediment samplers, which were developed by the Federal Inter-Agency River Basin Committee (1952). The first of these samplers requires suspension on a rod and is usually used when a stream is wadable. The other two are suspended on cables extending from bridges or cableways. All three are nozzle-type samplers that were designed to collect a water-sediment mixture whenever the nozzle is submerged at an intake velocity that approximates the horizontal velocity of the stream at the nozzle intake. The samplers are generally lowered and raised at a constant rate while they collect a depth-integrated sample of a water-sediment mixture from the stream surface to within centimetres of the streambed (Colby, 1963). Data reliability in studies of sediment loads of rivers has been discussed by several authors (Kleiber & Erlebach, 1977; Walling, 1977; Dickinson, 1981). These authors, however, were primarily concerned with data estimated by rating curves as well as questionable data collection techniques in many developing countries. In the eastern United States and Canada, daily samples were taken at each of the study sites with the *standard* suspended sediment samplers.

The resulting sediment loads were converted to sediment yields ($t\ km^{-2}\ a^{-1}$). Twice daily sampled sediment loads were given in both the USGS and Environment Canada datasets, in addition to the basin area. From this information the discharges could be averaged for each year and then averaged for the entire period of record. When divided by basin area, this provided a yield of sediment for each location. Drainage areas ranged from just under 1 $km^2$ (Nursery Run at Cloverly, Maryland) to almost 30 000 $km^2$ (Potomac River at Washington, D.C.). The gauging stations used in this study collected daily information on stream discharge as well as sediment load. Stream discharges ranged from 0.128 $m^3$ $sec^{-1}$ (Northeast Pond River, Newfoundland) through 41 000 $m^3$ $sec^{-1}$ (Susquehanna River at Conowingo, Maryland). Duration of coverage ranged from one complete year of record to forty-two years of record (Appendix A). It was discovered that sediment yields varied in both time and space along eastern North America, and that in some locations, sediment yields were far greater than had been anticipated. These results are discussed in Chapters Three through Eight.

## 2. 4 Methodology

### 2.4.1 Methods of Spatial Interpolation

The maps of sediment yield patterns throughout this thesis were generated using Hardy's (1971) multiquadric (MQ) spatial interpolation technique. There are numerous spatial interpolation techniques which have been used for geographical applications. With sufficient data, any interpolation procedure will give good results because the sampled surface is known so well. It has been found, however, that some techniques work more accurately and efficiently than others (Shaw & Lynn, 1972; Franke, 1982). In terms of visual smoothness, goodness-of-fit, flexibility and variable distribution of data, the multiquadric method of analysis is an invaluable analytical technique. Interpolation methods against which multiquadric interpolation has been compared include inverse distance weighted methods, rectangle based blending methods, and Foley's method (Franke, 1982).

Interpolation begins with the idea that a measurement at a point is a unit of information that describes the value of some quantity at that particular location and, with less certainty, a limited section of the surrounding area. This proximal region has been termed the kernel of influence (Hardy,1971). The surface representing a set of spatially-extended data is therefore a collection of these kernels. The difference between one interpolation technique and another is related to the manner in which the influence of the datum is assumed to decline for more distant interpolation points, and the computational maneuvers necessary to process the elected influence function (Watson, 1992).

### 2.4.2 Multiquadric Method

Hardy's(1971) multiquadric technique is a global interpolation procedure, in which the interpolant is dependent on all data points, and addition or deletion of a data point, or the repositioning of a data point, will affect the entire domain (Franke, 1982). A local method, on the other hand, is typically thought of as meaning that addition or deletion of a point, or a change in one of the coordinates of a datum, will affect the interpolant only at nearby points, and the interpolant will be unchanged at distances greater than some given distance. The multiquadric method was originally used to represent topography (Hardy, 1971), but it has been adopted in other areas of data interpolation, such as areal distribution of rainfall (Shaw & Lynn, 1972), mining applications (Sirayanone, 1988), computational fluid dynamics (Kansa, 1990) and more recently for fluid speed (Saunderson, 1992), fluid vector applications (Saunderson & Brooks, 1994), drumlin field investigations (Conrad, 1994) , fluid patterns around woody channel debris (Beebe, 1997) and sediment yield patterns (Conrad & Saunderson, 1999).

### 2.4.3 Solution of the Equations

Maps depicting spatial variation of suspended sediment yield were generated using the multiquadric (MQ) method of interpolation. Hardy's (1971) MQ method can be used to generate surfaces where $z = f(x,y)$, $z$ being the scalar dependent variable and $x$, $y$ the locational coordinates of $z$. Mapping the regional pattern of time-averaged yields ($t\ km^{-2}\ a^{-1}$) required, as a first step, solution of the following multiquadric equation:

$$\sum_{j=1}^{n} c_j[(x_i - x_j)^2 + (y_i - y_j)^2]^{0.5} = z_i \qquad (2.1)$$

where $c_j$ is a coefficient representing the slope of a cone whose apex is at the (known) location [$x_j$, $y_j$], and having known height. Interpolation of any intermediate values for sediment yields ($z_p$) was then derived from the equation:

$$\sum_{j=1}^{n} c_j[(x_j-x_p)^2+(y_j-y_p)^2]^{0.5}=z_p \tag{2.2}$$

with the column vector of coefficients $c_j$ being the solution of a set of simultaneous, linear equations (Saunderson, 1994).

## 2.5 Discussion and Summary

This thesis is a detailed investigation of the patterns of fluvial suspended sediment yields in eastern North America. Although other researchers (e.g. Meade, 1982) have considered sediment yields in areas of this region, a detailed investigation has not been previously undertaken. The availability of a database spanning both time (up to 42 years) and space facilitates this investigation. The importance of the results which will be discussed in the following chapters is not only in the context of understanding sediment yields of rivers in eastern North America, but also in elucidating the complexity of the temporal and spatial patterns of yields, and the factors causing those patterns.

# CHAPTER 3

# REGIONAL PATTERNS OF YIELDS

## 3.1 Introduction to Regional Analysis of Suspended Sediment Yields

Suspended sediment data have been used to assess regional and global patterns of erosion (Walling and Webb 1996a). This chapter reports on the *regional* patterns of sediment yield for a selected section of the study area and the implications of using different record lengths when generating maps of variations in suspended sediment yield. Although long-term records are probably required to establish any trends in sediment yields (Walling 1997), the length of sampling interval required to identify the presence or absence of trends is still an open question. In a spatial context, the initial question is: What will maps of sediment yields look like when different time-averaged yields are used to produce the patterns? To-date, other researchers (i.e. Dedkov & Mozzherin, 1984; Jansson, 1988) have generated single maps illustrating sediment yield patterns, but if yields are non-stationary, then patterns might be expected to change.

If a period of record has been one of stable conditions within and across the drainage basins (that is, the record has "stationarity": highs/lows do not change location through the period of study), the record would be expected to show the average sediment load of the rivers under those conditions, and the accuracy of the average would be related directly to the length of the period of record (Meade et al.,1990). If the period of record has been one of changing conditions within and between basins (non-stationary), then patterns of yields would be expected to shift, and the non-stationarity of the data could be used as a guide to the effects of changing basin conditions (e.g. land use, climate). Changes inevitably occur over space and time, with the changes perhaps leading ultimately to a state of equilibrium. The length of record, however, may not be sufficient to fully elicit the non-stationary behaviour. Important questions to ask, then, are: How representative are the sediment loads of the time period covered in this thesis of longer-term loads; and would further data collection generate different results than the ones from this research?

This research relies on the available collected lengths of records at the gauging sites. In most cases, gauging locations have closed as sufficient records are believed to have been collected (e.g. Nova Scotia Department of the Environment, 1988).

### 3.2 Sediment Yields of Eastern North America

Once each of the sites with sediment load information were compiled (from the data sources described in section 2.2), yields could be calculated. For each location, total annual loads were given. These were converted from imperial to metric units for the American portion of the study area. Basin areas were also given, and again converted for the American portion of the study area. These values were entered into a database and then converted to sediment yields. By calculating the total tonnage of sediment for the entire period of record, dividing by the basin area, and the number of years of record, a yield was calculated for each site ($t\ km^{-2}\ a^{-1}$).

Intervals of record ranged from one to 42 years. Table 3.1 gives a breakdown of the number of sites and years of record (by state and province). Most stations have less than ten years of record, but some have more than 20 years. Some states have many more years of record than others (e.g. Pennsylvania vs. Maine). There are large ranges and variability in suspended sediment yields within and between data sets from the rivers of eastern North America. For example, the graph of suspended sediment (Fig.3.1) for the Potomac River in Maryland, U.S. shows an example of variability in the suspended load over time. Had data collection at this station been concluded prior to the dramatic event indicated by the peak on the graph (Nov. 1985), the yield calculated at this station would have been very different. It is difficult to ascertain the reason for such a dramatic increase in the sediment load. A hurricane event would have been a likely causal factor, however the most recent hurricane in the area struck a full month (Hurricane Gloria, on September 27, 1985) prior to the peak in sediment. The focus of this chapter is the initial investigation of sediment yields of eastern North America, which is followed by a discussion of the complex causal factors for the temporal and spatial patterns of yields for selected areas in subsequent chapters.

| State/Province | Number of sites | <10 yrs. data | 10-20 yrs. data | >20 yrs. data | Max. period of record |
|---|---|---|---|---|---|
| Connecticut | 7 | 7 | 0 | 0 | 1981-1990 |
| Delaware | 2 | 1 | 0 | 1 | 1948-1980 |
| Georgia | 13 | 13 | 0 | 0 | 1959-1963 |
| Maine | 2 | 2 | 0 | 0 | 1966-1972 |
| Maryland | 12 | 6 | 5 | 2 | 1959-1993 |
| Massachusetts | 2 | 2 | 0 | 0 | 1966-1972 |
| New Jersey | 15 | 12 | 2 | 1 | 1949-1982 |
| New York | 20 | 20 | 0 | 0 | 1954-1979 |
| North Carolina | 10 | 7 | 2 | 1 | 1951-1993 |
| Pennsylvania | 61 | 54 | 5 | 1 | 1951-1993 |
| South Carolina | 2 | 4 | 0 | 0 | 1966-1972 |
| Virginia | 19 | 16 | 0 | 3 | 1951-1993 |
| | | | | | |
| New Brunswick | 9 | 6 | 2 | 1 | 1966-1988 |
| Newfoundland | 5 | 5 | 0 | 0 | 1979-1990 |
| Nova Scotia | 8 | 4 | 4 | 0 | 1967-1988 |
| Prince Edward Island | 6 | 3 | 3 | 0 | 1972-1986 |
| | | | | | |
| Total | 193 | 162 | 23 | 10 | |

**Table 3.1: Available Suspended Sediment data for Eastern North America.**
Data used in this study can be broken down into a number of years of record. Although most sites have <10 years of continuous, daily data, there are some which have a significantly long period of continuous record (1951-1993).

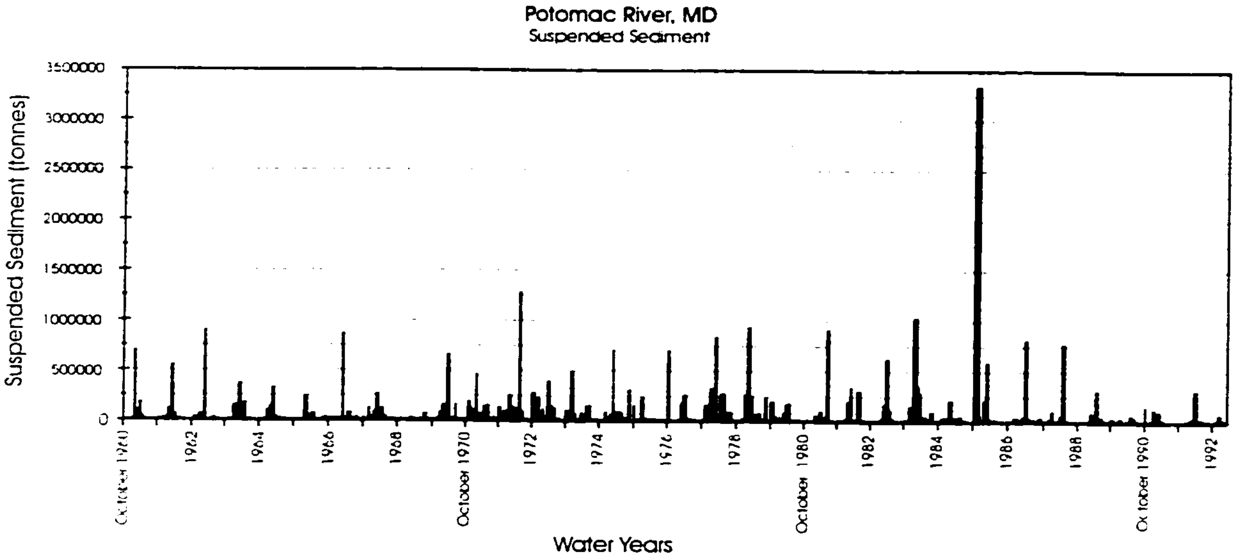



Figure 3.1: Time-Series of Suspended Sediment Loads (tonnes) from 1960 through 1992. The extreme peak took place in November, 1985.

| State/Province | Sed. Yield | Max. Yield | Min. Yield |
| --- | --- | --- | --- |
| Connecticut | 20 | 30.6 | 9.3 |
| Delaware | 119.9 | 173 | 66.7 |
| Georgia | 62.3 | 152.9 | 1.5 |
| Maryland | 62.9 | 155.4 | 5.7 |
| Massachusetts | 13.8 | 18.4 | 9.2 |
| New Jersey | 18.8 | 58.3 | 2.2 |
| New York | 108.5 | 425.2 | 4.6 |
| North Carolina | 157.3 | 1017 | 17.5 |
| Pennsylvania | 114.4 | 1436.2 | 12 |
| South Carolina | 12.6 | 21.8 | 3.4 |
| Virginia | 372.9 | 3156.7 | 3.2 |
| **Eastern States:** | **96.7** | **3156.7** | **1.5** |
| New Brunswick | 25.2 | 69.4 | 2 |
| Newfoundland | 12.9 | 30.7 | 3.5 |
| Nova Scotia | 12.4 | 34.8 | 5.6 |
| Prince Edward Island | 22.2 | 40 | 10.6 |
| **Atlantic Provinces:** | **18.2** | **69.4** | **2** |

Table 3.2: Sediment Yield for the Individual States and Provinces.
Overall sediment yield, maximum and minimum yield averaged for the entire U.S. and Canadian sections of the study area are in bold for comparison.

The sediment yield for each state and province and the maximum and minimum yields within that state or province are shown in Table 3.2. Sediment yields for the 15 states range from 12.6 to 372.9 $t\ km^{-2}\ a^{-1}$. Maximum yields (from the 165 individual U.S. sites) ranged from 18.4 to 3156.7 $t\ km^{-2} a^{-1}$. Minimum yields (at a station) ranged from 1.5 to 66.7 $t\ km^{-2}\ a^{-1}$. Sediment yields for the 4 provinces range from 12.4 to 25.4 $t\ km^{-2}a^{-1}$. Maximum yields (from the 28 individual Canadian sites) ranged from 30.7 to 69.4 $t\ km^{-2}a^{-1}$. Minimum yields (at a station) ranged from 2 to 10.6 $t\ km^{-2}a^{-1}$. Several observations can be made based on the sediment yields across the regional study area. Sediment yields for the eastern United States are larger than those of the Atlantic provinces (factors which might explain this observation are discussed in Chapters 5-8). Sediment yields of the individual states are also greater in most cases than the yields of the individual provinces. Maximum yields are also greater for most of the eastern states. Minimum yields across the study area are comparable, with the exception of Delaware, which has a larger minimum yield for all gauging sites in that state (66.7 $t\ km^{-2} a^{-1}$). Figure 3.2 shows the relationship between sediment yield and latitude. All of the gauging sites were used in plotting the graph, and there appears to be a general trend of decreasing sediment yield with increasing latitude, graphically portraying the relationship which the initial calculations had shown.

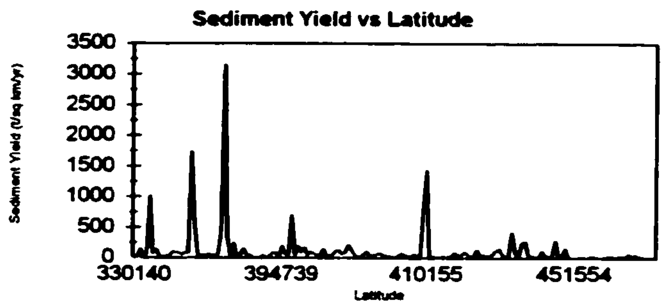



Figure 3.2: Relationship between Sediment Yield and Latitude (degrees,minutes,seconds)for Eastern North America.

There are numerous explanations for the inverse relationship of increasing sediment yield with decreasing latitude. In conjunction, three main factors stimulate this relationship: climatological conditions (the influence of seasonality with the ground frozen for extended lengths of time with increasing latitude); geological and geomorphological conditions (the aquifer depth increases with decreasing latitude, a consequence of the presence, in higher latitudes, of the Wisconsinan glaciation or absence, in lower latitudes, of the Wisconsinan glaciation); and land use (more land is affected by intensive agricultural activities in the lower latitudes). The contrast between the higher yields in the eastern United States and the lower yields in eastern Canada has been noted by Stichling (1973), and is discussed further in Chapter 7.

The sediment yield values indicate that the sediment yield of the eastern US and Canada may also be much greater than previously calculated (Table 3.3).

| Author/Year | Susp. Sed. Yield Estimate: t/ sq.km/ yr. |
|---|---|
| Fournier (1960) | 10 - 60 |
| Strakhov (1967) | 10 - 50 |
| Milliman & Meade (1983) | 17 |
| Dedkov & Mozzherin (1984) | 50 - 100 |
| Walling & Webb (1987) | 10 - 500 |
| Lvovitch et al. (1991) | 20 - 200 |
| Conrad & Saunderson (1998) | 1.5 - 3160 |

Table 3.3: Estimates of suspended sediment yield in eastern North America according to various authors

There are a number of reasons which can explain these larger estimates. The first difference is one of research area. All researchers (Table 3.3) derived their sediment yield estimates from a global area, whereas in the present study, sediment yield was determined over a smaller, regional area (meaning that more sites from eastern North America were included in this study than for those studies encompassing the entire globe). Sediment yields were calculated using the standard estimate of $t\ km^{-2} a^{-1}$ at the sample stations. The difference in the present approach is the increased number of sites (193) utilized in calculating sediment yields. At the global scale, however, researchers (such as those in Table 3.3) generally use only a few sites in each region. Milliman & Meade (1983), for example, used only two data points when determining the sediment yield for the same portion of the globe as the present study. Sites on major rivers of the world are generally used, with smaller rivers and tributaries excluded. The result has been a regional, and probably world-wide underestimation of the world's sediment yields. The more data sites, the closer the spatial average will be to the true sediment yield of any region. Small rivers and tributaries (including some from eastern North America), with smaller floodplain storage than major rivers, can have larger sediment yields. In fact, a number of small rivers may contribute as much or more sediment than large ones. Stave Run near Reston, VA, with a basin area of only 0.2 $km^2$, has a sediment yield of 3157 $t\ km^{-2}\ a^{-1}$, whereas the Hudson River in New York State, with a basin area of 12 000 $km^2$ has a yield of only 20 $t\ km^{-2}\ a^{-1}$.

The final difference is temporal. Not only are more data points over a smaller area included in this study, but a longer period of time is also covered. A problem with estimates of global suspended sediment yield can therefore be seen when comparing the results to a detailed regional analysis. Differences in values of these magnitudes remain a problem when researchers are using different rivers spanning different time periods at different scales.

### 3.3 Spatial Analysis

Multiquadric surfaces were generated (Conrad & Saunderson, 1999) initially of the eastern United States section of the study area with sufficient data (therefore New England is missing from the maps). The Canadian portion of the spatial analysis is discussed in Chapter 6. Maps of sediment yields averaged over five-year, ten-year, and total intervals of record were produced. The pattern of suspended sediment yields based on five years (those sites with any full five-year coverage), of record (Fig. 3.3) shows largest yields associated with tributaries of the Potomac, (~ 400 $t\ km^{-2}\ a^{-1}$) and in the western corner of Virginia, associated with

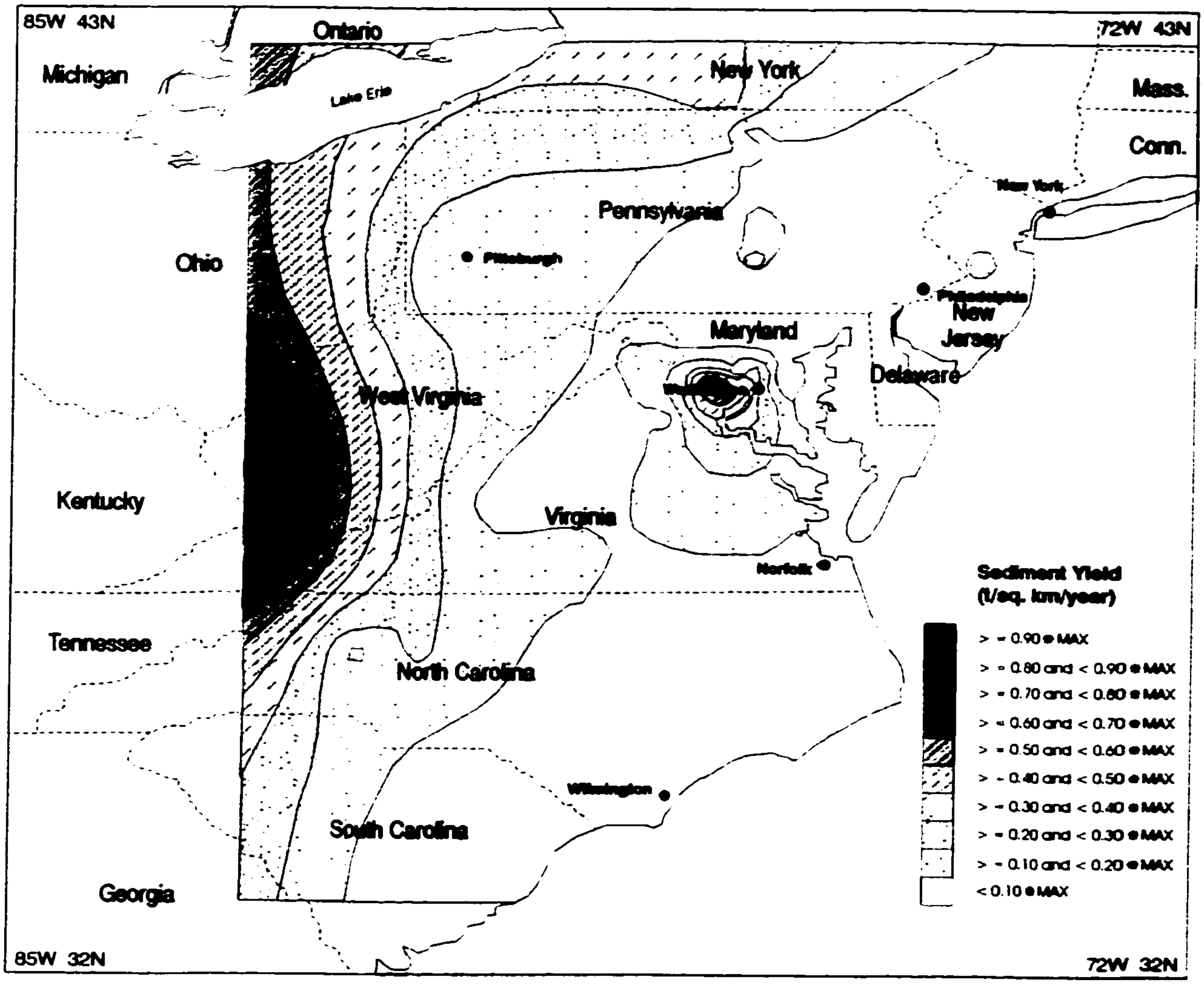



Figure 3.3: Sediment Yield Patterns Based on a Five Year Time-Average (max. Yield = ~ *580 t km$^{2}$ a$^{-1}$*)

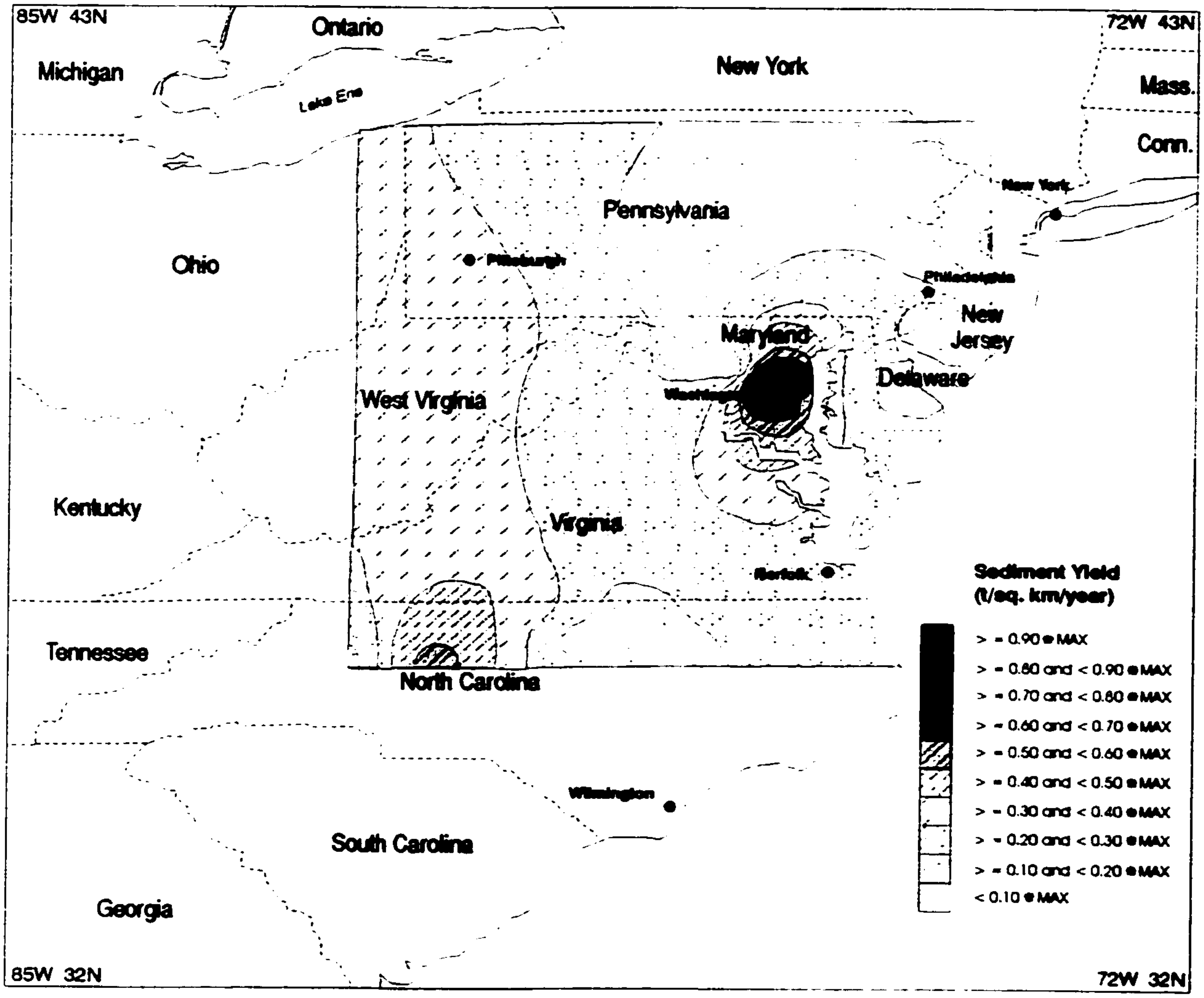



Figure 3.4: **Sediment Yield Patterns Based on a Ten Year Time-Average** (max. yield = ~ ***250 t km$^{-2}$ a$^{-1}$***)

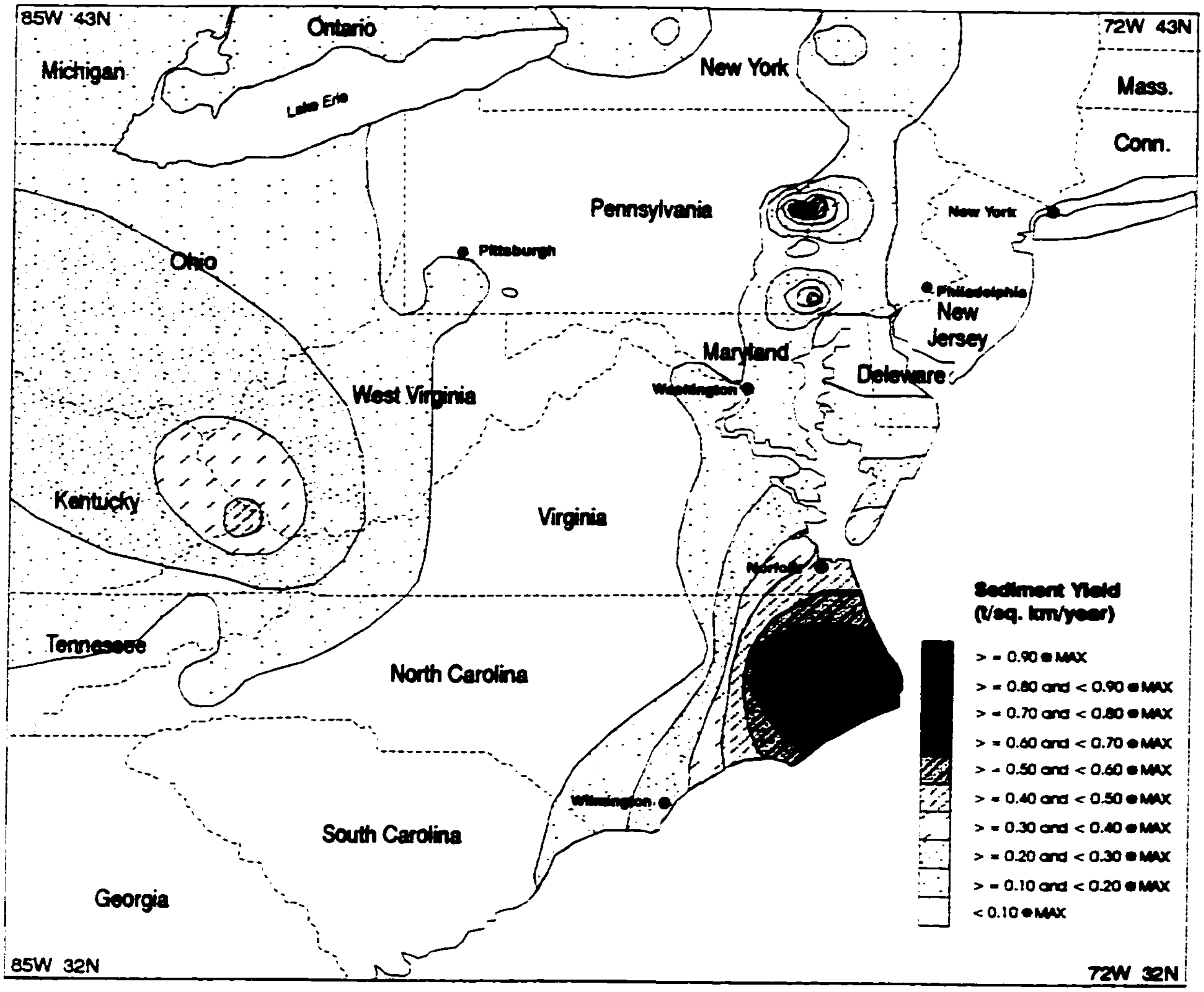



Figure 3.5: Sediment Yield Patterns Based on a Sample of (79) Records (max. 42 year record) (max. Yield = ~ *900 t km$^{-2}$ a$^{-1}$*)

Ohio River tributaries (~ 580 $t\ km^{-2}\ a^{-1}$). The area around Washington, D.C. also has five-year high sediment yield values. Figure 3.4 shows the results of mapping suspended sediment yields which have been averaged over a ten-year interval of record. This map depicts a smaller region since there are now fewer stations which have a continuous ten-year record. The regions around Washington, D.C. and Reston, Virginia still emerges as high yield regions on the ten-year record, with largest yields of up to ~ 250 $t\ km^{-2}\ a^{-1}$. Figure 3.5 is based on 79 of the total 189 stations (every second record in the entire data set). Lengths of record ranged from one to 42 years. Yields are now as high as ~ 900 $t\ km^{-2}\ a^{-1}$ which are found in Pennsylvania, where tributaries to the Susquehanna yield large amounts of sediment. There is a marked difference between Figure 3.3, the map of five-year, time-averaged yields, and Figure 3.5, the map of entire length of record. For example, there are large yields in North Carolina, whereas the former high yield centred around Washington is no longer evident. These results indicate that the spatial patterns of suspended sediment variability will change depending on the number of years of record used. In addition, the spatial pattern will be affected by the timing of the record. Different results would be expected for records spanning a wet decade compared to a dry decade, for example.

These maps of sediment yields with varying time-averages (Figures 3.3,3.4, and 3.5)show that spatial patterns of yields are time-dependent. These maps, however did not, for all sites, have over-lapping years of coverage. One might therefore suspect that different climatological conditions in different years might

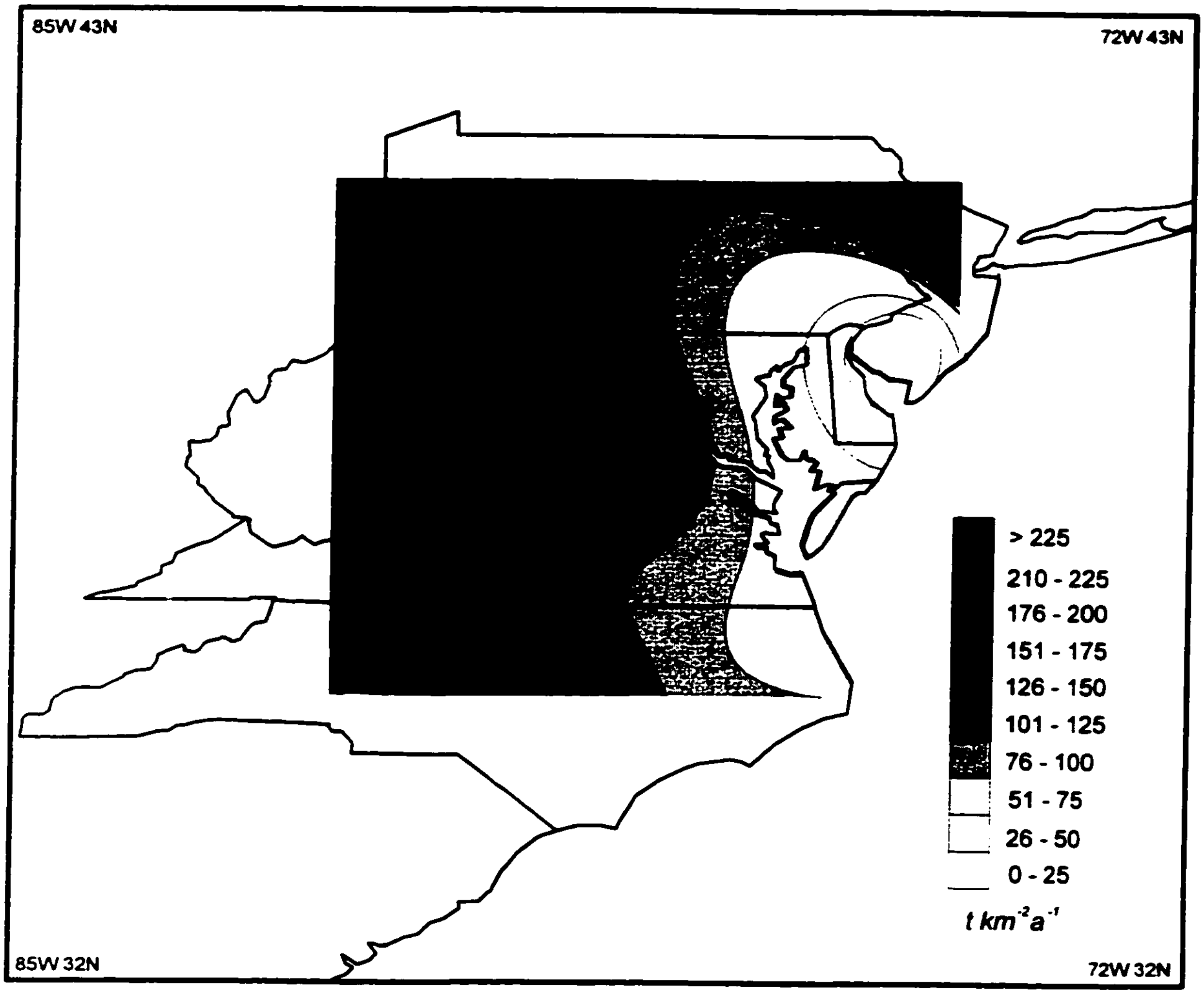



Figure 3.6: Sediment yield patterns based on five-year time-average (same 5 years: 1959-1963)

change the results that were observed in those figures. A five-year map of sediment yields (with all of the thirteen stations used to generate the map having a time-averaged sediment yield for 1959-63) was also produced (Figure 3.6). The pattern of yields for this map has changed from that of Figure 3.3, with highest yields now extending into north-central North Carolina (the Yadkin River, with the maximum yield of 257 $t\ km^{-2}\ a^{-1}$). A ten-year map with over-lapping coverage could not be produced, since there were insufficient sites with the same 10 years of coverage. One might suspect, with new stations opening, old ones closing, meteorological conditions varying from one year to the next, and human activities varying from one year to the next, that time-averaged maps of sediment yields will change. This facet of spatial sediment yields should be accounted for when observing global or regional maps of yields, which are often presented as *the* pattern of yields, and indirectly, of erosion. If yields are always changing with time, then different maps will always result. Perhaps, then, it is most reliable to produce sediment yield maps with as much detail as possible (as many stations and longest lengths of record available) to provide an overview of the spatial variations, keeping in mind that the pattern could shift as a consequence of a change in weather or land use that occurs tomorrow. A further investigation of the temporal patterns of yields and changes in spatial patterns of yields from one year to the next is made in the subsequent chapters (Chapters Four and Five respectively). Prior to this, the variability and reliability of the actual yields that were calculated over different lengths of time (by use of a statistical analysis) are discussed in the following section.

| SITE | YEARS OF RECORD | SPAN | SEDIMENT YIELD | SD |
|---|---|---|---|---|
| Great Egg Harbour, NJ | 5 | 1965-70 | 1.9 | 1.4 |
| Edisto, SC | 5 | 1967-72 | 3.4 | 1.1 |
| Choptank, MD | 11 | 1980-91 | 6.2 | 3.8 |
| Susquehanna, MD | 9 | 1984-92 | 8.3 | 4.4 |
| Coginchaug, CT | 6 | 1980-87 | 12.3 | 3.9 |
| Delaware, (@Dunn.)NJ | 10 | 1965-76 | 12.8 | 6.2 |
| Salmon, CT | 8 | 1982-90 | 14.2 | 11.5 |
| Yantic, CT | 5 | 1975-80 | 15.4 | 6.4 |
| Baldwins C, NJ | 7 | 1962-69 | 16 | 8.8 |
| NB Rock, MD | 10 | 1967-77 | 16.8 | 13.3 |
| Merrimack, MA | 5 | 1967-72 | 18.5 | 4.7 |
| Chicod, NC | 10 | 1976-86 | 21.2 | 19.2 |
| Pee Dee, SC | 5 | 1967-72 | 21.8 | 5.3 |
| Patuxent, MD | 6 | 1985-91 | 21.9 | 6.8 |
| Passaic. NJ | 5 | 1963-68 | 22.2 | 8.5 |
| Bixler Run, PA | 16 | 1954-70 | 23.3 | 7.7 |
| Juniata, PA | 40 | 1951-91 | 26.3 | 17.2 |
| James (Buchanan), VA | 5 | 1951-56 | 33.4 | 18.4 |
| Corey, PA | 11 | 1956-68 | 35.7 | 23.7 |
| Delaware, (@Trenton), NJ | 32 | 1949-81 | 36.4 | 22.8 |
| Little, NC | 15 | 1961-76 | 37.4 | 26.7 |
| Potomac, MD | 31 | 1960-92 | 38.9 | 35.1 |
| Susquehanna, PA | 14 | 1963-78 | 41.9 | 35.2 |
| Mohawk, NY | 5 | 1954-58 | 43.8 | 34.4 |
| Steam Valley, PA | 5 | 1972-77 | 45.9 | 34.4 |
| Conococheague, MD | 13 | 1967-80 | 46.8 | 29.4 |
| Elk, PA | 13 | 1954-67 | 47.2 | 31.5 |
| James (Scottsville), VA | 5 | 1951-56 | 47.6 | 26.1 |
| Monocacy, MD | 9 | 1960-69 | 50.8 | 9.8 |
| Roanoke, VA | 26 | 1954-81 | 52.5 | 42.3 |
| Rapidan, VA | 5 | 1951-56 | 54.9 | 30.8 |
| Rappahannock, VA | 42 | 1951-93 | 55.8 | 32.6 |
| Stoney BR.,NJ | 11 | 1959-69 | 57.4 | 18.3 |
| Monongahela, PA | 6 | 1973-79 | 58.4 | 15.2 |
| NB Potomac, MD | 16 | 1964-78 | 61.6 | 24.9 |
| Conogo (Trib.1) PA | 7 | 1969-76 | 62.6 | 46.7 |
| Brandywine, PA | 15 | 1963-78 | 63.4 | 31.9 |
| Brandywine, DE | 31 | 1947-80 | 67.9 | 34.7 |
| S. Yadkin, NC | 9 | 1958-67 | 74.2 | 32.9 |
| Stony Fork (Elliottsville), PA | 8 | 1977-90 | 82.6 | 38.7 |
| Dan, VA | 26 | 1954-81 | 87 | 44.6 |
| Stony Fork, PA | 12 | 1977-90 | 89.7 | 33.7 |
| Blockhouse Cr., PA | 5 | 1972-77 | 95.3 | 73.2 |
| Blockhouse,(Buttonwood) PA | 5 | 1972-77 | 100.9 | 91.2 |
| Enlow Fork, PA | 5 | 1980-85 | 100.9 | 56.3 |
| Blockhouse, (Liberty) PA | 5 | 1972-77 | 102.7 | 93.4 |
| Yadkin, NC | 41 | 1951-92 | 137.9 | 60.8 |
| Conogo (Trib.3) PA | 7 | 1969-76 | 143.6 | 104.8 |
| Tioga, NY | 5 | 1974-80 | 173.6 | 70.7 |
| NW B Anacostia, MD | 13 | 1962-75 | 246 | 94.8 |
| Snakeden (@Reston), VA | 5 | 1973-78 | 399.8 | 103.9 |
| Levisa Fork, VA | 9 | 1973-81 | 578.9 | 367.3 |

Table 3.4: Eastern United States: sites with at least five years of record, with the years of coverage. Sediment yields and standard deviations (SD) for the full time of coverage are given.

### 3.4 Statistical Analysis of Sediment Yields

Standard deviations and standard errors of estimate were calculated for stations with at least five full years of record. Many of the stations in the database contain record lengths that are less than five full years so that the problem with confidence limits arises. The station with the highest sediment yield (Stave Run) includes only one full year of record, and yet there is little way of knowing how representative this high yield (>3000 *t* $km^{-2}$ $a^{-1}$) is of yields that might be determined in any other given year. Standard deviations (S.D.) within the database are high in many cases (Table 3.4), increasing with increasing sediment yield (Figure 3.7).

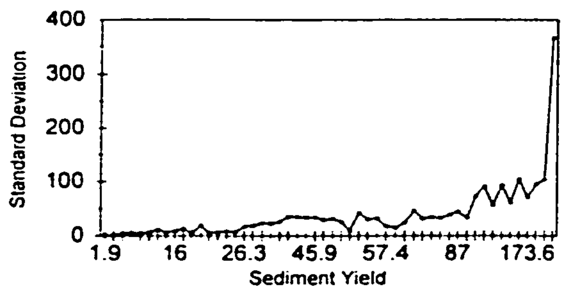



Figure 3.7: Standard Deviation vs Sediment Yield(stations listed in Table 3.4).

In addition, standard deviation varies depending on the number of years used to calculate the sediment yield. Table 3.5 (those stations with at least ten complete years of record) indicates how S.D. changes when calculated for different record lengths. In many cases the S.D. for shorter record lengths is smaller. When adding confidence limits the results are very different. In Table 3.6 (those stations

| SITE | YEARS OF RECORD | SEDIMENT YIELD | S.D. (full record) | S.D. ( 5 yrs.) | S.D. (10 yrs.) | S.D. (15 yrs.) | S.D. (20 yrs.) |
|---|---|---|---|---|---|---|---|
| Brandywine, DE | 31 | 67.9 | 34.7 | 29.4 | 27 | 30.9 | 27.7 |
| Choptank, MD | 11 | 6.2 | 3.8 | 4.2 | | | |
| NB Potomac, MD | 16 | 61.6 | 24.9 | 24.9 | 22.3 | | |
| Conococheague, MD | 13 | 46.8 | 29.4 | 42.1 | 32.7 | | |
| Potomac, MD | 31 | 38.9 | 35.1 | 5.9 | 12 | 18.9 | 20.2 |
| NB Rock, MD | 10 | 16.8 | 13.3 | 15.7 | | | |
| NW B Anacostia, MD | 13 | 246 | 94.8 | 29.4 | | | |
| Stoney BR.,NJ | 11 | 57.4 | 18.3 | 23.8 | | | |
| Delaware, (@Dunn.)NJ | 10 | 12.8 | 6.2 | 3.2 | | | |
| Delaware, (@Trenton), NJ | 32 | 36.4 | 22.8 | 21.3 | 30.3 | 27.8 | 26.4 |
| Little, NC | 15 | 37.4 | 26.7 | 11.9 | 13.4 | | |
| Yadkin, NC | 41 | 137.9 | 60.8 | 47.9 | 58.6 | 54.1 | 55.7 |
| Brandywine, NC | 15 | 63.4 | 31.9 | 8.1 | 30.3 | | |
| Corey, PA | 11 | 35.7 | 23.7 | 27.7 | | | |
| Elk, PA | 13 | 47.2 | 31.5 | 35.7 | | | |
| Juniata, PA | 40 | 26.3 | 17.2 | 9.4 | 9.8 | 11.3 | 11.1 |
| Bixler Run, PA | 16 | 23.3 | 7.7 | 3.7 | 6.1 | | |
| Susquehanna, PA | 14 | 41.9 | 35.2 | 18.5 | | | |
| Stony Fork, PA | 12 | 89.7 | 33.7 | 40.5 | | | |
| Rappahannock, VA | 42 | 55.8 | 32.6 | 21.3 | 24.6 | 23.1 | 23.1 |
| Roanoke, VA | 26 | 52.5 | 42.3 | 41.2 | 36.2 | 34 | |
| Dan, VA | 26 | 87 | 44.6 | 44.1 | 38.5 | 41.9 | |

Table 3.5: Eastern U.S. sites with at least ten years of data. Standard deviations for the full record length, and for a five, ten, fifteen and twenty year record are given.

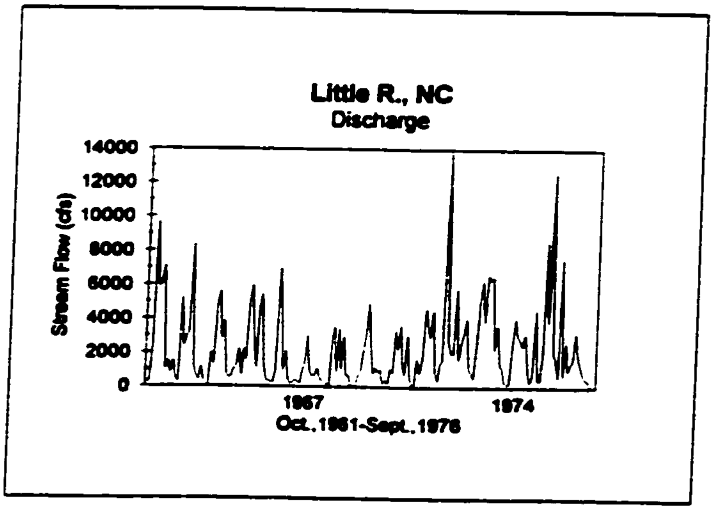
with at least 30 complete years of record), the range of values calculated according to the standard errors of estimate is included in brackets adjacent to the S.D. for those years of coverage. These values show the range of sediment yields with a 95.4% confidence limit (although the non-normality of the data reduces the confidence somewhat). There is, therefore, a 0.954 probability that a given sediment yield will be +/- those values in brackets. The smaller the value, the smaller the standard error of estimate of the standard deviation. This table shows that the probability of a sediment yield being larger or smaller than the mean is greater for the shortest record lengths. In addition, the calculated values for a twenty-year and full-coverage average(30-42-years) are in many cases, very similar, or the same (bold values in Table 3.6).

| SITE | S.D. ( 5 yrs.) | S.D. (10 yrs.) | S.D. (15 yrs.) | S.D. (20 yrs.) | S.D. (full record) |
|---|---|---|---|---|---|
| **Brandywine, DE** | 29.4 (36.8) | 27 (24) | 30.9 (22.4) | **27.7 (17.6)** | **34.7 (17.6)** |
| **Potomac, MD** | 5.9 (7.2) | 12 (10.8) | 18.9 (13.6) | 20.2 (12.8) | 35.1(17.6) |
| **Delaware, (@Trenton), NJ** | 21.3 (26.6) | 30.3 (26.8) | 27.8 (20.4) | 26.4 (16.8) | 22.8 (11.4) |
| **Yadkin, NC** | 47.9 (59.8) | 58.6 (52) | 54.1 (39.2) | 55.7 (35.2) | 60.8 (26.8) |
| **Juniata, PA** | 9.4 11.6) | 9.8 (8.8) | 11.3 (8.4) | **11.1 (7.2)** | **17.2 (7.6)** |
| **Rappahannock, VA** | 21.3 (26.8) | 24.6 (22) | 23.1 (16.8) | **23.1 (14.8)** | **32.6 (14)** |

Table 3.6: Stations with at least 30 years of record. Standard deviation is noted for 5-, 10-, 15-, and 20-year record lengths. The values in brackets are the ranges of sediment yields for those record lengths based on a 0.954 probability, calculated from the standard error of estimate.

### 3.5 Interpretation of Results

To account for global or regional variations in sediment yield, the complexity of the controls involved must be considered. Present-day sediment yields are



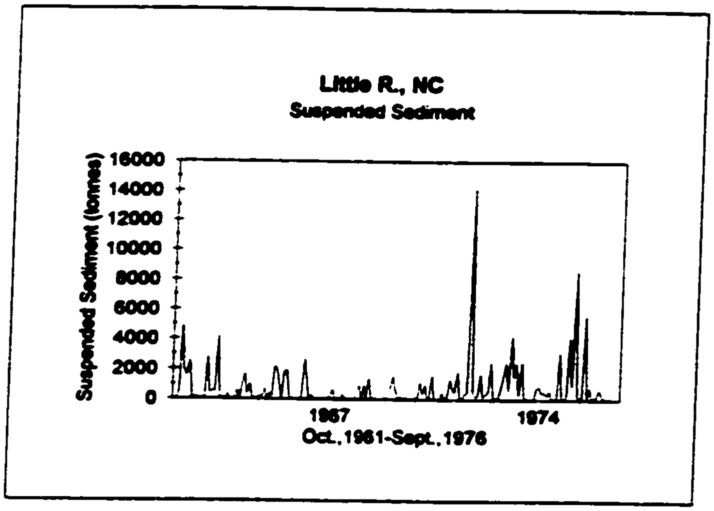




Figure 3.8: Monthly discharge and sediment loads for the Little River, NC (October, 1961 - September, 1976)

influenced by natural factors, anthropogenic factors, or combinations of natural and anthropogenic factors. These influences may be grouped into four major categories: climate, geology (including soil type), relief, and land use (Walling & Webb 1987, Meade et al.,1990). The relationship between spatial sediment yield patterns and contributing factors at the regional scale is apparent. For example, in an initial investigation of the possible relationship between discharge and suspended sediment load, plots were compared for those stations with at least five years of continuous data. Results show that the peak discharge and peak sediment load correlate (e.g. Figure 3.8) in approximately half of the sites (out of 48 stations, maximum peak discharge and maximum peak sediment load matched at 21 of the sites). To some extent, however, the sediment load and discharge will inevitably be correlated because sediment load is the product of the discharge and the concentration. Meteorological conditions explain high discharges of water and sediment in approximately half of the cases. If climatic factors influence the sediment yields in approximately half of the cases, how significant are the geologic, relief, and land use factors? Many of the channels in the eastern regions of the United States (Figure 2.4) traverse thick outwash and coastal deposits (Figures 2.3 and 2.6). Generally, lower sediment yields are typical of rivers in areas that were stripped of sediment during the last glaciation. The influence of human activity in the high yield area surrounding Washington has been noted by Costa (1975, p.1285), who suggested that construction activity, which was rapidly increasing in the 1960s and 70s, "...may help to explain some of the amazingly large sediment

| Station Name | Total #Yrs. Record | Sed. Yield: 5 yrs. | 10 yrs. | 15 yrs. | Entire Record |
|---|---|---|---|---|---|
| Brandywine C.,DE | 32 | 63.9 | 54.5 | 62.6 | 66.7 |
| Potomac R.,MD | 32 | 33.7 | 30.4 | 39.6 | 43.7 |
| Delaware R.,NJ | 32 | 46.9 | 48.8 | 42.7 | 37.6 |
| Little R.,NC | 15 | 36.3 | 27 | 37.4 | 37.4 |
| Yadkin R.,NC | 42 | 116.7 | 149.8 | 139.6 | 142.7 |
| Brandywine C.,PA | 15 | 39.8 | 59.3 | 63.4 | 63.4 |
| Juniata R.,PA | 40 | 36.6 | 31.7 | 27.2 | 26.3 |
| Bixler R.,PA | 16 | 28.8 | 24.8 | 22.4 | 23.3 |
| Rappahannock R.,VA | 42 | 46.4 | 50.1 | 46.5 | 55.8 |
| Roanoke R.,VA | 26 | 62.2 | 58.6 | 47.2 | 52.5 |
| Dan R.,VA | 26 | 91.3 | 104.6 | 85.7 | 87 |

Table 3.7: Eastern U.S. stations with more that fifteen years of record. Comparison of sediment yields for the full length of record, and for five, ten, and fifteen years.

loads...". Expanding urban land uses in this heavily populated region, as well as the availability of soft, erodible alluvium, are probable factors contributing to these high yields. In chapters 5 and 6, the influence of natural and anthropogenic factors on sediment yields is investigated in more detail.

Perhaps a critical minimum number of years of data collection is necessary in order to account for temporal fluctuations in suspended sediment load. Four of 11 stations with a minimum record of 15 years (Table 3.6) have higher yields for the longest interval available. Seven of 11 stations have lower values. These differences over time were thought to perhaps be a result of land use changes, including reservoir development. Further analysis of station data is conducted in the following Chapter to address the statistical variation in the time-series and to deduce whether these variations possibly relate to land use change.

## 3.6 Summary and Discussion

Sediment yield data for the world's rivers can provide a valuable means of studying the global denudation system. Regional patterns of sediment yields in a selected portion of eastern North America were presented in this chapter and it was shown that patterns of yield will vary depending on the length of data collection and which years are used to calculate the time-averaged sediment yields. These maps are novel in that comparisons of patterns based on differing record lengths were made, as well as because of utilizing more data than had previous authors.

Highest yields were located in the area surrounding Washington, D.C. in both the five-year and ten-year time-averaged yield maps (Figures 3.3 & 3.4). A general inverse relationship of decreasing sediment yield with increasing latitude (Figure 3.2). The questions at the beginning of the chapter that were posed were; How representative are the sediment loads of the time period considered in this thesis of longer-term loads, and would further data collection generate different results than the ones from this research? By calculating the standard error of estimate (S.E.E.) for the differing lengths of data collection for sediment yields, it was found that the S.E.E. appeared to remain the same or closest to that of the full record length after twenty years of record (Table 3.6). This might lead one to conclude that at least a twenty-year period of coverage is required for sediment yields to be indicative of longer-term yields. Most stations do not have this length of record, however. The temporal characteristics of sediment yields are investigated in further detail in the following chapter (Chapter 4).

# CHAPTER 4

# STATIONARITY OF DATA OVER TIME

## 4.1 Time Series Analysis

To investigate changes in the sediment load data over time, time-series for all of the stations were produced. A common trend was not observed, nor could trend lines be plotted for any of the graphs. Contrary to Walling's (1997b) findings for a number of rivers in eastern Europe, no patterns of either increasing or decreasing loads could be discerned. The sites with at least fifteen years of record (Table 4.1) were selected in order to conduct a more detailed time series analysis for these station locations. Sites with fewer than fifteen years of record were not used, since patterns over time would not be evident from the short record lengths. A total of sixteen sites representing three provinces and six states was used for further analysis (Table 4.1).

Time-series analysis is the analysis of data in which time is an independent variable. A time series may be composed of only deterministic events, only stochastic events or a combination of the two. Most generally a hydrologic time series will be composed of a stochastic component superimposed on a deterministic component. For example, a series composed of average daily temperature at some point would contain seasonal variation, the deterministic component, plus random deviations from the seasonal values, the stochastic component. The deterministic components may be classified as a periodic component, a trend, a jump or a combination of these (Haan, 1977).

| STATION NAME | YEARS OF RECORD |
|---|---|
| Annapolis River, N.S. | 18 |
| Kennebecasis River, N.B. | 21 |
| Petitcodiac River, N.B. | 16 |
| North Brook, P.E.I. | 15 |
| Wilmot Creek, P.E.I. | 15 |
| Brandywine Creek, DE | 32 |
| Potomac River, MD | 32 |
| Delaware River, NJ | 32 |
| Little River, NC | 15 |
| Yadkin River, NC | 42 |
| Brandywine Creek, PA | 15 |
| Juniata River, PA | 40 |
| Bixler Run, PA | 16 |
| Rappahanock River, VA | 42 |
| Roanoke River, VA | 26 |
| Dan River, VA | 26 |

Table 4.1: Sites in eastern North America with fifteen or more years of continuous sediment load data.

### 4.1.1 Smoothing of Suspended Sediment Loads and Discharge Data

Raw data tend to be composed of two components: the "signal" generated by the investigated process and the "noise" caused by random interference. Smoothing is an effective way to reduce noise in time series data, especially for the purpose of graphical clarity. The principle is that noise tends to occur at high frequencies and hence has inconsistent effects on adjacent observations; consequently, it can be reduced by "averaging out" over a short series of observations (Swan & Sandilands, 1995). Smoothing of the data was produced by applying a moving-average on the annual data values. Moving average analysis smooths fluctuating data points by plotting progressive averages. Starting with the first point in the series, $n_1$, an average of a specified period of points is constructed. If the period of time is three, for example:

$$N_1 = n_1 + n_2 + n_3 / 3 \tag{4.1}$$

would be the first point in the smoothed series and:

$$N_2 = n_2 + n_3 + n_4 / 3 \tag{4.2}$$

would be the second point in the smoothed series, and so on in this manner. In this way, each point is tempered by previous points and data is smoothed to show a

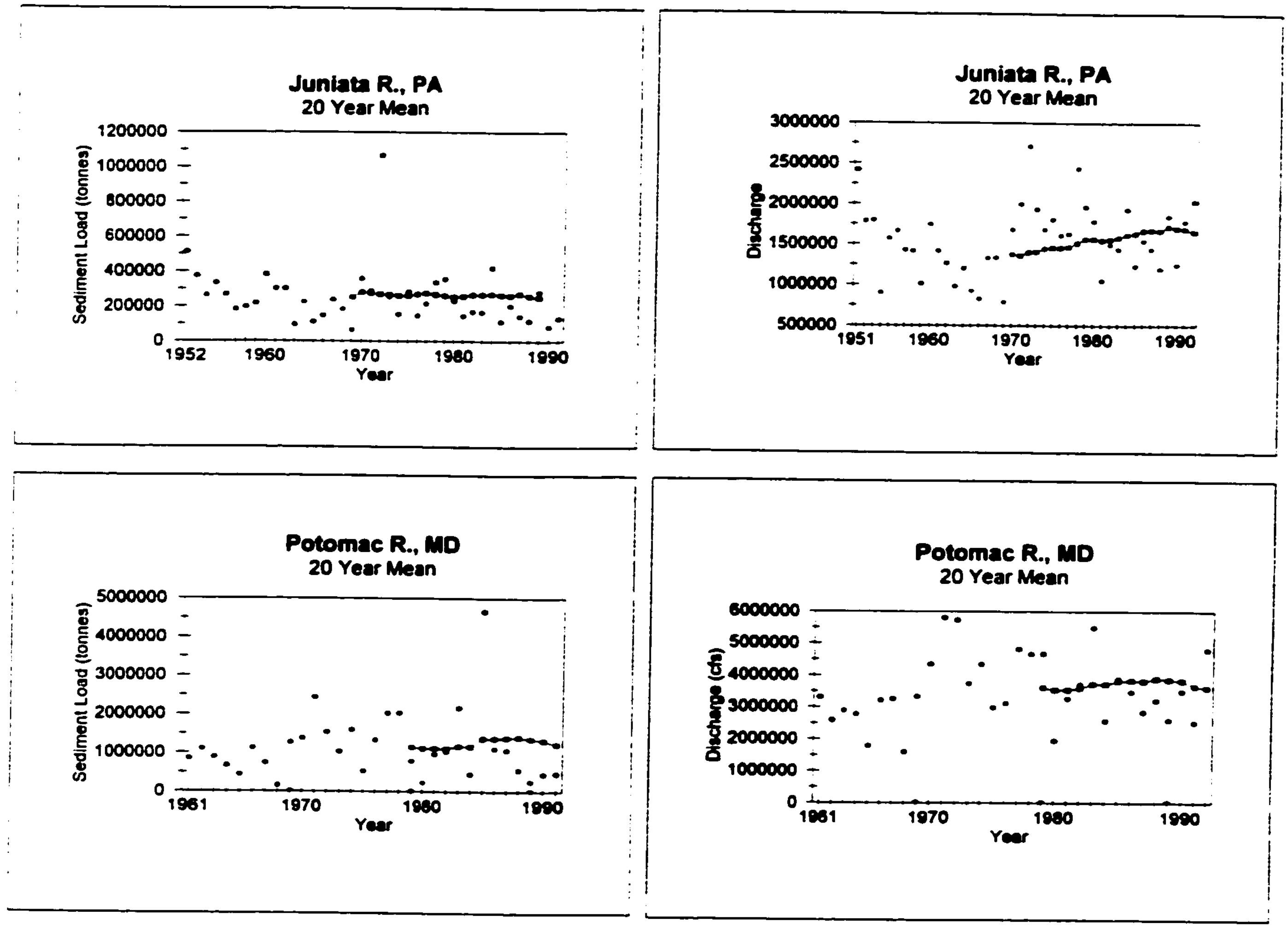



Figure 4.1: Twenty-year moving averages of sediment load and discharge at two eastern U.S. sites

general trend. Periodic variations will be eliminated when the smoothing period equals the period of the periodic component; thus the choice of smoothing interval is not an arbitrary decision. If the smoothing interval is less than the period, the periodic component will be dampened (McCuen & Snyder, 1986). A moving-average of several years length was tested on the raw data. Four through ten-year averages were tested on discharge and sediment load data at all sixteen sites. Four through twenty year averages were tested on the sites with the longer years of record. The longer averages were not tested on the sites with shorter record lengths (<25 years) since any trend was completely removed. At approximately twenty years the "signal" was also removed for those sites with longer record lengths (Figure 4.1).

In order to observe whether any kind of trend in the data exists, the same moving-average was used to compare all sixteen sites. An interval of seven years was selected for two reasons. First, it neither entirely removed the signal in the data nor continued to make it too "noisy" to observe the trend. Second, a length of seven years has also been successfully used for other hydrological applications (McCuen & Snyder, 1986). Figures 4.2, 4.3, 4.4 and 4.5 illustrate the results of the 7 year moving averages for the raw sediment load data. The line on the individual graphs is the smoothed trend and the scattered points on the graphs are the raw data points. In Figure 4.2, Bixler River, PA shows a falling limb throughout the 1960s. Dan River, VA has a high, followed by a dip between 1965 and 1970, rising through the 1970s, followed by a dip into the 1980s. Brandywine Creek, DE also dips at 1970 and rises immediately thereafter. The Juniata River, PA also dips towards1970, rises to a peak around 1975 and continues to fall through 1990. In Figure 4.3, the Potomac River, MD has a gently rising trend climbing from 1970, dropping around 1985 and then rising again around the early 1990s. The Roanoke River, VA has a falling limb from 1960 through 1970 followed by a rise and subsequent decline through 1980. The Rappahanock River, PA has a marked oscillation with a low between 1965 and 1970 and peak around 1975 with a subsequent drop. The Yadkin River, NC, also has a marked oscillation, with a pattern very similar to that described for the Rappahanock. The trends in Figure 4.4 may initially seem dissimilar to those in the previous two figures, however, the length of record for these four sites was not as long. The Little River, NC does indicate a low around 1967 with the initiation of a rising limb towards 1974. The Petitcodiac River, N.B., has a gentle rise from 1970 through 1980, where it appears to begin a descent. North Brook of P.E.I. appears to have a near horizontal trend, as does the Wilmot River, also of P.E.I. These two locations may have been the exception to the selection of a 7 year mean, since, with only 15 original raw data points, the trend, if any, has potentially been masked. In Figure 4.5, the Annapolis River, N.S. indicates a rise from the 1970s through 1980 and a subsequent decline. Brandywine Creek, PA appears to have an almost steady rise through 1967 to 1975. The Kennebecasis R., N.B. has a slight rise from the 1970s to about 1980, followed by a slight decline. Finally, the Delaware R., NJ shows a falling limb from 1950 to a low around 1965, followed by a rising limb towards 1975, with another drop around 1980.

Several observations can be made based on the graphs in Figures 4.2, 4.3, 4.4

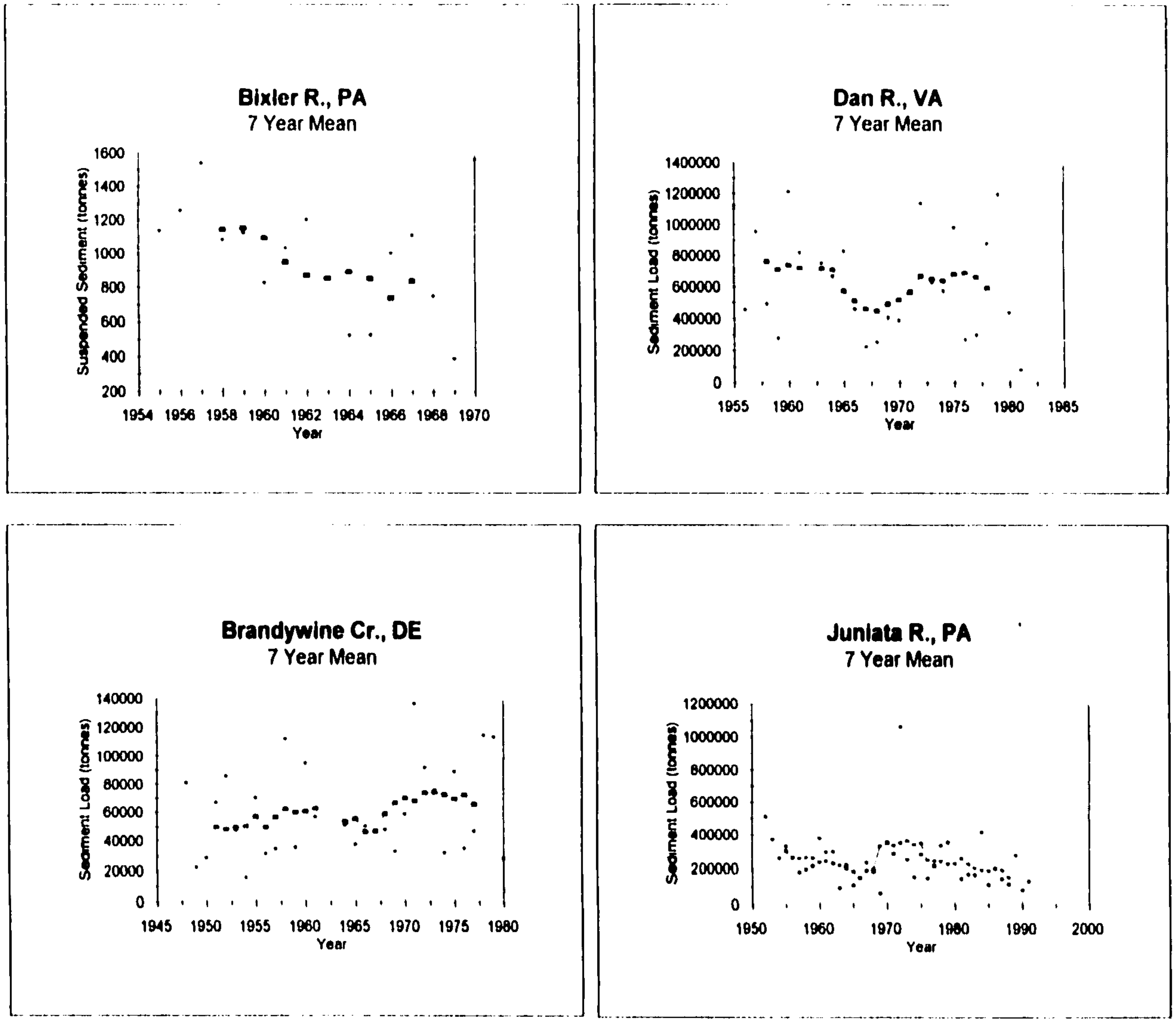



Figure 4.2: Seven-year moving averages of suspended sediment load for Bixler Run, PA; Dan River, VA; Brandywine Creek, DE and the Juniata River, PA. The line on the graph is the moving average, and the remaining data points are the annual totals (tonnage of sediment) from which the smoothed data was derived.

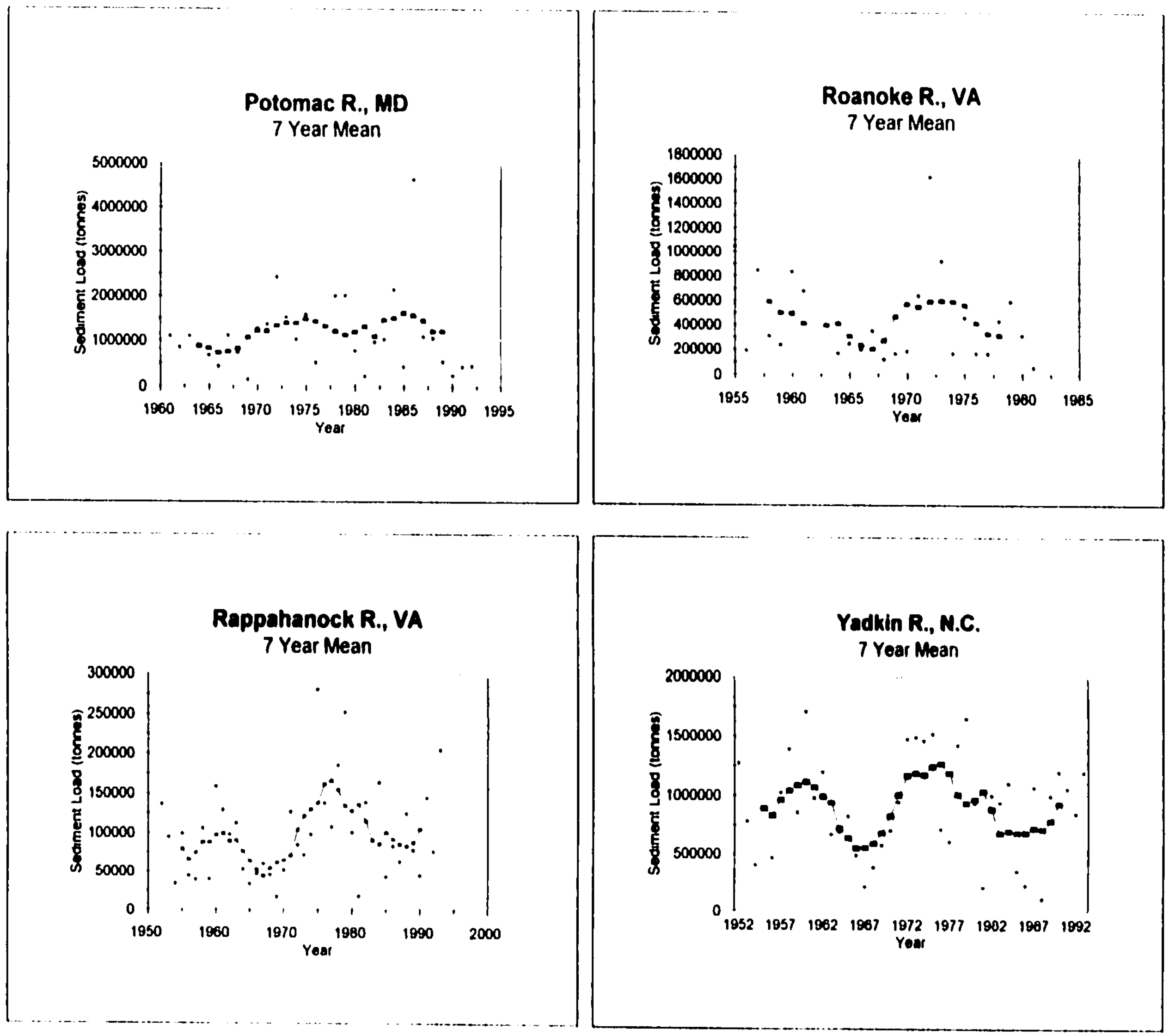



Figure 4.3: Seven-year moving averages of suspended sediment load for the Potomac River, MD; Roanoke River, VA; Rappahanock River, VA and Yadkin River, NC.

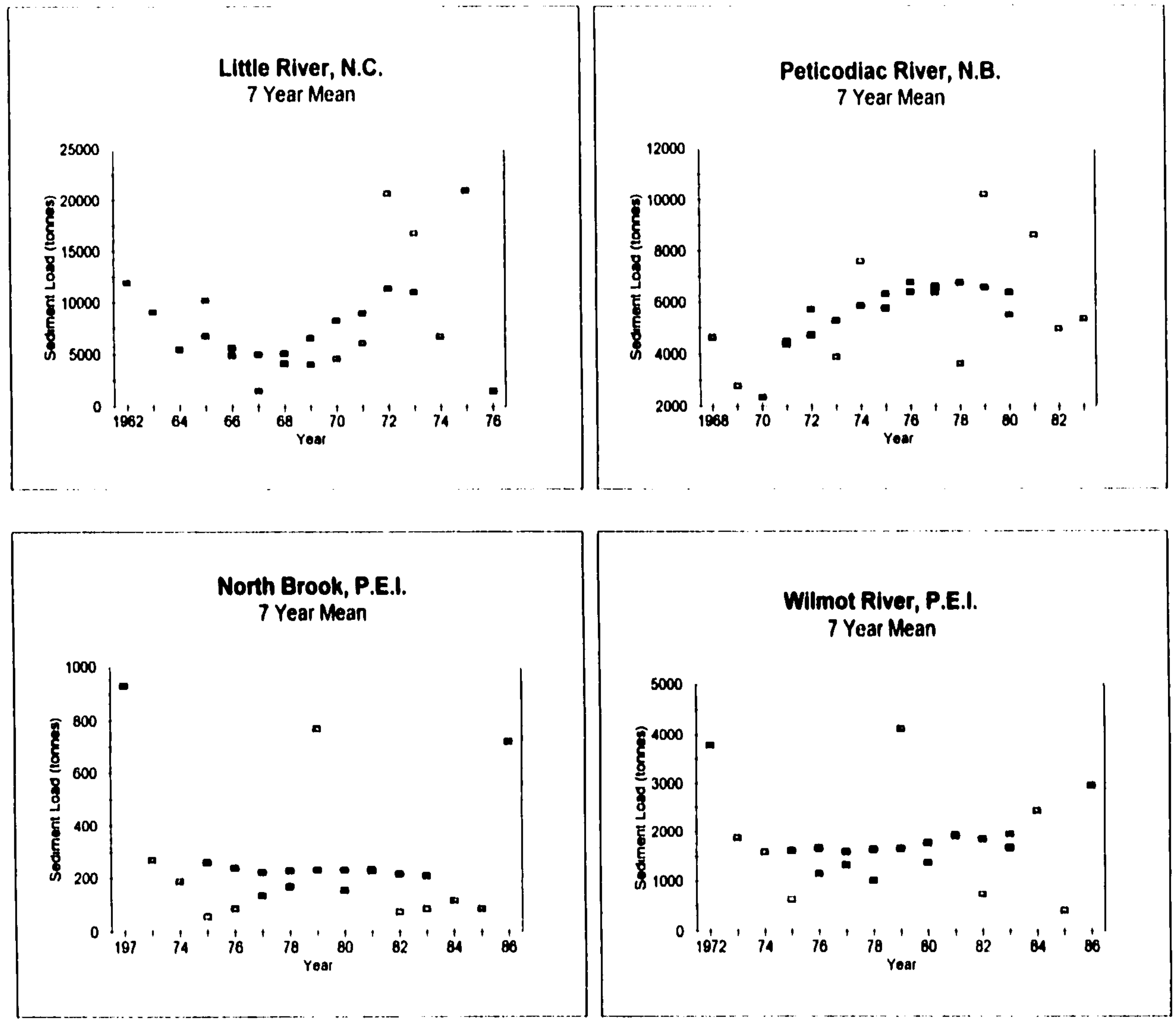



Figure 4.4: Seven-year moving averages of suspended sediment loads for the Little River, N.C.; Peticodiac River, N.B.; North Brook, P.E.I. and Wilmot River, P.E.I.

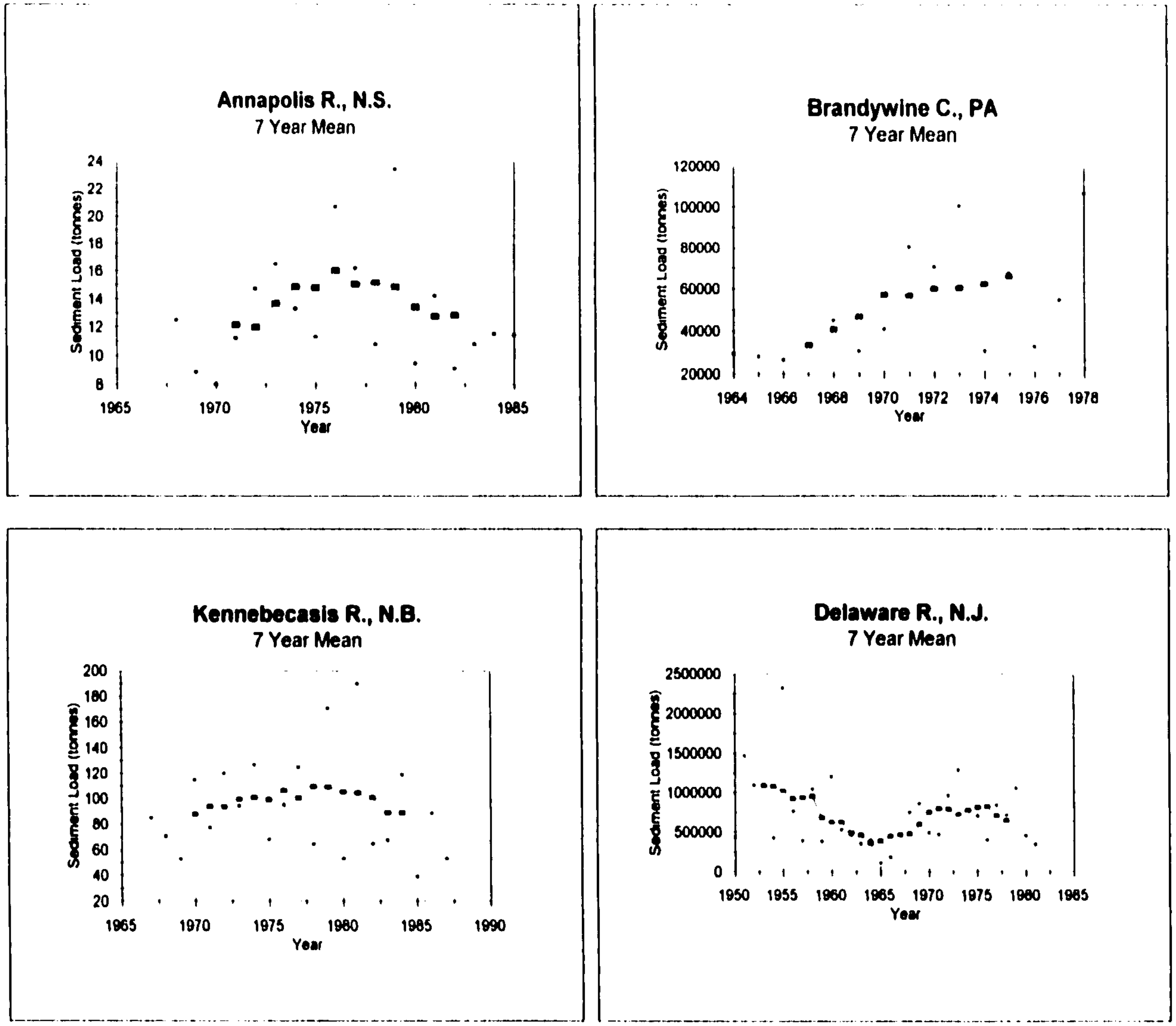



Figure 4.5: Seven-year moving averages of suspended sediment loads for the Annapolis River, NS; Brandywine Creek, PA; Kennebecasis River, NB and Delaware River, NJ.

and 4.5:

- there is an almost universal low around 1967
- the data does not illustrate a random pattern
- the data is non-stationary
- the data may be illustrating a decadal cyclicity even though the limited length of the time series does not allow this to be conclusively determined
- the sites with data prior to 1970 show a drop in sediment yield that might have been interpreted as a declining trend (e.g. Fig 4.2, Bixler R., PA) had these sites not been placed into the context of the pattern observed at other stations with a longer record
- the sites with data after 1970 show a rise in sediment yield that might have been interpreted as a continuously rising trend (e.g. Fig 4.4, Little R., NC).

The fact that three provinces and six states all illustrate this common pattern points to possible external forces driving the temporal behaviour of sediment loads. Regardless of the magnitude of sediment loads (i.e. 24 tonnes per annum at Annapolis R., N.S. vs 5 *million* tonnes per annum at the Potomac R., MD) the pattern can be seen. Similar plots of discharge for all of the same locations were made in order to observe whether discharge had a similar temporal behaviour.

Figures 4.6, 4.7, 4.8 and 4.9 are 7 year average plots of discharge. The lines are the 7 year averages and the scattered points are the raw data. When the plots of discharge are compared to the plots of sediment load, an astoundingly similar pattern can be seen. There is an almost identical trend in every case. In fact, for some

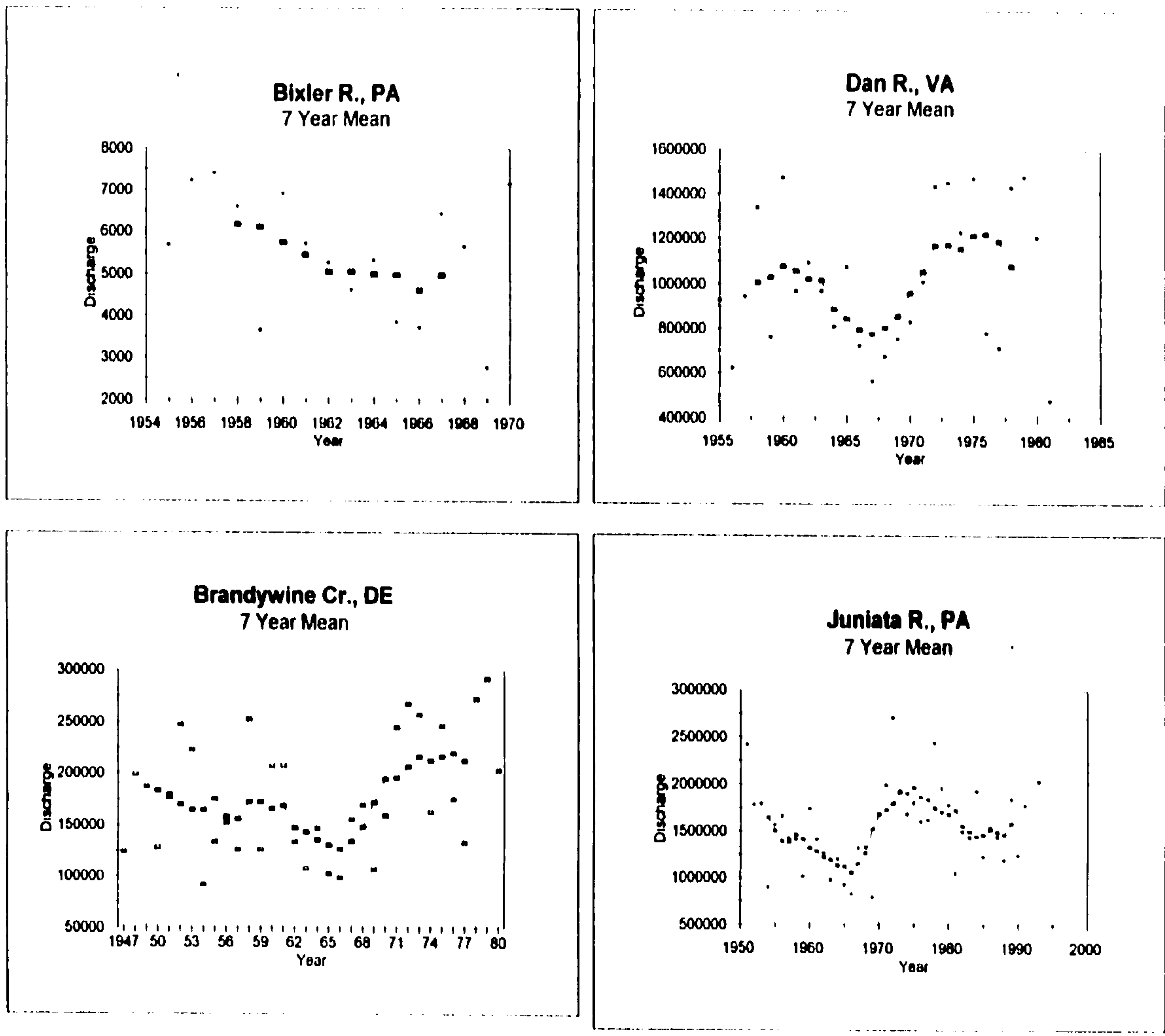



Figure 4.6: Seven-year moving averages of discharge for the Dan River, VA; Bixler Run, PA; Brandywine Creek, DE and Juniata River, PA.

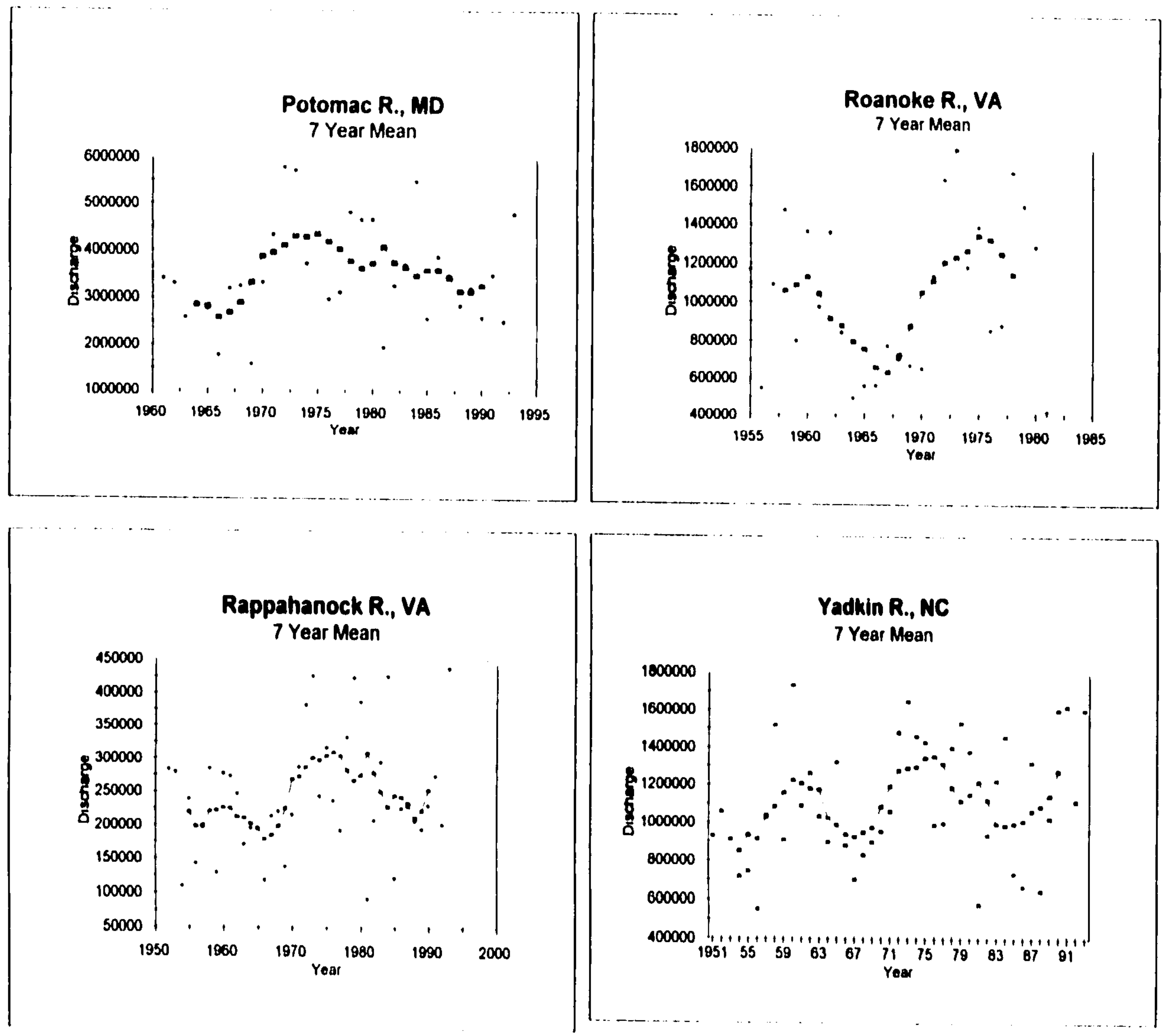



Figure 4.7: Seven-year moving averages of discharge for the Potomac River, MD; Roanoke River, VA; Rappahanock River, VA and YAdkin River, NC.

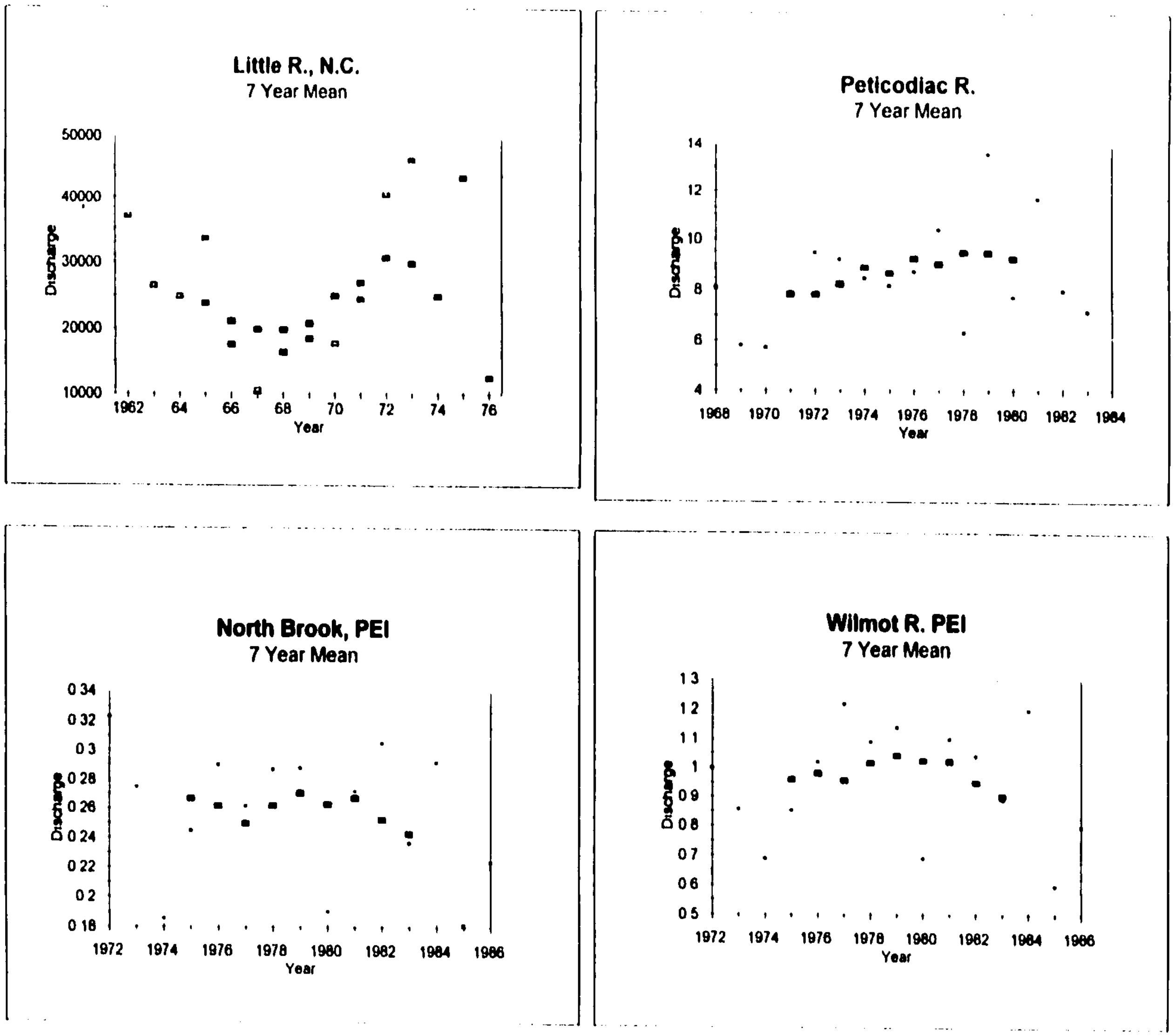



Figure 4.8: Seven-year moving average of discharge for the Little River, NC; Peticodiac River, NB; North Brrok, PEI and the Wilmot River, PEI.

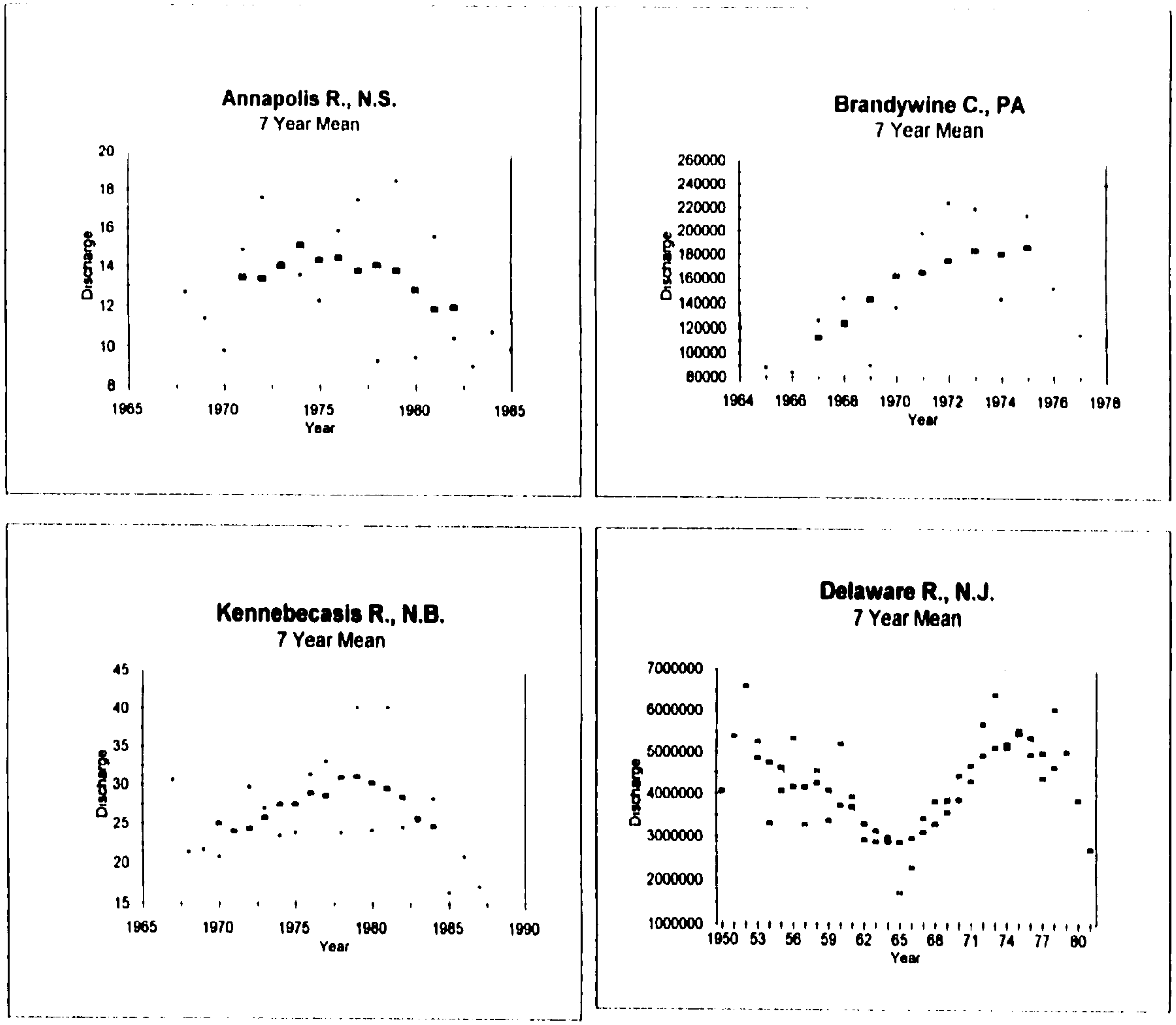



Figure 4.9: Seven-year moving averages of discharge for the Annnapolis River, NS; Brandywine Creek, PA; Kennebecasis River, NB and the Delaware River, NJ.

locations (i.e. Yadkin R., NC, with a 42 year record) the plots of sediment load and discharge are almost indistinguishable. No previous research has illustrated such a trend (Walling, 1998).

Believing that this might be a more general phenomenon, plots of two western rivers were made (the Oldman River in Alberta, and the Saskatchewan River in Manitoba). The same trend was not obvious, however these are glacially-fed channels and might be expected to have dissimilar trends. The sediment loads of three rivers in Ontario were then plotted (Figure 4.10; Big Creek, the Humber River, and the Ausable River, with 21, 29, and 25 years of record respectively). The increase in sediment yields from the 1970s through to the peak in the 1980s and subsequent decline can also be observed for these gauging locations, meaning that the trend observed from eastern North America may extend throughout an even larger regional area.

### 4.1.2 Autocorrelation of Suspended Sediment Loads

The stations with the longest records ( Yadkin R., NC; Juniata R., PA; and Rappahanock R., VA, with 42, 40 and 42 years respectively) all appear to illustrate a cyclicity in the data. The other stations have not had data collected for a long enough period for the full pattern to emerge. On relatively short time-scales, cycles are well-known in ordinary experience: daily, tidal, lunar and yearly cycles are understood. Decadal cycles have not been documented in hydrological systems. In order to test the three stations which might be illustrating a cyclicity, a further statistical analysis was necessary. Autocorrelation involves correlating a sequence of data with a time-

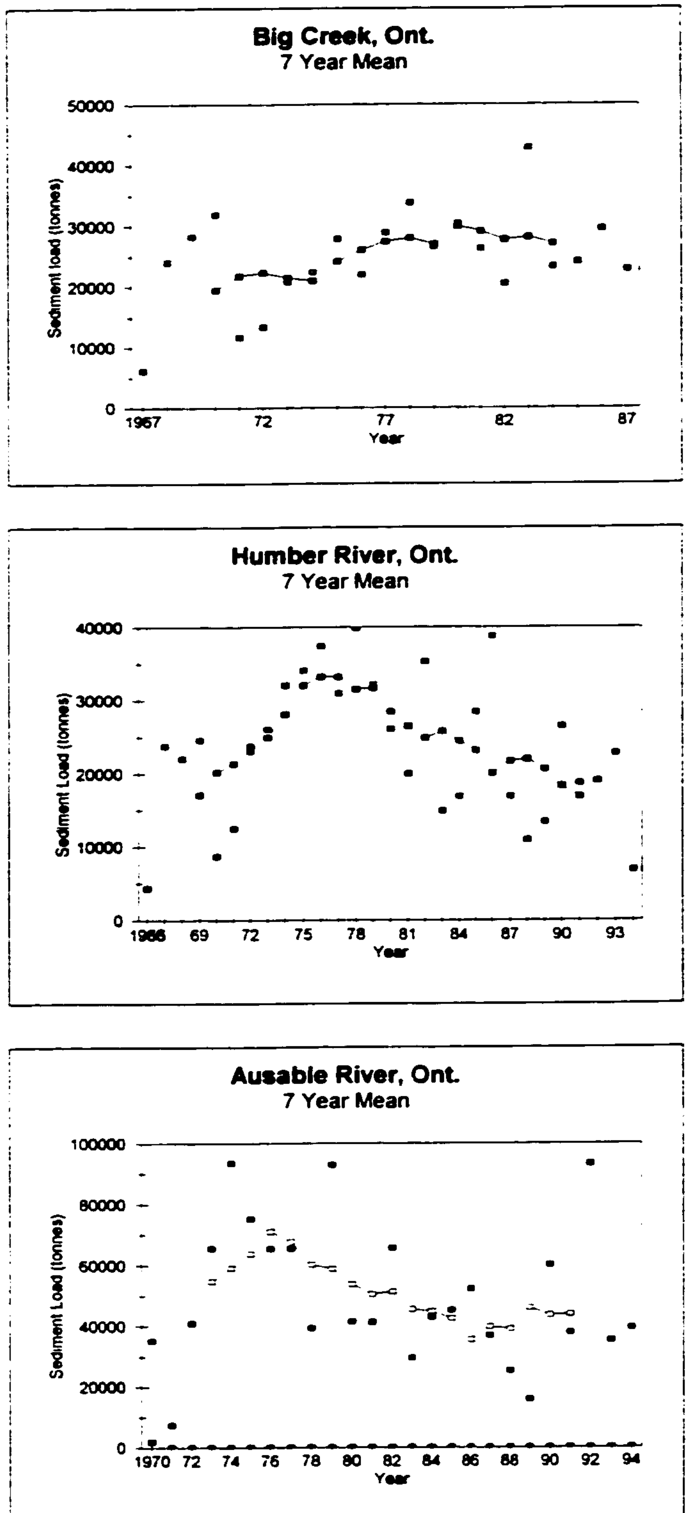



Figure 4.10: Seven-year moving averages of sediment loads for the Big Creek, Humber River, and Ausable River, Ontario.

```
          Auto- Stand.
  Lag     Corr.    Err. -1   -.75   -.5 -.25    0    .25  .5   .75   1
                       +----+----+----+----+----+----+----+----+
    1    .292    .149                .     I******
    2    .089    .147                .     I**   .
    3    .041    .145                .     I*    .
    4   -.050    .143                .    *I     .
    5   -.061    .141                .    *I     .
    6   -.299    .140                ******I     .
    7   -.265    .138                .*****I     .
    8   -.249    .136                 *****I    .
    9   -.222    .134                 .****I    .
   10   -.133    .132                 . ***I    .
   11   -.062    .130                 .   *I    .
   12   -.001    .127                 .    *    .
   13    .011    .125                 .    *    .
   14    .088    .123                 .    I**  .
   15    .087    .121                 .    I**  .
   16   -.028    .119                 .   *I    .

 Plot Symbols:      Autocorrelations *     Two Standard Error Limits .
```

Figure 4.11: Autocorrelation of Sediment Load Data for the Yadkin River, NC (1950 - 1992).

```
     Auto-   Stand.
Lag  Corr.   Err. -1  -.75 -.5  -.25  0   .25  .5   .75   1
                  +----+----+----+----+----+----+----+----+
  1   .176   .151               .     I**** .
  2   .075   .149               .     I**   .
  3   .127   .147               .     I***  .
  4   .224   .145               .     I**** .
  5  -.001   .143               .     *     .
  6  -.336   .141              *.*****I     .
  7  -.108   .139               .   **I     .
  8  -.127   .137                . ***I    .
  9   .030   .135                .    I*   .
 10  -.254   .133                *****I    .
 11  -.058   .130                .   *I    .
 12  -.082   .128                .  **I    .
 13   .026   .126                .    I*   .
 14   .119   .124                .    I**  .
 15  -.008   .121                .    *    .
 16   .069   .119                .    I*   .

Plot Symbols:      Autocorrelations *     Two Standard Error Limits .
```

Figure 4.12: Autocorrelation of Sediment Load Data for the Rappahanock River, VA (1950 - 1992).

```
       Auto-  Stand.
Lag    Corr.   Err. -1   -.75  -.5 -.25   0   .25  .5   .75   1
                    +----+----+----+----+----+----+----+----+
  1     .101   .152               .     I**   .
  2     .046   .150               .     I*    .
  3    -.093   .148               .   **I     .
  4    -.138   .146               .  ***I     .
  5     .018   .144               .     *     .
  6     .000   .142               .     *     .
  7    -.017   .140               .     *     .
  8     .020   .138               .     *     .
  9    -.153   .136                . ***I    .
 10    -.042   .134                .   *I    .
 11    -.036   .131                .   *I    .
 12     .189   .129                .    I****.
 13    -.183   .127                .****I    .
 14    -.078   .124                .  **I    .
 15    -.175   .122                . ***I    .
 16    -.106   .120                .  **I    .

Plot Symbols:       Autocorrelations *      Two Standard Error Limits .
```

Figure 4.13: Autocorrelation of Sediment Load Data for the Juniata River, PA (1950 - 1990).

offset copy of itself (McCuen & Snyder 1986). For example, when sediment loads are high for given years, would high yields in adjacent years also be expected? The analysis actually examines the change in correlation as the separation distance increases. The separation distance is referred to as the lag, and the plot of the correlation coefficient versus time lag is called a correlogram. If a sequence of data is correlated with itself, the result is a correlation coefficient of 1.0. The actual process of correlation involves calculation of duplicates of the time series which are displaced relative to one another. The two sets of numbers to be correlated are arrived at by pairing each value $y_i$ with $y_{i+\tau}$ where $i$ gives the time or position in the time series and $\tau$ is an integer value of displacement (the lag). The correlation coefficient between the time series and a displaced copy of itself is known as the autocorrelation coefficient, $r_\tau$ . It is calculated at successive lags (or sliding the time series past itself) and the resulting series of $r_\tau$ reveals information about the structure of the data by plotting the $r_\tau$ vs. $\tau$ on a graph (autocorrelogram). This analysis was conducted for the three previously mentioned stations with the use of a statistical package (SPSS). The results of this analysis are presented on the following pages (Figures 4.11, 4.12 and 4.13). In all of these figures, the first column is the lag ($\tau$), the second column is the autocorrelation coefficient ($r_\tau$). A similar pattern emerges for both the Yadkin and Rappahanock Rivers, with the autocorrelation coefficient rising initially toward 0.25 and then dipping around -0.25 through a lag of 10, and then rising again, although not as much as the initial lags of the autocorrelogram. The pattern for the Juniata River is somewhat different, with a pattern not emerging as distinctly as the previous two rivers. This makes sense given the more dramatic oscillation of the time-series for the Yadkin and Rappahanock Rivers (Figure 4.2). The observed autocorrelation could be real cyclicity or due to random effects. A longer time-series would certainly clarify this, as a Fourier analysis could not be conducted due to the insufficient length of the time series (there should be at least 50 observations in the time series) (McCuen & Snyder, 1986).

### 4.2 Discussion of the Temporal Results

Given the temporal patterns of sediment loads and stream discharge, one needs to explore those factors which may have changed over time to explain these trends. It might be suspected that human alterations of the landscape have caused such variations, but given the similarities between the discharge and sediment load trends, it might also be suspected that climatic factors have resulted in the observed temporal trends. It is also quite likely that human activities superimposed on the time series will amplify or lessen the pattern of loads that is occurring as a result of climatic factors. A human activity such as construction, occurring at a location in time where a peak in the time series exists may result in a *magnified* sediment load. It is unlikely, given the varied locations of the stations (spanning several states and provinces and having extended the analysis outside of the study area) that a human "intervention" occurred which could have affected all of the rivers at approximately the same time. Global warming's impact on the hydrology at the regional scale is a possible exception, but further research is required to elucidate the existence of such a relationship. It was thought that dam and reservoir construction and resulting management of those structures could perhaps be a contributing human factor for the observed trends. An investigation of a U.S. database (U.S. Army Corps of Engineers, National Inventory of Dams CD-ROM) showed that nine of the eleven U.S. sites in the database had dams prior to the period of data collection, with no co-ordinated or synchronized period of dam construction, closure or regulation (Table 4.2). Therefore, any effect that the dams have had will undoubtedly have pre-dated collection of the sediment load and discharge data.

| STATION NAME | PERIOD OF DATA | DAMS | YEAR(S) OF CONSTRUCTION | FUNCTION |
|---|---|---|---|---|
| Brandywine C.,DE | 1948-1980 | 1 | 1878 | water supply |
| Potomac R., MD | 1961-1993 | 5 | 1913,1930,1936, 1953,1954 | recreation, flood control, water supply |
| Delaware R., NJ | 1951-1983 | 2 | n/a | recreation |
| Little R., NC | 1961-1976 | 6 | 1900,1917,1919, 1920,1927,1958 | recreation, hydro |
| Yadkin R., NC | 1951-1993 | 6 | 1897,1917,1919, 1927,1962 | water supply, hydro |
| Brandywine C., PA | 1964-1978 | 0 | n/a | n/a |
| Juniata R., PA | 1950-1992 | 1 | 1906 | hydro |
| Bixler R., PA | 1954-1970 | 0 | n/a | n/a |
| Rappahanock R.,VA | 1950-1992 | 1 | 1925 | water supply |
| Roanoke R., VA | 1955-1981 | 3 | 1906,1953,1964 | hydro |
| Dan R., VA | 1955-1981 | 6 | 1870,1904,1910, 1938(2),1975 | recreation, hydro |

Table 4.2: Dam and reservoir characteristics for selected sites in the eastern U.S.

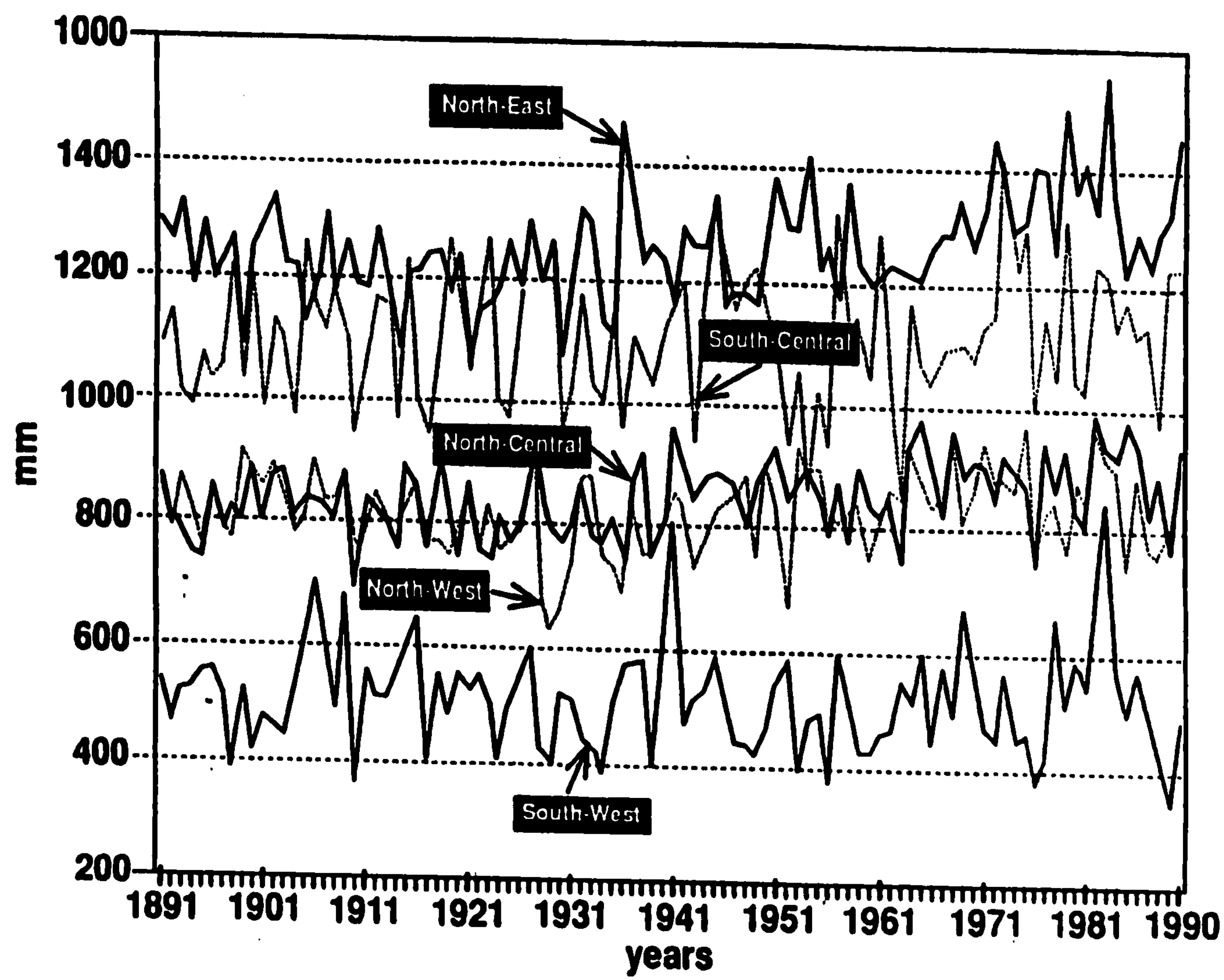



Figure 4.14: Annual Precipitation Changes over the United States and Canada, Averaged over the Five Regions Depicted (From: Groisman and Easterling, 1994).

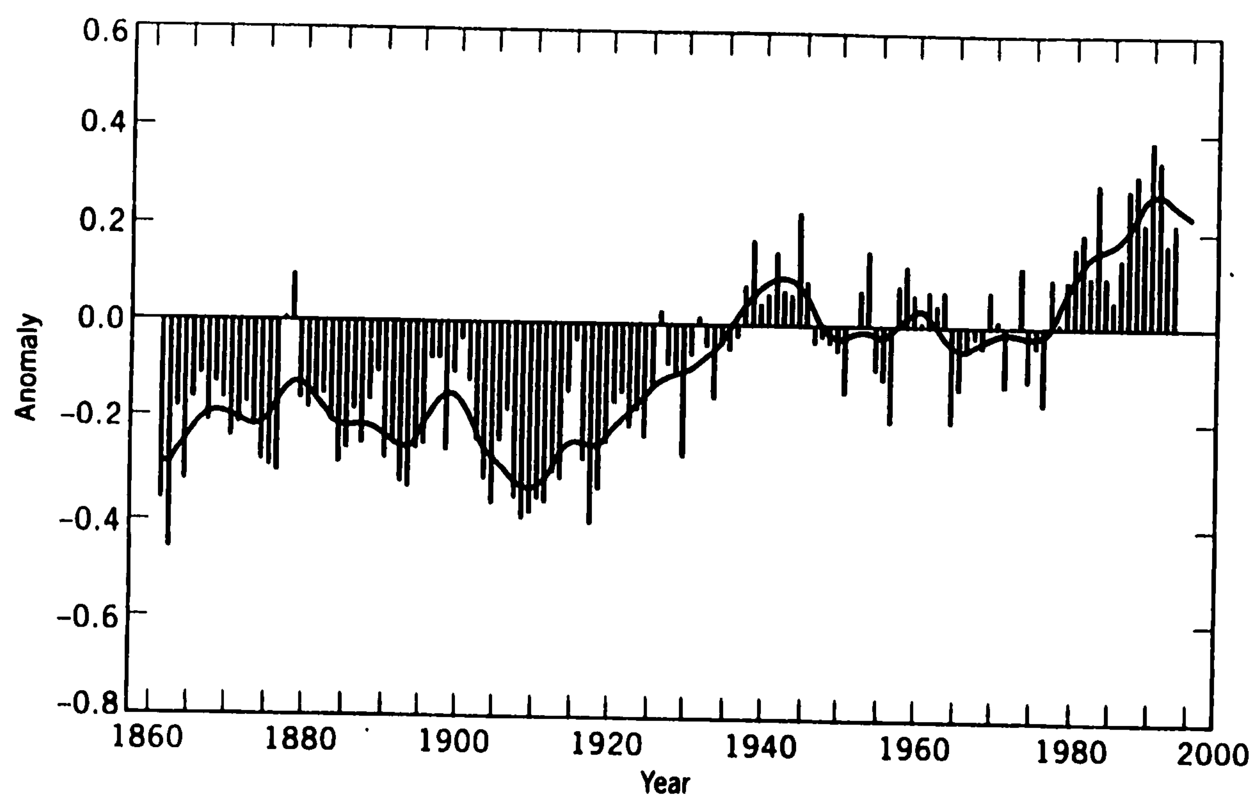



Figure 4.15: Global Average Surface Temperature Record
(From: Horel & Geisler, 1997)

Since human factors were unlikely to account for temporal patterns over such a vast areal extent, it was believed that climatic factors are likely causing the trends over time. Since discharge is an estimate of the volume of flow of water, and is closely linked to the overall hydrological cycle, the pattern of both sediment loads and discharge are largely a function of meteorological conditions. Time series of precipitation calculated for the same time period in the Northeastern U.S.(Groisman & Easterling 1994) show that low values of precipitation were evident for the period of approximately 1958-1968, which was followed by a wetter period leading into the early 1980s, followed by a dramatic drop and then subsequent rise in 1990 (Figure 4.14; top line). This general precipitation pattern correlates with both the discharge and sediment load patterns. Precipitation for the northeastern United States (top line of the graph of Figure 4.14) shows a drop in annual precipitation(mm) into the 1960s, followed by a rise in precipitation into the mid-1970s through early 1980s. This is a trend that was also observed for both sediment loads and discharge for the same period of time. The period from 1950 through 1970 was also a cooler, drier period than the years immediately before or after. Figure 4.15 shows the annual temperature anomalies (above or below average surface temperature).

Sediment yields throughout the eastern region of North America share a general pattern of higher yields in the early 1960s, a period of lower yields between 1965-70, followed by subsequent higher yields into the 1980s. Regardless of relief, geology, or land use, the trend emerges. Climatological factors can be attributed to the trends, but the precise mechanisms are complex. A similar trend in the temperature anomalies can also be seen (Figure 4.15) and the trend for the precipitation graph (Figure 4.14) is also evident, although the data is a little "noisy" the decline around 1960-70, followed by an increase in the 1980s can still be observed. The relationship between wetter years and increased sediment loads in rivers is clear. Discharge and velocity increase and consequently the ability of the river to remove and transport more sediment also increases. The relationship between warmer years and higher precipitation and sediment loads is less clear. Is the relationship a coincidence or can conclusions be drawn from the coincident highs and lows? The consequence of warmer surface temperatures has been noted (Robinson & Henderson-Sellers, 1999), with responses being more severe floods, more severe droughts, more frequent heavy rains, or a combination of these. Karl et al. (1996) concluded, for the conterminous United States, that the1970s were a decade of below average precipitation and temperature and the 1980s a decade with at least 4% greater precipitation and temperature. It is possible that the combination of warmer (with shorter lengths and depths of frozen ground) and wetter (with increased discharge) years through the 1960s and 1980s resulted in higher sediment loads. Extreme weather events could also have resulted in higher yields throughout those decades. Hurricane activity, which undoubtedly has had an impact on fluvial discharge and sediment loads has also been documented. During the late 1960s/ early1970s, few severe storms threatened the east coast of North America, in stark contrast to the severe hurricanes of the 1950s (Barnes, 1995). The period between 1953 and 1960 saw nine major hurricanes hit the east coast. Since 1886, the greatest number of intense hurricanes to strike the Atlantic coast (categories 3 to 5) recorded in one year was seven, which was recorded in 1961 (Environment Canada, 1999).

The non-stationarity of the spatial patterns of sediment yields has been discussed and initial maps of yields presented (Chapter 3) and the temporal trend of sediment loads across the study area has been noted in this chapter. Differing spatial patterns have emerged but similar temporal patterns have been observed. With initial explanations for the temporal patterns given, further explanations for the spatial patterns are required. In the following two chapters, selected basins are used to investigate more closely the reasons for the magnitude differences.

# CHAPTER 5

# CASE STUDY: SELECTED HIGH YIELD BASINS DRAINING TO CHESAPEAKE BAY

"The Potomac rises in the mountains, is fed by wooded streams, and picks up the rolling Shenandoah. Farms dot its banks...and thirsty towns, too. Rich in history it runs through our Nation's capital. Here it broadens, becomes navigable and its plantation ports mark the way to Chesapeake Bay. But, strip mines scar the soil and pollute the water. Rural slums blight its banks while industry darkens the air. Raw sewage adds its share to the river's befoulment. Erosion muddies its clear streams..."

(U.S. Federal Interdepartmental Task Force on the Potomac, 1966)

## 5.1 Introduction

"...clean up the river and keep it clean..."
President Johnson, 1965

The words of the then President of the United States of America came to fruition in the U.S. Federal Interdepartmental Task Force on the Potomac (1966). Certainly the Potomac's pollution must have become severe for the President to acknowledge the issue, or perhaps this may be documented as the largest case of "not-in-my-backyard" on record. The Potomac River Basin was to be studied in detail in the 1960s and 1970s. A number of research initiatives considered the effects of construction on fluvial sediment loads, specifically in channels draining the Potomac Basin (Wolman & Schick, 1967; Vice,et al., 1969). The occurrence of unusually high sediment loads was recorded as being a consequence of construction activities. Work was also undertaken, however, to understand the

Figure 5.1: NASA Space Agency Shuttle image looking south from Chesapeake Bay, illustrating the sediment-laden flows of the water entering the Bay. (Source: Space Shuttle Earth Observations Project.

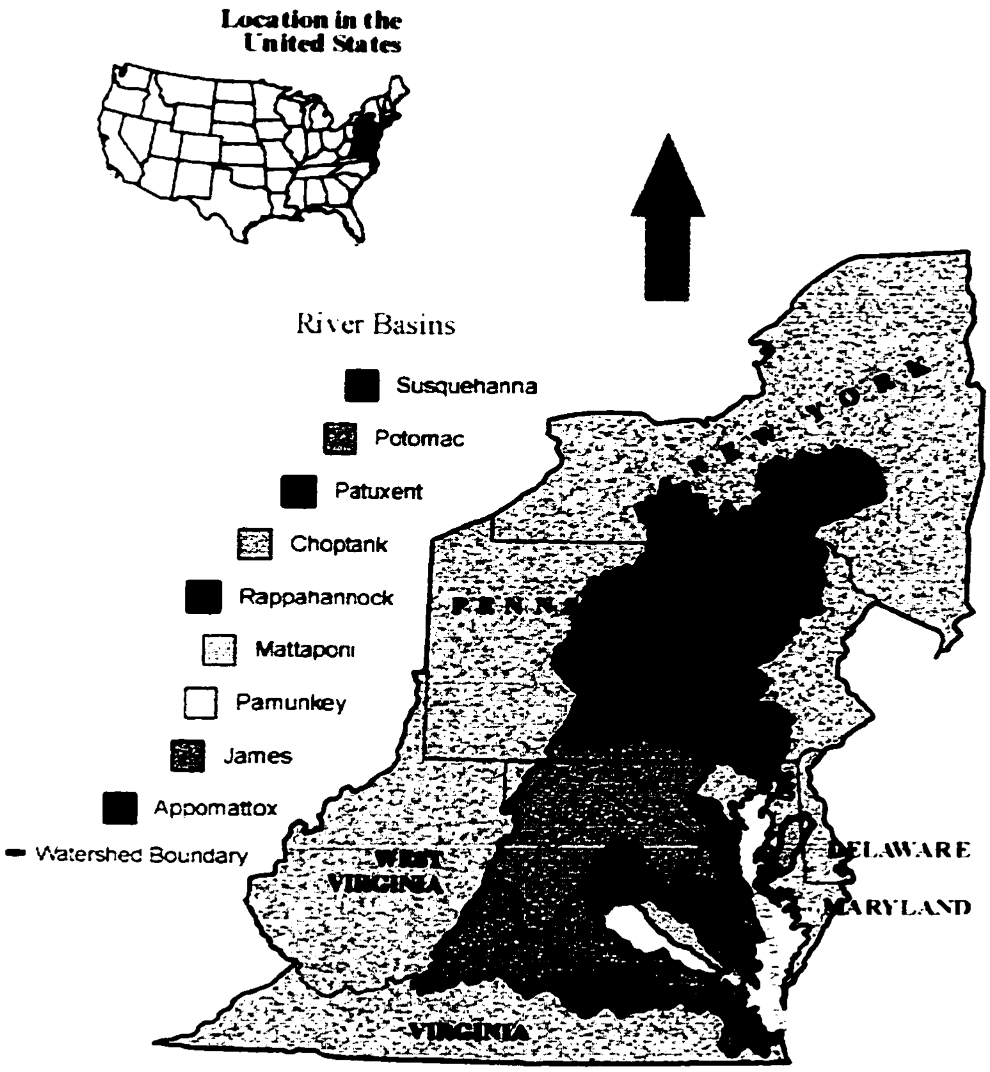



Figure 5.2: Location of Chesapeake Bay watershed and major river basins (From: USGS, 1999).

effects of agriculture (e.g. Costa, 1975). High sediment loads of the tributaries to the Potomac were attributed to human inputs. Research and initiatives then began to decline into the latter decades of the twentieth century. As a result of the deterioration of the ecosystem of the Chesapeake Bay, noted in the early 1980s in the form of nutrient enrichment, toxic substances, sediment, and over-harvesting of shellfish and finfish, the Chesapeake Bay Program (CBP) was initiated in 1987. The on-going goal of this multi-agency restoration effort has been to reduce controllable nutrient loads in the estuary by 40% by the year 2000 (USGS, 1998). The Potomac River and its drainage basin is one of a number which empties into Chesapeake Bay (Figures 5.1 and 5.2), the largest estuary in the United States and one of the most productive in the world (CBP, 1999). The United States Geological Survey has operated a network of sediment stations in the basins draining to the Chesapeake for over fifty years.

The growth and development of the United States has been dependent on the availability of water resources. As the population grew during the late 1800s, people began to move west into more arid regions where the flow of rivers was less dependable than in the humid east (USGS, 1998). The necessity of reliable water supplies led to the need for streamflow data with which to design storage and distribution facilities. In 1889, the first stream-gauging station operated in the U.S. by the United States Geological Survey (USGS) was established on the Rio Grande, New Mexico. The establishment of this early station was part of an initiative to train individuals to measure the flow of rivers and streams and to define standard

| REF # | STATION # | STATION NAME | LAT | LONG | DRAINAGE AREA (sq. km) | PERIOD OF CONT. SED. RECORD | SED. YIELD |
|---|---|---|---|---|---|---|---|
| | **MARYLAND** | | | | | | |
| 1 | 1491000 | Choptank R., nr Greensboro | 385950 | 754710 | 292.67 | 1980-91 | 6.23 |
| 2 | 1578310 | Susquehanna R. @ Conowingo | 761031 | 393926 | 70189 | 1984-92 | 9.8 |
| 3 | 1594440 | Patuxent R. nr Bowie | 385721 | 764136 | 901.32 | 1985-91 | 6 |
| 4 | 1603000 | NB Potomac R. nr Cumberland | 393719 | 784624 | 2266.25 | 1964-78, 1980-82 | 61.6 |
| 5 | 1614500 | Conococheague R. @ Fairview | 394257 | 774928 | 1279.5 | 1967-80 | 46.75 |
| 6 | 1638500 | Potomac R. @ Point of Rocks | 391625 | 773235 | 24996.09 | 1960-80,1981-92 | 38.92 |
| 7 | 1643000 | Monocacy R. nr Frederick | 392316 | 772248 | 2116.03 | 1960-69 | 50.8 |
| 8 | 1647685 | Williamsburg R. nr Olney | 390832 | 770548 | 5.83 | 1967/68 | 111.55 |
| 9 | 1647740 | NB Rock C. nr Rockville | 390609 | 770712 | 32.38 | 1967-77 | 16.8 |
| 10 | 1650085 | Nursery R. @ Cloverly | 390705 | 770024 | 0.9 | 1962-64 | 52.86 |
| 11 | 1650500 | NW B Anacostia R. nr Colesville | 390355 | 770148 | 54.65 | 1962-75 | 246.02 |
| | **VIRGINIA** | | | | | | |
| 12 | 1631000 | SF Shenandoah R. @ Front Royal | 385450 | 781240 | 4252.78 | 1953-56 | 47.91 |
| 13 | 1634000 | NF Shenandoah R. nr Strasburg | 385836 | 782011 | 1989.12 | 1955-56 | 3.26 |
| 14 | 1644291 | Stave R. nr Reston | 385656 | 772216 | 0.2072 | 1972-74 | 3156.72 |
| 15 | 1644295 | Smilax Br. @ Reston | 385710 | 772204 | 0.83 | 1972-76 | 345.21 |
| 16 | 1645784 | Snakeden Br. @ Reston | 385548 | 772043 | 2.049 | 1974-79 | 399.82 |
| 17 | 1646580 | Potomac R. @ Washington, D.C. | 385546 | 770702 | 29966.3 | 1979-82 | 44.94 |
| 18 | 1663500 | Hazel R. @ Rixeyville | 383530 | 775755 | 743.3 | 1951-55 | 60.14 |

Table 5.1: Stream gauging locations in the Potomac River basin with period of record, and sediment yield (tonnes per square km per annum).

stream-gauging methods. By 1994, 7292 continuous-record stream-gauging stations were being operated in the United States, Puerto Rico, and the Trust territory of the Pacific Islands (USGS, 1998). This chapter summarizes the spatial and temporal patterns of suspended sediment yield in the basins draining to the Chesapeake, as a result of the high yields noted in this region in previous chapters, and attempts are made to account for those patterns.

## 5.2 Sediment Yields of Rivers Draining to Chesapeake Bay

Of the 165 gauging stations used in this study for the eastern United States, 18 lie within the boundaries of the Potomac River Drainage Basin, which had been determined to have the highest sediment yields in the regional study area for the period of investigation. Chapter Three illustrated the patterns of sediment yields for the eastern United States, and high values were found to exist in this area draining to Chesapeake Bay. This chapter will discuss in greater detail the sediment yields of this region and attempt to account for factors which may explain the high yields.

Table 5.1 provides information on the sites within the Potomac Basin. Sediment yields for the period of coverage range from 3 t $km^{-2}$ $a^{-1}$ (NF Shenandoah, VA) to 3156 t $km^{-2}$ $a^{-1}$ (Stave R., VA). Periods of continuous record fall within the years 1951 to 1992. The number of stations operating during a given year within this period varies, however. Figure 5.3 shows the number of stations operating during each year from 1960 to 1992, with the highest number of stations in operation during 1974.

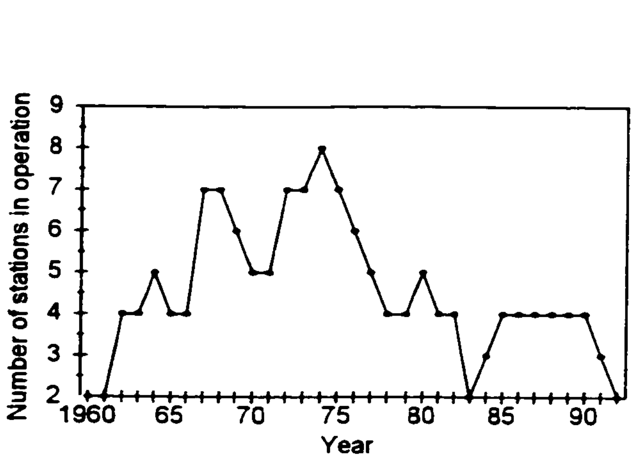
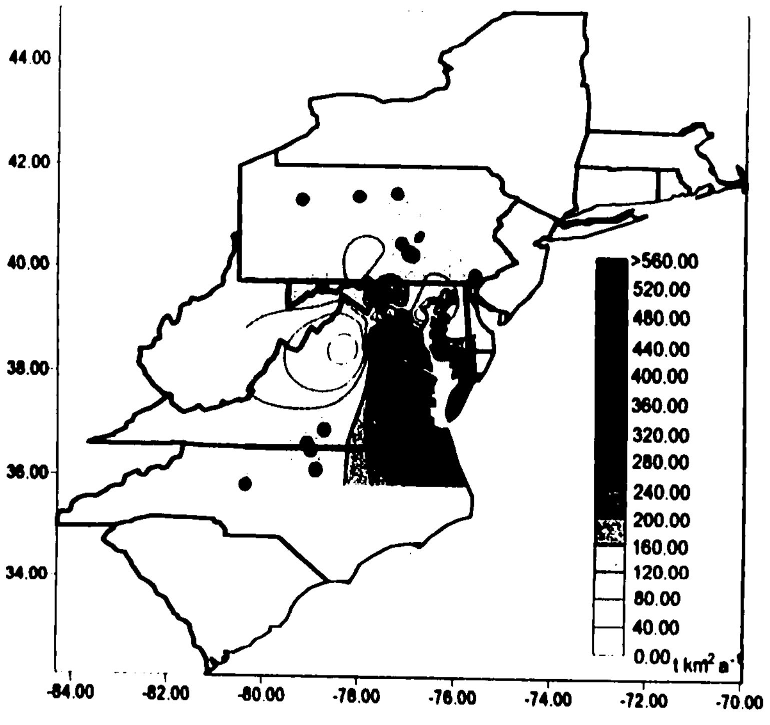
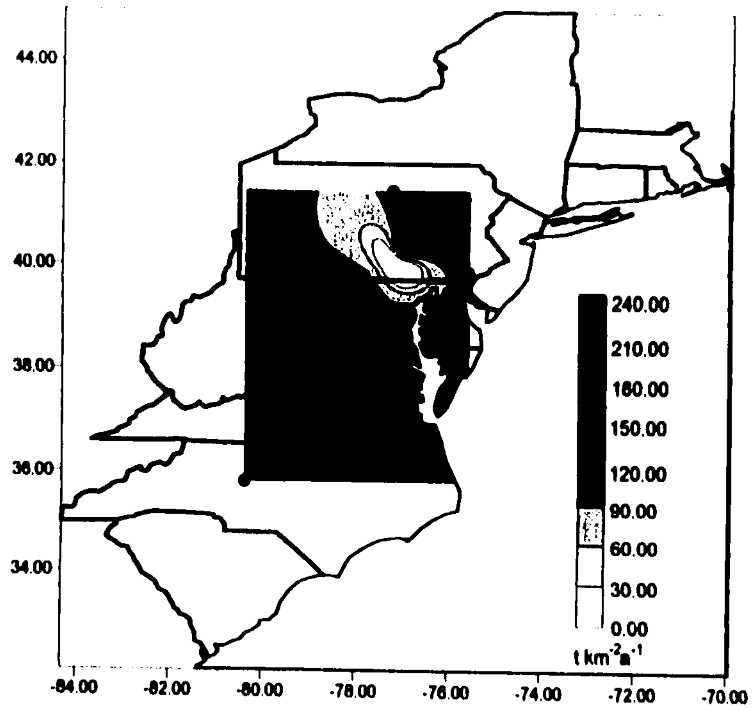



Figure 5.3: The number of stations operating in the Potomac drainage basin from 1960 to 1992. 1974 had the largest number of stations in operation.

These stations, along with stations lying outside the Potomac basin were used as the basis for generating multiquadric surfaces. Maps of annual sediment yield patterns were produced (every year from 1960 to 1990). The first map in Figure 5.4 shows the pattern of sediment yield for the 1960-61 water year. The highest yields are indicated by black, and lower yields progressively move through shades of grey to white, the lowest yield. In 1960-61 the highest yields are situated around the Yadkin River Valley in central North Carolina. The yield remains highest in that area until the following year, where in 1962-63 the highest yield shifts to the Potomac River Valley near Washington, D.C. The reason for this shift may not be so much that the yield has decreased in North Carolina, as that new gauging stations have now begun collecting information around Washington, where yields have always

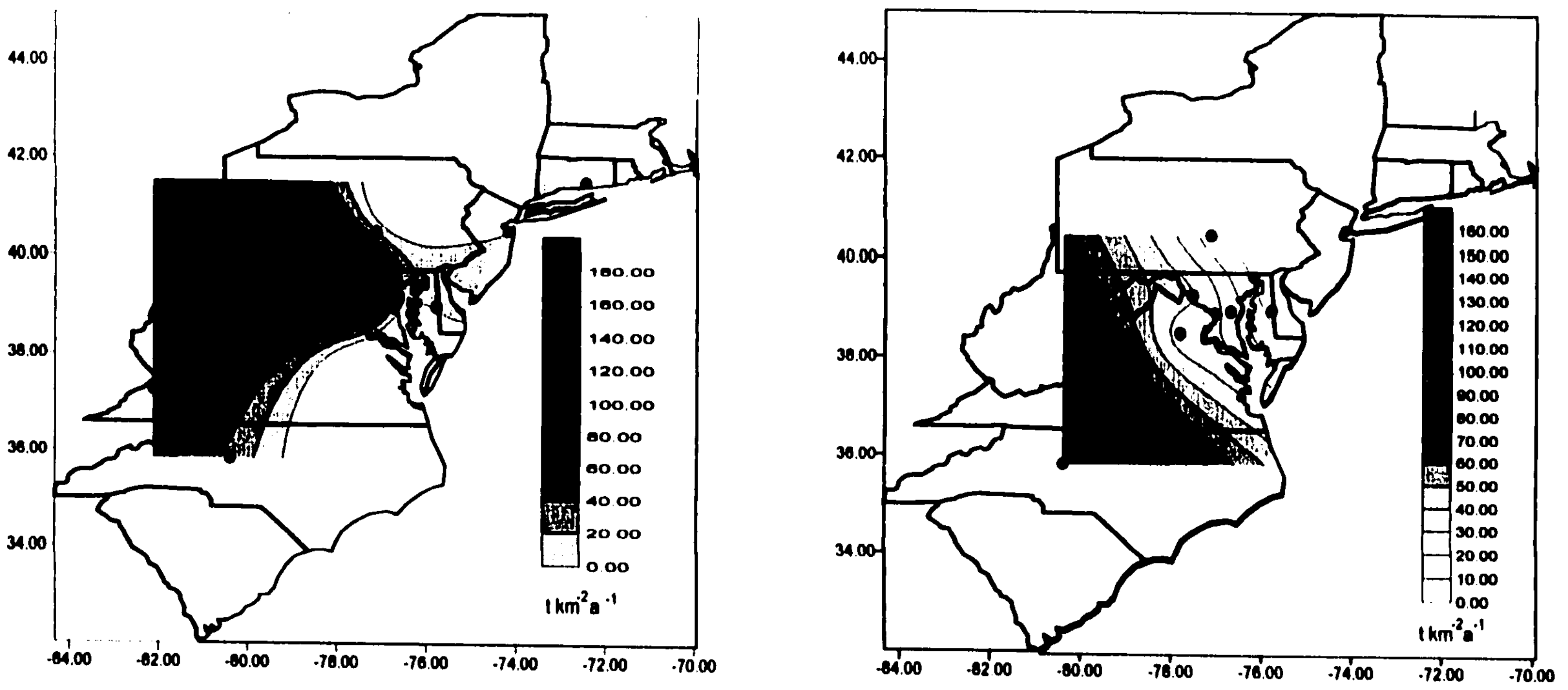



**Eastern United States Sediment Yield, 1972-73 Water Years**
(Maximum yield = 2200 t $km^{-2}a^{-1}$)




**Eastern United States Sediment Yield, 1973-74 Water Year**

Figure 5.5: Sediment yield patterns for a portion of the eastern U.S. for 1972-73 and 1973-74.




Eastern United States Sediment Yield, 1985-86 Water Year

Eastern United States Sediment Yield, 1986-87 Water Year

Figure 5.6: Sediment yield patterns for a portion of the eastern U.S. for 1985-86 and 1986-87.

been high. Yields in the Potomac drainage basin remain the highest for the eastern states from the 1962-63 water year until the 1973-74 water year.

Figure 5.5 shows yields for the eastern United States for the 1972-73 and 1973-74 water years. The high yield in 1972-73 is concentrated in a small area around Washington, D.C. and Reston, VA. The pattern in this year is reflecting the extremely high yield at one station (Stave Run, near Reston, VA). Data continues to be collected at this station the following year, but the highest yield shifts to Pennsylvania, in tributaries to the Susquehanna. With the exception of a brief return to highest yields in the Potomac (Figure 5.6:1985-86), patterns of annual yields are not located in this region again.

### 5.3 Factors Influencing the Patterns of Sediment Yields

Why are high sediment yields located in the Potomac River Basin in the years 1962 - 1973? Why do high yields shift from this area to other basins from 1973 - 1985, only to reappear for a year and then move to other areas again for the remainder of the period of record under investigation? The answer lies partially in the duration of coverage at the gauging stations. Some of the gauging stations within the Potomac Basin were not initiated until the 1980s. Some were closed in the late 1970s and others were only in operation for a short period of time, such as the station which recorded the highest yields for any period along the entire eastern region of North America (Stave Run, VA). Other factors have played a role in the initially high (1962-1973) and subsequent low (1974-85) yields of the Potomac region.

### 5.3.1 Human Factors Influencing Sediment Yields

Early in 1965, President Johnson gave John Udall, Secretary of the Interior, the responsibility of preparing a plan to make the Potomac a cleaner river. By 1965, many problems had already been noted in the Basin, problems that "...urgently need decision and action" (Udall, 1966, p.iv). Sedimentation was noted as one of several problems spoiling the river and its estuary. Udall initiated a 10 year program for stepping up Federal, State and local land use adjustment and land treatment activities, in order to wipe out pollution, and to provide an adequate water supply (Task Force report, 1966). It would seem that the high yields in the area of the Potomac River Basin are coincident with the Task Force report. High yields are evident in the area from 1963 to 1973, approximately ten years into the mandate of the Task Force. The "...marked reduction of erosion and sedimentation in the Basin..." (Task Force Report, 1966, p. 10) was to be accomplished through watershed planning and improvement, erosion control during highway and road construction, soil surveys, cropland and pasture improvement, and improved forest practices and management. Forest fire protection was also noted as being an essential element in reducing erosion and sediment. The implementation of the program was intended to "...eliminate nearly half of the sediment that is presently being discharged into the estuary..." (Task Force Report, 1966, p. 10), a result which certainly did not come to fruition. Figure 5.7 is a time-series plot of one of the gauging stations within the Potomac basin. A declining trend in suspended sediment loads is not apparent, and a large increase can be seen around 1972. Time-series plots were generated for each station within the Potomac basin and a decline in sediment loads was not noted with the exception of one. Changes in sediment loads through this period of time have been noted elsewhere (e.g. Trimble, 1981; 1983) in the United States, as a consequence of the effects of land use changes on sediment yields, and as a result of changes in sediment storage capacity.

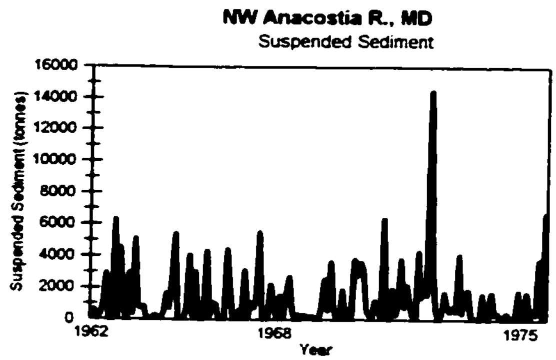



Figure 5.7: Times series of suspended sediment for the Northwest Branch of the Anacostia River, Maryland (1962-1975).

Figure 5.8 is a plot of the north branch of the Potomac River, near Cumberland, Maryland. A visible decline can be seen from the years of 1967 through 1977, which lies within the time period that the Potomac was being "cleaned up". Sediment loads increase again, however, in 1978.

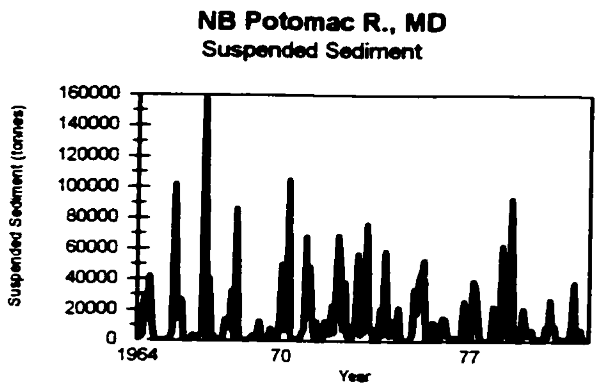



Figure 5.8:Time series of suspended sediment for the North Branch of the Potomac River, Maryland (1964-82).

The need for such a Task Force on the Potomac was primarily a result of human activities in the area that can be outlined from the region's history. The first disruptions to the land draining to Chesapeake Bay can be traced to the political upheaval in Europe and failures in Continental tobacco markets in the late 17$^{th}$ and early 18$^{th}$ centuries. The repercussions of these events meant that Americans would need to provide for themselves, and did so by moving towards new and financially important crops such as wheat and other grains (Boyd, 1968; Carr et al.,1991). With grain came a technological innovation (the iron moldboard plough, which turns the soil rather than just breaking ground) which significantly changed the agricultural practices of the Chesapeake Bay area. Repeated deep tillage of the soil and increased levels of soil eroded off the landsurface were the end results (Bosch, 1992).

Erosion, the results of which could be seen in the muddied water of the Potomac and its tributaries, was initially considered a rural problem, but with the increase of various kinds of urban construction, the largest sedimentation rates in the basin have been noted on land stripped of vegetation for roadbuilding and homebuilding as well as commercial construction, especially in the Washington metropolitan area (Task Force Report, 1966). The equivalent of many decades of natural or even agricultural erosion may take place during a single year from areas cleared for construction. In the 1960s, the cities of Baltimore and Washington and their associated suburban areas were rapidly expanding. The populations of both cities exceeded 2 million by that time. Estimates of sediment yields for rural and wooded regions had been determined to range from 200-500 t $mi^{-2}$ $a^{-1}$ (70-175 t $km^{-2}$ $a^{-1}$). Wolman & Schick (1967) calculated sediment yields from areas in the Potomac Basin undergoing construction to range from 1000-100 000 t $mi^{-2}$ $a^{-1}$ (350-35 027 t $km^{-2}$ $a^{-1}$). Wolman and Schick's results were limited and the estimates of yields in areas undergoing construction appear inflated. However, even a large reduction in their reported values indicates that construction certainly is an important factor in increasing sediment loads in river channels, and the quantity of sediment derived from areas undergoing construction is from 2 to 200 times as large as that derived from comparable areas (similar precipitation and soils) in a rural or wooded condition.

Vice et al. (1969) noted the importance of construction as an influence on sediment yields. Areas of low yields existed near land covers consisting of forest, grass, and established urban areas. Areas of intermediate yield were near cultivated landscapes and gravel pits, and areas of high yield were situated near

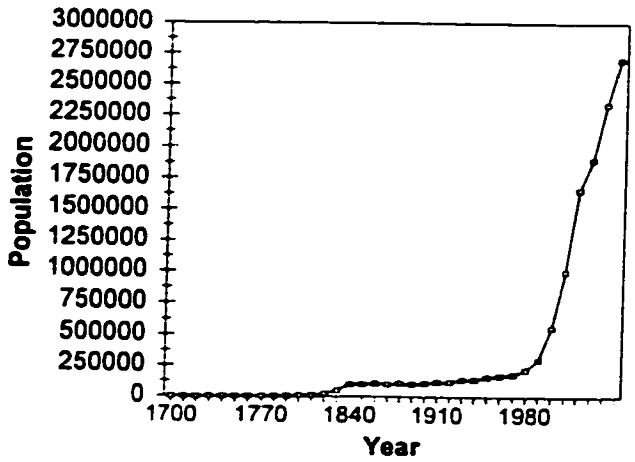



Figure 5.9: Population growth in the Patuxent River Basin from 1700 to 2000 (From: USGS, 1998).

exposed and disturbed soils in construction areas. Construction activities in the Washington area during 1960 through 1964 consisted of three highways, interstate highway 495, an airport highway, state highway 123, a subdivision and a number of industrial construction zones. The conversion of rural land to urban use during this period is certainly seen in the high yields centered around this area in Figure 5.4.

The human influence on sediment yields of the rivers flowing to Chesapeake Bay can be attributed to increases in population (Figure 5.9) and the resulting pressure that human-related activities exert on the landscape. The form of human influence has changed over the course of history throughout the basins draining to the Chesapeake. In the late 1600 and early 1700s, large plantations were beginning to dot the once entirely forested landscape. Increases in population and economic demand meant that by the middle of the 1700s, crop rotation had been also eliminated and soils were in production without rest. Although agricultural practices were much improved (including crop rotation, better ploughing and planting grasses and clovers) by the 1800s, larger numbers of people also resulted in more land clearance (Bosch, 1992). From the middle of the 1800s through to the early 1900s, the population was increasing and farming was a successful enterprise. Agricultural practices throughout this period resulted in environmental degradation and deforestation (Carr et al.,1991). By the middle of the twentieth century, the source of the human influence on the landscape had changed. Most areas of land throughout the drainage basins of the region were no longer dominated by agriculture as urban and suburban growth increasingly expanded with construction activities, now providing a major source of sediment to the rivers and streams flowing to the Bay. Sediment being transported into rivers and streams as a result of land use change can continue to have an effect on sediment yields several years beyond the time of actual disturbance since sediment can remain in storage for extended lengths of time (Trimble, 1981;1983).

### 5.3.2 Geological Factors Influencing Sediment Yields

The Potomac and other rivers flowing to Chesapeake Bay are situated on varied geology and geomorphology. The Potomac basin is situated on Valley and Ridge (Ordovician in age), Blue Ridge (Precambrian), Piedmont (some Precambrian, mostly Cambrian to Mesozoic) and Coastal Plain (Cretaceous to Tertiary) Physiographic Provinces. These provinces follow the general trend of the

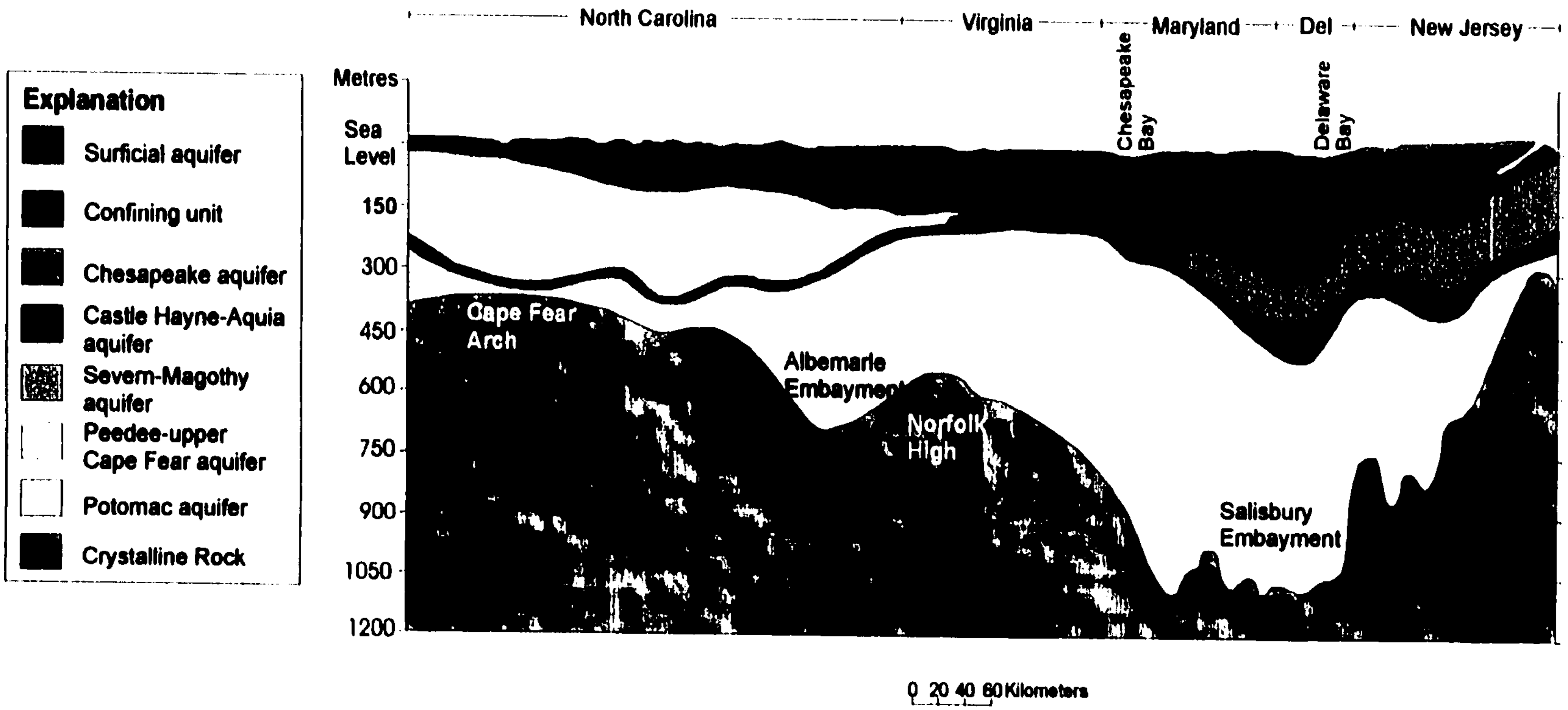



Figure 5.10: The aquifer system for a portion of the eastern United States.
The depth is thinner where parts of the underlying crystalline rock surface have been up-warped and thicker where the crystalline rocks have been down-warped (Modified from: USGS, 1997).

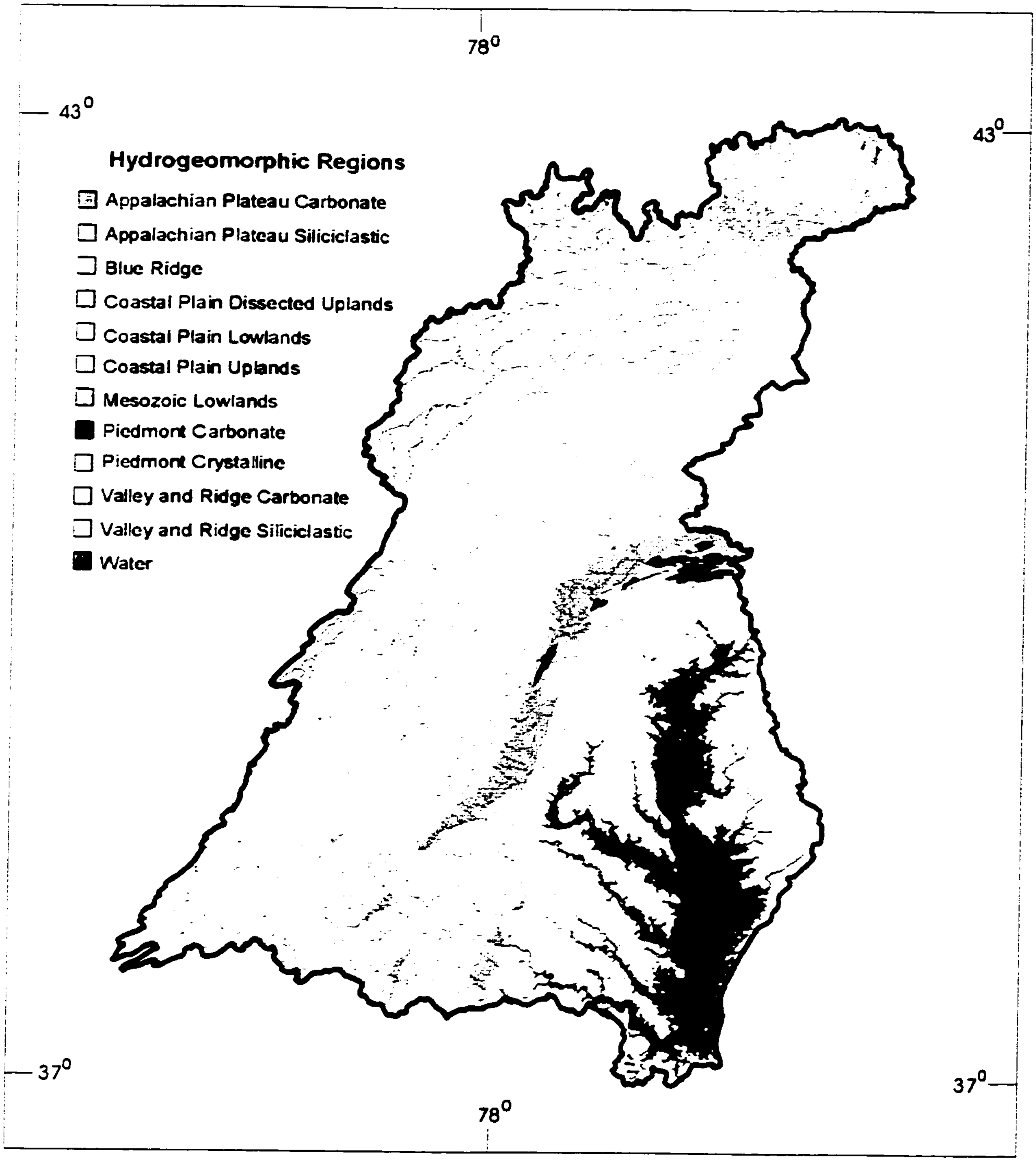



Figure 5.11: Hydrogeomorphic regions spanning the basins draining to the Chesapeake Bay (From: USGS 1999)

Atlantic Coast (Figure 2.8). The Precambrian igneous and metamorphic rocks make up the Blue Ridge Province, and these crystalline rocks are generally resistant to erosion and weathering (Trapp & Horn, 1997). This is reflected in the lowest yield of the Potomac basin at the north fork of the Shenandoah River (3.26 $t\ km^{-2}\ a^{-1}$), which flows over the Precambrian bedrock channel. High yields were calculated for those gauging stations situated in the Piedmont Province of the Potomac (e.g. Stave Run: 3157 $t\ km^{-2}\ a^{-1}$, Smilax Branch: 345 $t\ km^{-2}\ a^{-1}$, and Snakeden Branch: 400 $t\ km^{-2}\ a^{-1}$, all of which are locations in Reston, VA). The Piedmont Plateau ranges from the fall line in the east to the Appalachian Mountains in the west. The fall line marks the transition from Piedmont to Coastal Plain. Waterfalls and rapids clearly mark this line, with cities such as Washington, D.C., Baltimore, MD, and Richmond, VA developing along the fall line taking advantage of the potential water power generated by the falls (Chesapeake Bay Program, 1999). Several types of crystalline rock, including schists, slates, marble and granite underlie the eastern side and sandstones, shales and siltstones the western side. Overlying the basement rock are thick deposits of sediments. These deposits thicken towards the fall line and onto the coastal plain. In addition, extensive thick sedimentary deposits are concentrated in the Delaware through Chesapeake region (Figure 5.10). Thick accumulations of erodible material are therefore available to supply sediment to the rivers traversing this terrain (Trapp and Horn, 1997; USGS,1997).

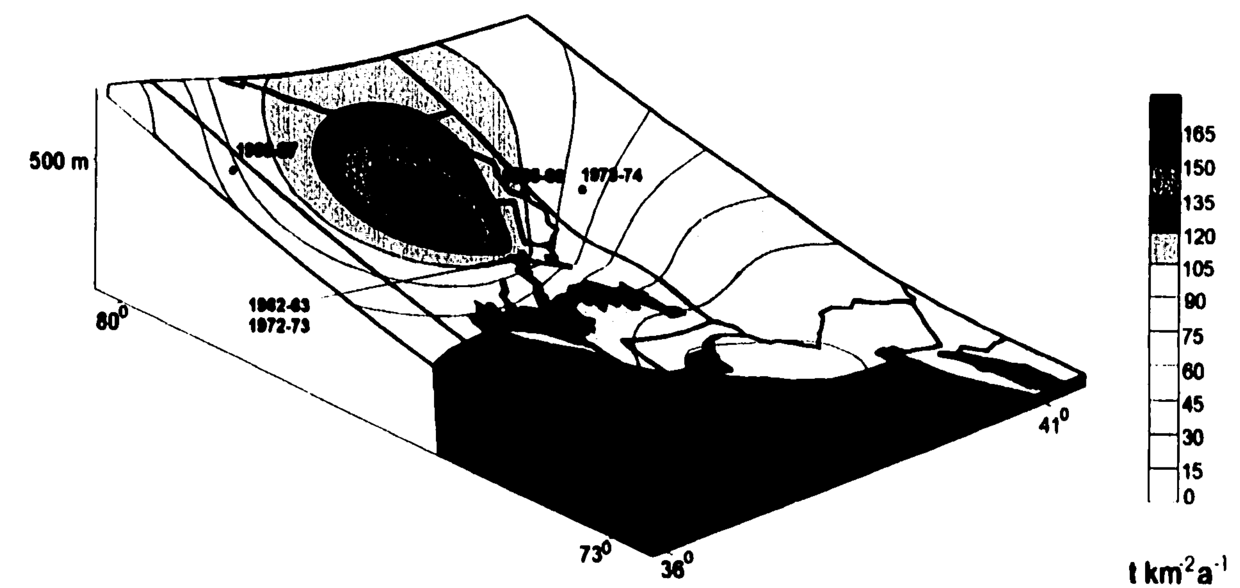



**Figure 5.12: Sediment yield pattern (1987-88) superimposed on elevation**

The points on the map with years show the locations of highest yields in selected previous years, indicating the non-stationarity of the yields.

### 5.3.3 Relief as an Influence on Sediment Yields

The Potomac region is an unglaciated surface of highlands to the west and lowlands extending to the coast. Highest peaks in the region are about 1025 metres towards the western section of the Potomac basin (Ross, 1995). The narrow section of mountain ridges in the west gives way to lower lying elevations of the Piedmont and Coastal Plain. Only the easternmost sections of the Appalachian Mountains are to be found within the Potomac basin (Figure 5.11). It has been questioned whether relief, by itself, is an independent influence on sediment yields (Meade et al.,1990) because it is difficult (as with many contributing factors) to differentiate the effects (as expressed in increased sediment yields) of one factor from another. For example, how much of a larger sediment yield is due to relief alone and how much is related to a greater erodibility of material?

Figure 5.12 illustrates the composite of a pattern (1987-88) of sediment yield and elevation. The points with the adjacent years also on the map indicate the locations of highest yields in other years. The relief and geology of the area remain the same (at this time-scale) but the factors that do vary from one year to the next are either human land-use changes or hydrological/climatological.

### 5.3.4 Hydrologic Factors Influencing Sediment Yields

Average annual precipitation ranges from less than 90 centimetres in parts of western Maryland to a 100 cm average annual precipitation in the remainder of the basin. Average annual precipitation reaches highs of approximately 200 cm in the western region of North Carolina, where the highest peaks of the Appalachian Mountains are found. The Valley and Ridge Province, which comprises a large area of the Potomac River basin, has the lowest average annual precipitation values in the eastern States, primarily a result of being in the rain shadow of the Appalachian Plateau. Ross (1995) referred to the area as a desert. Mean annual precipitation is also nearly evenly distributed throughout the twelve months of the year. Intensities, however, may be much higher in the summer months. Some of the winter precipitation is in the form of snow, but snow cover rarely persists overnight (Wolman & Schick, 1967).

With increased precipitation comes increased fluvial discharge, enabling the river to physically remove and transport larger amounts of sediment. Time series graphs of sediment loads and fluvial discharge were produced for all of the sites in the eastern United States. Peak sediment loads correspond with peak discharge 43.75% of the time. Within the Potomac basin, peak sediment loads correspond with peak discharge 67% of the time. Figure 5.13 provides an example of a plot for one of the sites within the basin (NB Rock C.,MD). The close relationship between high discharge and sediment load can be clearly seen by the correlation of peaks in 1972. Higher discharges in 1971 and 1975-76 are also associated with higher sediment loads.

### 5.4 Summary and Discussion

In most areas, research has indicated that the influences of different factors

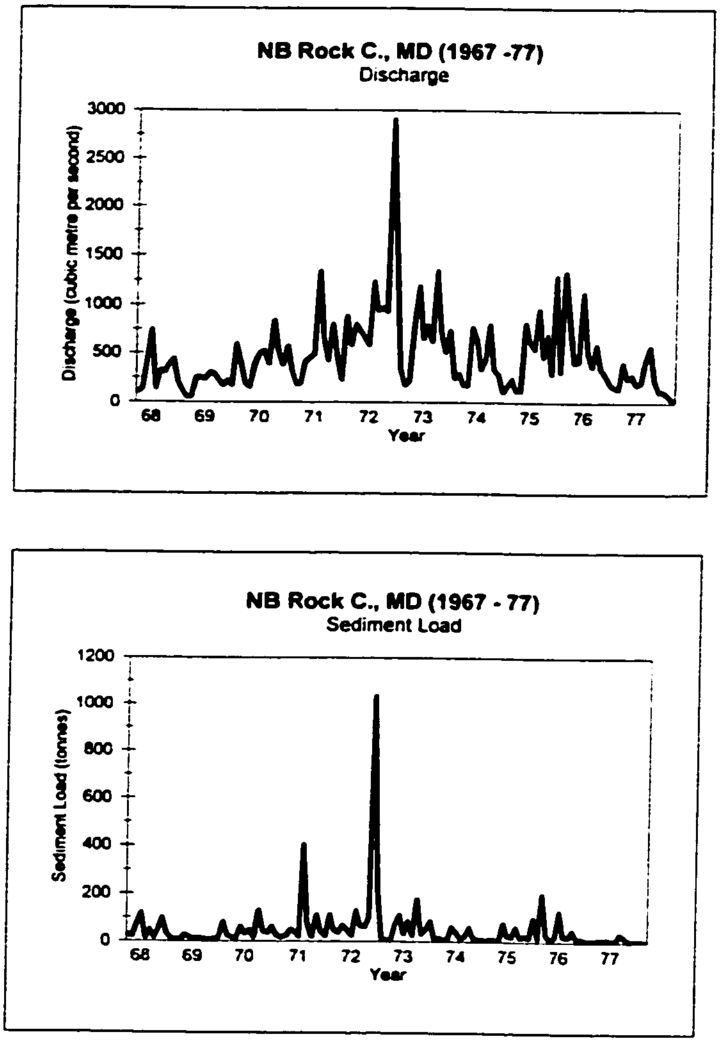



Figure 5.13: Discharge and sediment load trends for the North Branch Rock Creek, MD for 1968 - 1977, with corresponding peaks between 1972-73.

on sediment yield are difficult to discriminate from each other (Dickinson & Wall, 1977; Jordan, 1979; Osterkamp, 1976; Slaymaker & McPherson, 1977). Several factors combine to explain why sediment yields in the Potomac River drainage basin are, in many cases, much higher than those yields determined for other parts of eastern North America. Large amounts of relatively easily eroded sediment are available to streams and rivers flowing across the region. The depth of deposits of erodible sediment just beyond the fall line are also found in other areas along the coastal plain of eastern North America, and yet sediment yields do not reach the highs that have been found in the Potomac basin. Coupled with the large supply of available sediment has been the dramatic increase in population throughout many of the basins flowing to the Chesapeake Bay. The disruptive and destructive land uses associated with more people have caused sediment to be removed from the land and to empty into rivers and streams. Initial agricultural disturbance, with land clearing and deforestation, followed by urban growth, with construction activity, have provided a mechanism for the natural supply of underlying sediment to be laid bare for removal.

Within the basins flowing to Chesapeake Bay, variations in magnitudes of yields also exist. On the contemporary time-scale investigated here, the geological and relief factors remain relatively constant. The factors which change from one year to the next are human changes in land use and climatological/hydrological. At a regional scale of analysis, the overall averaged values of sediment yields can be attributed to variations in geological and topographical factors, nevertheless, the spatial and temporal patterns of highs and relative lows will change from one year to the next as a function of land use changes and varying meteorological conditions.

The following chapter will investigate a region of the study area which has been found to have relatively low sediment yields. Chapter Seven is then a comparison between regions of high and low yields.

# CHAPTER 6

# CASE STUDY: SELECTED LOW YIELD REGION: ATLANTIC CANADA

## 6.1 Introduction

Detailed investigations of patterns of sediment yields in Canada are limited. Stichling (1973) was the first to consider regional patterns within Canada. However, many of the present Water Survey of Canada sediment sampling stations were not installed at the time of his work. A number of researchers have reported on the regional yields from basins in western and central provinces of the country (Slaymaker, 1972; Ashmore & Day, 1988; Church, et al., 1989; Stone & Saunderson, 1996). A detailed investigation of the yields of the Atlantic provinces has never been conducted.

The Water Survey of Canada has operated a network of sediment stations in drainage basins of Newfoundland, Nova Scotia, New Brunswick and Prince Edward Island for over thirty years. This chapter summarizes the spatial and temporal patterns of suspended sediment yield in the basins draining this region of eastern North America, and attempts are made to account for those patterns.

## 6.2 Sediment Yields of the Atlantic Provinces

There are twenty-eight stations within the Atlantic provinces which have at least one complete year of sediment load data. The sediment load data for the eastern provinces was obtained from *Greenland Engineering Group*, a private company which has consolidated hydrometric and sediment data from all of Environment Canada's monitoring stations on a cd-rom. All of the eastern provinces were searched for sites with at least one full year record of suspended sediment load data. Once compiled, sediment loads were converted into sediment yields as outlined in Chapter 3 (page 48). The stations with sediment loads in the eastern provinces are listed in Table 6.1 and their locations are shown in Figure 2.2. Unfortunately, gauging stations do not exist for the central region of Newfoundland, southern Nova Scotia and northern New Brunswick. Figure 6.1 illustrates the distribution of the record lengths: 43% fall in the 9 - 16 years of coverage range, and only 18% of the stations cover a 1 - 3 year period of record.

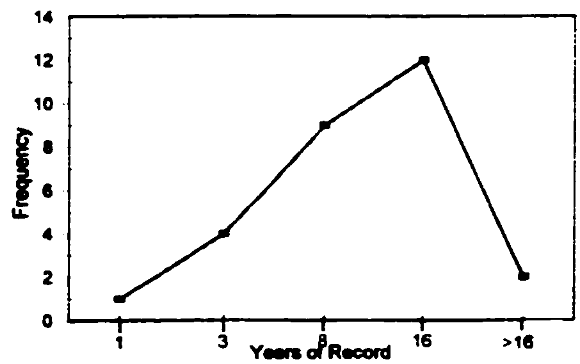



Figure 6.1: Frequency of gauging stations with various lengths of data collection (years of record) for the Maritime Provinces.

| REF # | STATION # | STATION NAME | LAT | LONG | DRAINAGE AREA (sq. km) | PERIOD OF CONT. SED. RECORD | MEAN DISCHARGE CUBIC M/SEC | TOTAL SUSP. SED. (tonnes) | SED. YIELD (t/sq. km/yr) |
|---|---|---|---|---|---|---|---|---|---|
| | NS | | | | | | | | |
| 1 | 01DC005 | ANNAPOLIS RIVER | 445659 | 650147 | 546 | 1968-1985 | 12.95 | 90360 | 9.19 |
| 2 | 01DD004 | SHARPE BROOK | 450130 | 643800 | 8.81 | 1969-1974 | 0.22 | 310.5 | 5.87 |
| 3 | 01DG018 | PEMBROKE RIVER | 451554 | 625629 | 73.3 | 1978-1986 | 2.26 | 3950 | 5.99 |
| 4 | 01DH002 | SALMON RIVER | 452209 | 631255 | 363 | 1968-1972 | 10.89 | 37150 | 20.47 |
| 5 | 01DH003 | FRASER BROOK | 452035 | 631005 | 10.1 | 1967-1975 | 0.24 | 541.1 | 5.95 |
| 6 | 01DL001 | KELLEY R. (MILL CR) | 453510 | 642705 | 63.2 | 1975-1986 | 1.99 | 4279.8 | 5.64 |
| 7 | 01DP004 | MIDDLE RIVER OF | 452950 | 624651 | 92.2 | 1970-1980 | 2.89 | 11376 | 11.22 |
| 8 | 01FB005 | APRIL BROOK | 461353 | 610830 | 6.22 | 1969-1978 | 0.25 | 2165 | 34.81 |
| | NFLD | | | | | | | | |
| 9 | 02YD002 | NORTHEAST BROOK | 505544 | 560644 | 200 | 1982-1987 | 4.9 | 5678 | 4.73 |
| 10 | 02YJ001 | HARRYS R. BELOW | 483431 | 582148 | 640 | 1980-1987 | 24.86 | 53840 | 10.5 |
| 11 | 02ZA002 | HIGHLANDS R. AT | 480633 | 584704 | 72 | 1982-1986 | 2.68 | 5389 | 14.97 |
| 12 | 02ZM006 | NORTHEAST POND R. | 473806 | 525014 | 3.63 | 1970-1978 | 0.128 | 114.87 | 3.5 |
| 13 | 02ZM008 | WATERFORD RIVER | 473145 | 524443 | 52.7 | 1979-1987 | 2.29 | 14576 | 30.73 |
| | NB | | | | | | | | |
| 14 | 01AJ007 | HOLMES BROOK NR. HOLMESVILLE | 463434 | 673543 | 31.3 | 1972-1973 | 0.28 | 4343 | 69.38 |
| 15 | 01AJ006 | HOLMES BROOK AT MOOSE MTN | 463646 | 673638 | 7.77 | 1972-1973 | 1.02 | 931 | 59.91 |
| 16 | 01AJ010 | BECAGUIMEC STR | 462027 | 672758 | 350 | 1976-1978 | 8.15 | 20550 | 19.57 |
| 17 | 01AK005 | MID. BR. NASHWAK-SIS NR. ROYAL RD | 460206 | 664205 | 26.9 | 1966-1978 | 0.52 | 2235.8 | 6.39 |
| 18 | 01AP004 | KENNEBECASIS R. | 454207 | 653605 | 1100 | 1967-1987 | 26.11 | 709900 | 30.73 |
| 19 | 01BO001 | SW MIRAMICHI R. | 464410 | 654936 | 5050 | 1985 | 72.8 | 10100 | 2 |
| 20 | 01BS001 | COAL BRANCH R. | 462637 | 650355 | 166 | 1985-1986 | 2.89 | 3140 | 9.46 |
| 21 | 01BU002 | PETICODIAC RIVER | 455637 | 651013 | 391 | 1968-1983 | 8.54 | 89160 | 14.25 |
| 22 | 01BU004 | PALMERS CREEK | 455314 | 643059 | 34.2 | 1968-1974 | 0.9 | 3625 | 15.14 |
| | PEI | | | | | | | | |
| 23 | 01CA004 | SMELT CREEK | 463606 | 635614 | 17.3 | 1968-1972 | 0.38 | 917.5 | 10.6 |
| 24 | 01CB004 | WILMOT R. NEAR | 462335 | 633935 | 45.4 | 1972-1986 | 0.95 | 27240 | 40 |
| 25 | 01CB005 | NORTH BROOK | 462049 | 633758 | 12.9 | 1972-1986 | 0.26 | 4068.2 | 21 |
| 26 | 01CB006 | EMERALD BROOK | 462134 | 633329 | 5.59 | 1975-1981 | 0.1 | 1130.9 | 28.9 |
| 27 | 01CE003 | BRUDENELL R. | 461202 | 623858 | 36 | 1967-1978 | 0.76 | 8496 | 19.7 |
| 28 | 01CE004 | BRUDENELL R. | 461207 | 623923 | 33.1 | 1980-1987 | 0.78 | 3430 | 13 |

Table 6.1: Locations, areas and periods of record for the hydrometric stations used in this chapter.

Table 6.2 shows the differences in yields between the provinces. Provincial mean yield is highest in New Brunswick ( 25 t $km^{-2}$ $a^{-1}$), followed by Prince Edward Island ( 22 t $km^{-2}$ $a^{-1}$), and Newfoundland and Nova Scotia with 13 and 12 t $km^{-2}$ $a^{-1}$ respectively. Yields in the Atlantic provinces range from a maximum of 69 t $km^{-2}$ $a^{-1}$ (Holmes Brook, New Brunswick, Station #01AJ007) to a minimum of 2 t $km^{-2}$ $a^{-1}$ (SW Miramichi River, New Brunswick, Station #01BO001 ). Mean sediment yield for the entire eastern States ( 96.7 t $km^{-2}$ $a^{-1}$) is five-fold that of the eastern provinces (18.2 t $km^{-2}$ $a^{-1}$). The maximum yield for the eastern States ( 3156.7 t $km^{-2}$ $a^{-1}$) is forty-five-fold that of the eastern provinces (69.3 t $km^{-2}$ $a^{-1}$) whereas minimum yields are approximately the same.

| Province | Mean Sed. Yield | Max. Yield | Min. Yield |
|---|---|---|---|
| Nova Scotia | 12.4 | 34.8 | 5.6 |
| Newfoundland | 12.9 | 30.7 | 3.5 |
| New Brunswick | 25.2 | 69.3 | 2 |
| Prince Edward Island | 22.2 | 40 | 10.6 |
| **Atlantic Canada** | 18.2 | 69.3 | 2 |
| **Eastern States** | 96.7 | 3156.7 | 1.5 |

Table 6.2: Mean, maximum and minimum sediment yields for each of the Atlantic provinces and overall values compared to those for the eastern United States.

The sediment data from Table 6.3 were used to generate multiquadric surfaces of yields for the sample space between longitudes 68 ° W and

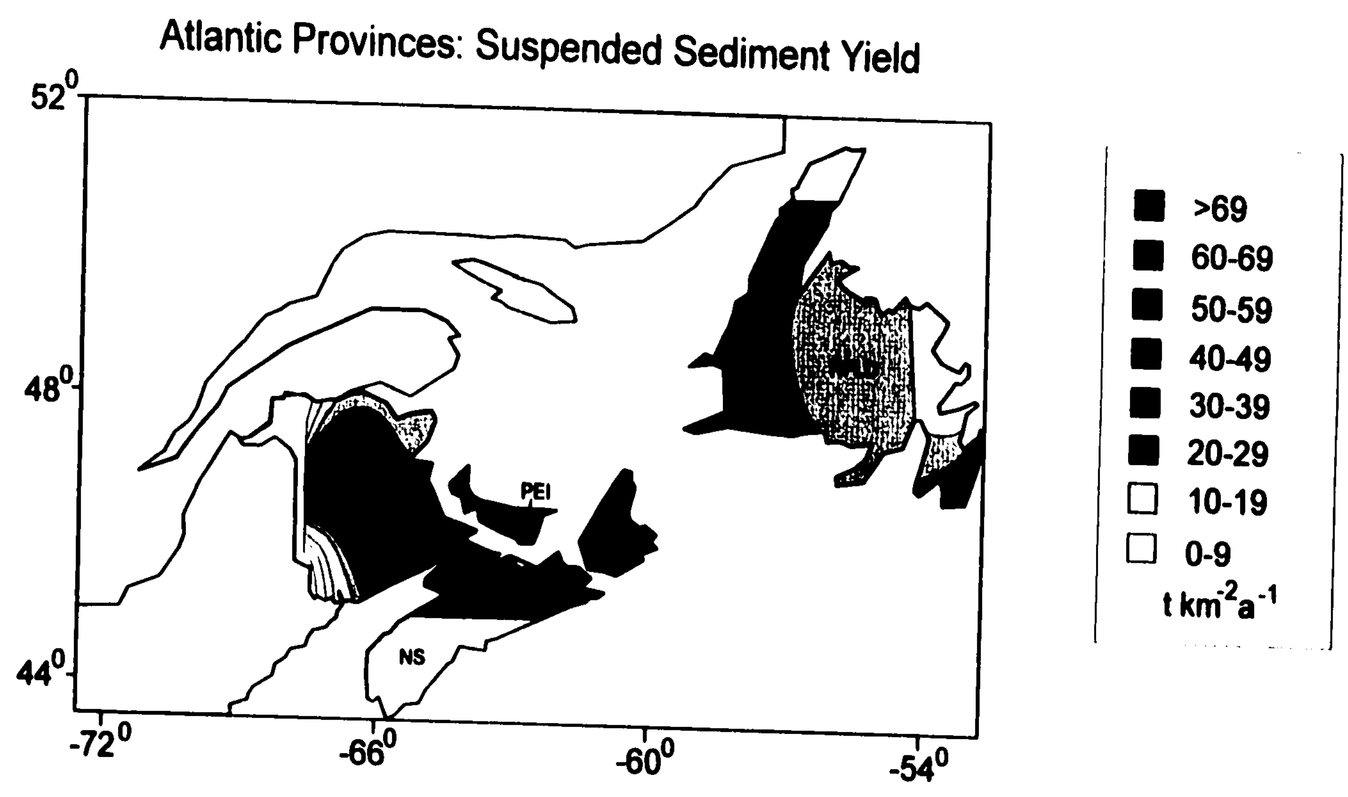



Figure 6.2: Sediment yield patterns in the Maritime provinces based on entire period of record

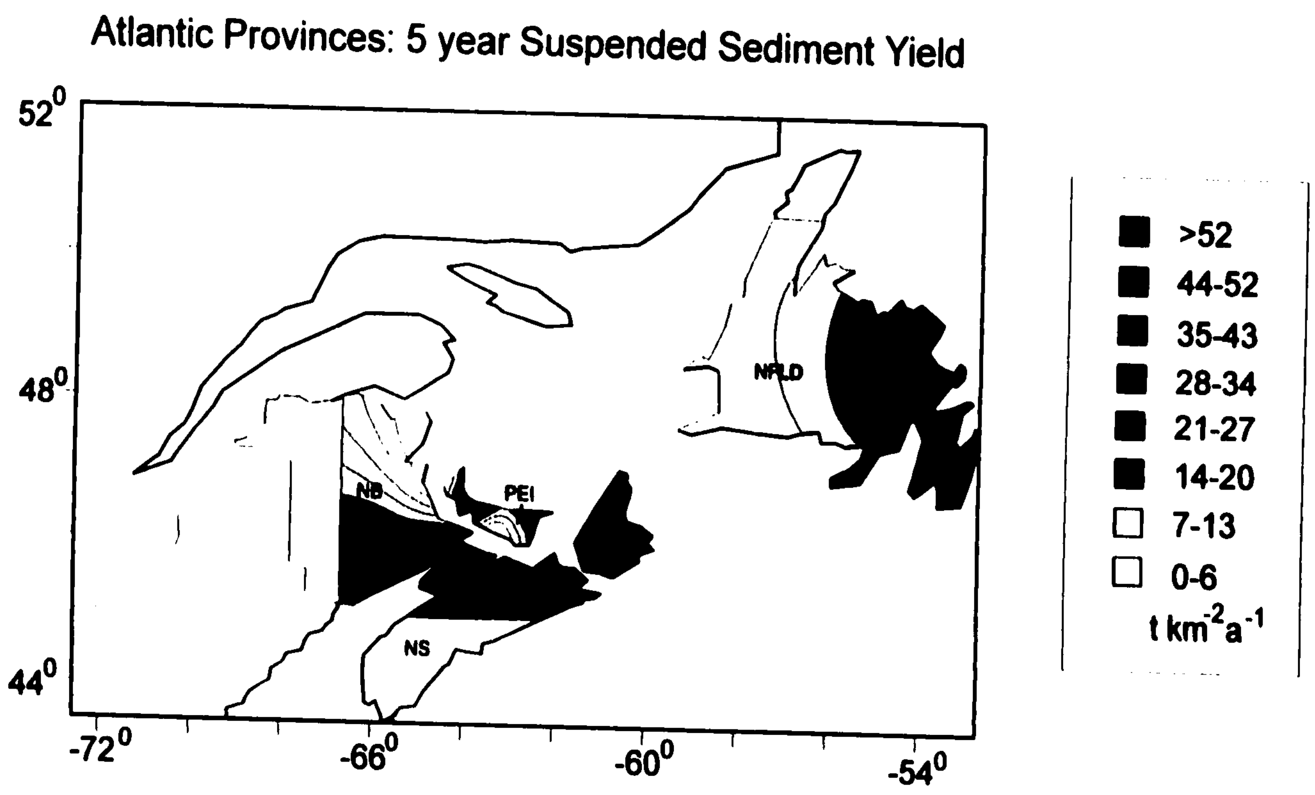



Figure 6.3: Sediment yield patterns in the Maritime provinces based on a five-year average

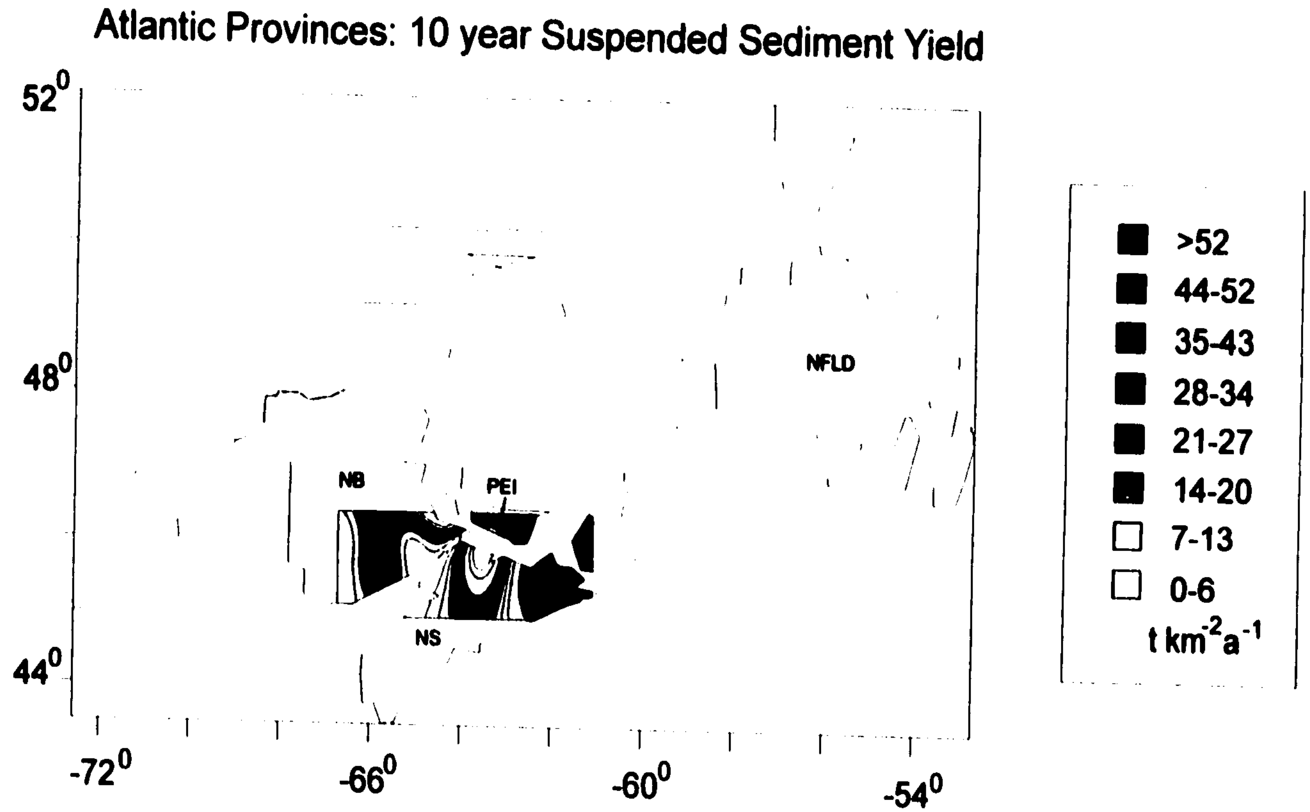



Figure 6.4: Sediment yield patterns in the Maritime provinces based on a ten-year average

| SITE # | LAT | LONG | TOTAL #YRS. OF RECORD | SED. YIELD ENTIRE RECORD | SED. YIELD AFTER 5 YRS. | SED. YIELD AFTER 10 YRS. | SED. YIELD AFTER 15 YRS. |
|---|---|---|---|---|---|---|---|
| 1 | 445659 | 650147 | 18 | 9.19 | 7.41 | 8.92 | 8.93 |
| 2 | 450130 | 6438 | 6 | 5.87 | 6.2 | | |
| 3 | 451554 | 625629 | 9 | 5.99 | 5.9 | | |
| 4 | 452209 | 631255 | 5 | 20.47 | 20.47 | | |
| 5 | 452035 | 631005 | 9 | 5.95 | 5.8 | | |
| 6 | 453510 | 642705 | 12 | 5.64 | 8.16 | 6.19 | |
| 7 | 452950 | 624651 | 11 | 11.22 | 13.73 | 11.27 | |
| 8 | 461353 | 610830 | 10 | 34.81 | 44.9 | 34.81 | |
| 9 | 505544 | 560644 | 6 | 4.73 | 5.4 | | |
| 10 | 483431 | 582148 | 8 | 10.5 | 11.15 | | |
| 11 | 480633 | 584704 | 5 | 14.97 | 14.97 | | |
| 12 | 473806 | 525014 | 9 | 3.5 | 3.1 | | |
| 13 | 473145 | 524443 | 9 | 30.73 | 37.7 | | |
| 14 | 463434 | 673543 | 2 | 69.38 | | | |
| 15 | 463646 | 673638 | 2 | 59.91 | | | |
| 16 | 462027 | 672758 | 3 | 19.57 | | | |
| 17 | 460206 | 664205 | 13 | 6.39 | 5.76 | 6.86 | |
| 18 | 454207 | 653605 | 21 | 30.73 | 26.65 | 30.09 | 33.42 |
| 19 | 464410 | 654936 | 1 | 2 | | | |
| 20 | 462637 | 650355 | 2 | 9.46 | | | |
| 21 | 455637 | 651013 | 16 | 14.25 | 10.18 | 13.01 | 14.29 |
| 22 | 455314 | 643059 | 7 | 15.14 | 15.7 | | |
| 23 | 463606 | 635614 | 5 | 10.6 | 10.6 | | |
| 24 | 462335 | 633935 | 15 | 40 | 39.8 | 41.37 | 40 |
| 25 | 462049 | 633758 | 15 | 21 | 23.72 | 23.19 | 21 |
| 26 | 462134 | 633329 | 7 | 28.9 | 21.9 | | |
| 27 | 461202 | 623858 | 12 | 19.7 | 20.4 | 21.3 | |
| 28 | 461207 | 623923 | 8 | 13 | 14.4 | | |

**Table 6.3: Eastern Canadian sites with sediment yields for full-length; 5-year; 10-year; and 15-year sediment yields.**

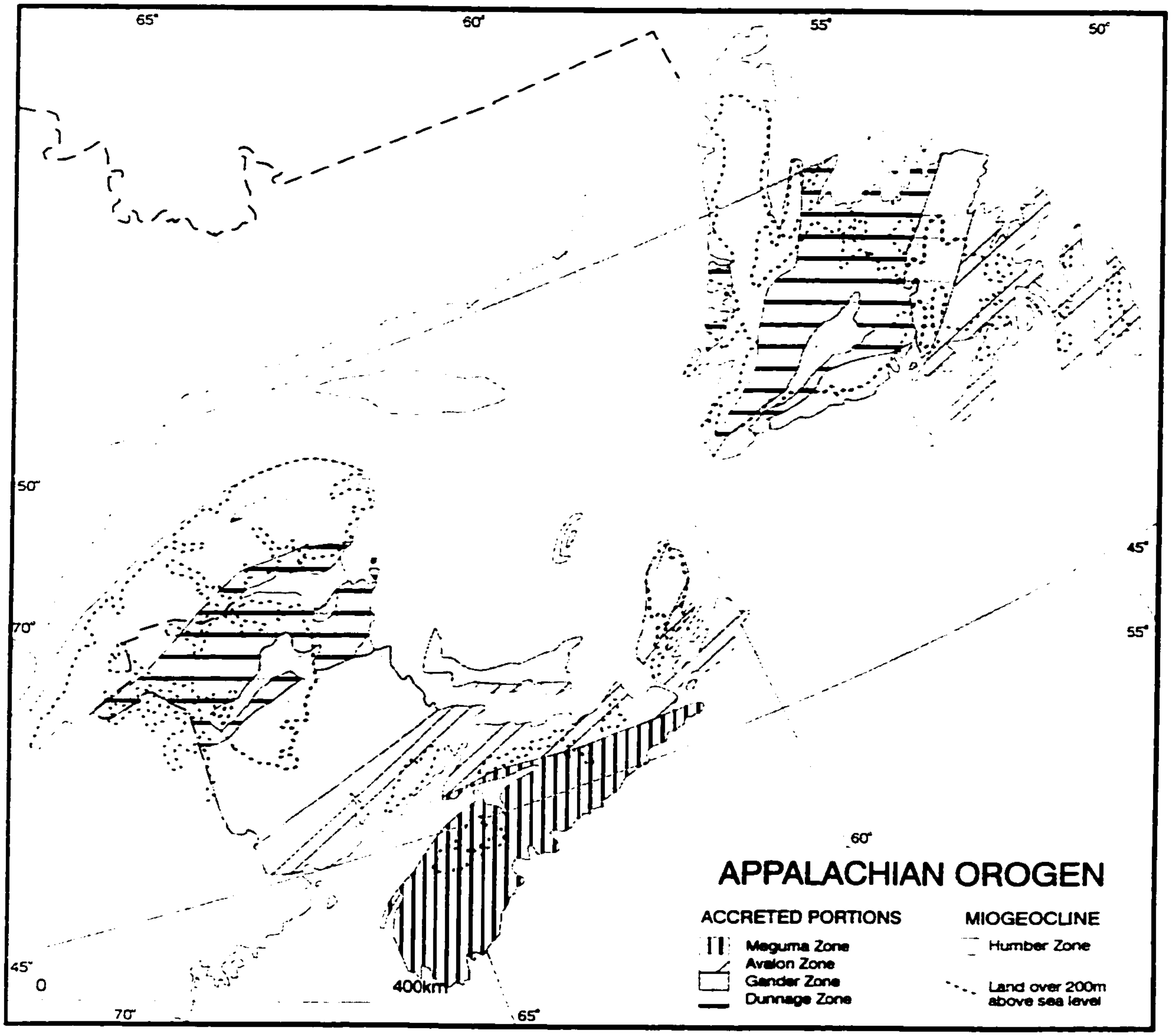



Figure 6.5: Geologic Divisions of the Appalachian Orogen in Eastern Canada (Source: Williams, 1995).

53 ° W and between latitudes 45 ° N and 51 ° N. Longitudes and latitudes within this region provided cartesian coordinates for each sample location and yields provided the scalar quantity to be mapped.

Figure 6.2 shows the spatial pattern of sediment yields for the entire period of record for data in the Atlantic provinces. Highest yields are indicated by black (darkest shades), with lower values in shades of gray and lowest yields in white. The highest yield on this map can be seen by the black portion of western new Brunswick, representing Holmes Brook. Lowest yields on this map can be found to the south (26 $km^2$) of the high yield area (Nashwaksis R., Station #01AK005) and to the east (5050 $km^2$) of the high (SW Miramichi R., Station #01BO001).

As was the case with the eastern U. S. maps, patterns of yields vary depending on the number of years of record that are used to produce the maps. Figure 6.3 shows a map of the same study area, generated using a five-year suspended sediment yield. The high in the western region of New Brunswick is no longer evident, with the highest yield now found in Cape Breton (April Brook, Station #01FB005). Figure 6.4 shows the patterns of yields using a ten-year suspended sediment yield. The surface area that is interpolated has now become smaller as a result of fewer gauging stations with at least ten years of record. The highest yield has shifted to Prince Edward Island (Wilmot R., Station #01CB004). This shift in relative highs and lows can be attributed to changing conditions across the region in addition to the changes in station locations in operation.

## 6.3 Factors Influencing Sediment Yields in eastern Canada

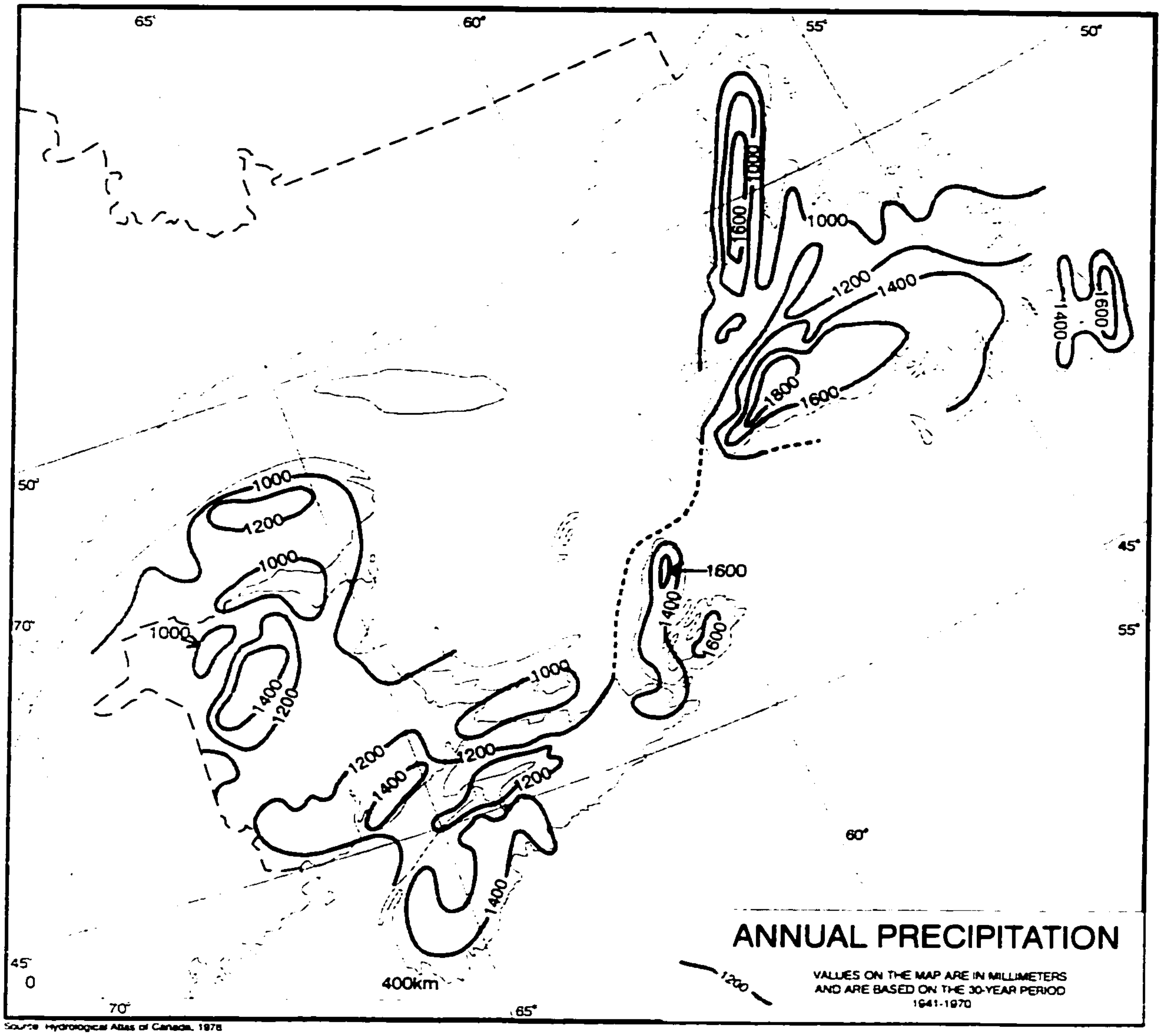
Even though the sediment yields of Atlantic Canada are, in many instances, much smaller than the yields of the eastern States, there is also considerable spatial variance within the provinces themselves. Factors explaining this spatial variation include geology, physiography, climate and hydrology, in addition to human influences. To better understand the importance of these factors, a discussion of each follows.

### 6.3.1 Geological Factors Influencing Sediment Yields

The Appalachian orogen forms the dominant topographic feature of the Maritime provinces. A number of distinct geological zones or terranes have been defined in this region (Figure 6.5 and Figure 2.7). Along the western side of the Appalachian orogen, the Palaeozoic rocks overlie a Grenville gneissic basement. This part of the orogen is known as the Appalachian miogeocline (Williams, 1995). The Appalachian miogeocline, or Humber Zone, comprises the Palaeozoic passive margin of eastern North America. The outer zones, moving east from the Dunnage, through the Gander, Avalon and the Meguma Zones, are suspect terranes, accreted to North America during the closing of the Paleozoic Iapetus Ocean. These zones are delimited by rapid facies contrasts and contrasting basement relationships.

The Humber Zone is primarily comprised of Palaeozoic rock (Cambrian through Carboniferous). Small sections of Precambrian sedimentary, metamorphic and volcanic rock may also be found in this region. The Dunnage Zone is entirely Palaeozoic, primarily Ordovician and Silurian in age. The Gander Zone is comprised of Ordovician through Carboniferous age rock. The Avalon Zone ranges in age from Precambrian granite and granitic gneiss to Upper Precambrian through Ordovician. This section of the Atlantic provinces has the oldest geologic history of the region. The Meguma Zone is primarily Ordovician in age.

The Palaeozoic volcanic and sedimentary bedrock in regions of the Gander Zone is less resistant to weathering than the Precambrian outcrops of quartzite, mica schist and gneiss in the Avalon Zone. The underlying material is of greatest significance to fluvial sediment loads where unconsolidated till or alluvium deposits are thin or rivers traverse a bedrock channel (i.e. western Newfoundland). In such locations the sediment loads will be low. For other rivers which traverse relatively thick deposits of unconsolidated material in the Avalon Zone (e.g. Prince Edward Island, much of New Brunswick) the underlying bedrock is of less contemporary significance, as a consequence of being located at greater depths. Sediment loads in these rivers will be larger than those flowing over bare bedrock or thin covers of unconsolidated material.



Source: Hydrological Atlas of Canada, 1978

Figure 6.6: Mean Annual Precipitation (1941 - 1970) in Eastern Canada

### 6.3.2 Physiographic Factors Influencing Sediment Yields

The Appalachians' hummocky nature contrasts with the St. Lawrence Lowlands to the northwest and the smooth flat surface of the Atlantic Continental Shelf to the southeast. Highest elevations are in the west and northwest where the rocks of the miogeocline form local highlands. Regions with elevations above 200m include most of Newfoundland, sections of Cape Breton and western Nova Scotia, and western New Brunswick. Moving east from the miogeocline, the land slopes gently southeastward to the coast. Lowlands of the Canadian Appalachian region occur around the Gulf of St. Lawrence.

Glacial advances and retreats during the Quaternary Period have had a profound effect upon the landscapes of the eastern Provinces. The physiography of the Canadian Appalachian region is a glaciated surface of highlands, lowlands, valleys and fiords. Glacial erosion and deposition contributed to the present landscape by surficial modification of former features (Williams, 1995). Pleistocene ice sheets advanced south and southeastward across the region, with much of Newfoundland being scoured by the ice moving across the land, but in other areas of New Brunswick, Prince Edward Island and Nova Scotia, a veneer of glacial till of varying thickness (up to 300 m in some areas) was deposited (Stea, et al.,1992). The thickness of sediments (e.g. ground moraine and other deposits of glacial origin) varies considerably across Provinces. The stations in Newfoundland and Cape Breton are located in areas with bedrock or a thin or discontinuous layer of till, while the stations in the remainder of Nova Scotia, Prince Edward Island and New Brunswick are located in areas of varying thicknesses of till, glaciofluvial deposits and alluvium (Agriculture Canada, 1977). The patterns of sediment yields (Figure 6.2, 6.3, & 6.4) indicate consistently high yields towards central and western New Brunswick, where glacial and alluvial deposits are thick and elevations are high. High yields emerge in other areas of the provinces, such as Prince Edward Island (which is typified by a large availability of erodible material) towards Cape Breton in Nova Scotia (which is typified by higher elevations). The eastern region of Newfoundland also has a high yield for the five-year time-average yield (Figure 6.3). This is an upland area with a dearth of readily available erodible material. Explanations for the higher yields may be related to local land disturbances. Over the course of ten years, the geology and physiography of the eastern Canadian provinces will not have significantly altered, and yet the patterns of sediment yields change over the course of this time-scale. This means that they can not solely be attributed to geologic and physiographic factors.

### 6.3.3 Climatic and Hydrologic Factors Influencing Sediment Yield

Precipitation highs of over 1600 mm $a^{-1}$ occur in the Cape Breton highlands and the highlands of Newfoundland. "Lows" of less than 1000 mm $a^{-1}$ are located in Prince Edward Island, northwestern New Brunswick and north-central Newfoundland, although 1000 mm is still a significant amount. Average annual precipitation throughout the maritimes does not vary significantly across the provinces (Figure 6.6).

Discharge varies from 0.1 $m^3$ $sec^{-1}$ for the Emerald Brook, Prince Edward Island, which has the smallest drainage basin area (5.59 $km^2$) to 72.8 $m^3$ $sec^{-1}$ for the Southwest Miramichi River in New Brunswick, which has the largest drainage basin area (5050 $km^2$). To investigate the relationship between discharge and sediment loads, time series graphs of both were produced for each of the twenty-eight sites, with peak sediment load corresponding with peak discharge at seventeen of the twenty-eight sites, or 60.7% of the time. High sediment loads are therefore not always a result of high discharge. This points to the fact that other variables must also be considered when attempting to account for the variation in sediment yields. It should also be kept in mind that "correlation is not causation" (Ehrlich & Ehrlich, 1996, p.29). The intensity of a river's discharge will only have correspondingly high loads if there is material to erode.

Figure 6.7 provides an example of a plot for one of the twenty-eight sites (Fraser Brook, N.S.). The close relationship between high discharges and sediment loads can clearly be seen in 1967 and 1972. Some years, however, do not have as strong a relationship. In 1969, for example, discharge rises, while the sediment load is lowest for the entire period of record. Conversely, in 1974, sediment load rises above the previous year while discharge declines.

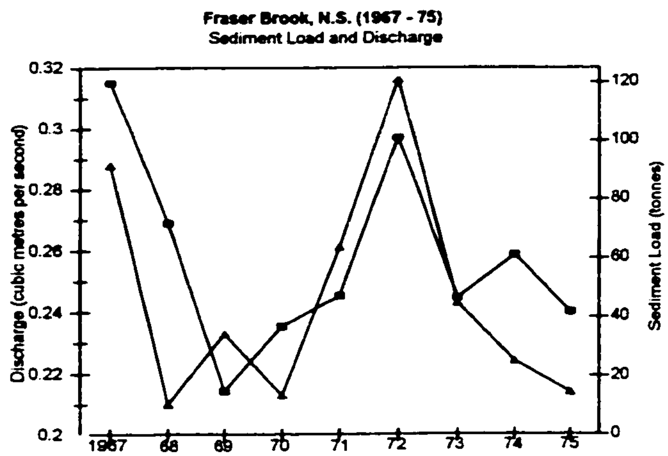



Figure 6.7: Time-series of discharge (▲) and sediment load (■) for the Fraser River, Nova Scotia from 1967 through 1975.

The range of discharge values compared to the range of sediment loads should also be noted. A small change in discharge results in a relatively large change in sediment load. Coefficients of variation of annual sediment loads and discharge were calculated for the stations with longest record lengths (Table 6.4 gives the results of the calculations).

A number of observations can be drawn from these results; with large coefficients of variation in both sediment loads and discharge, there would be large annual variations in temporal trends as well as non-stationarity of spatial patterns, with highs shifting from one region to another. In addition,

| Station | Load (tonnes) | Flow (cumec) | # of years |
|---|---|---|---|
| NOVA SCOTIA: | | | |
| Annapolis R. | 31.50% | 24.20% | 18 |
| Sharpe B. | 47.80% | 18.20% | 6 |
| Pembroke R. | 22.50% | 17.50% | 8 |
| Fraser R. | 40.60% | 12.50% | 9 |
| Salmon R. | 39.20% | 18.60% | 5 |
| Kelley R. | 51.20% | 23.20% | 12 |
| Middle R. | 45.60% | 19.70% | 11 |
| April B. | 63.70% | 12% | 10 |
| NEW BRUNSWICK | | | |
| Nashwaksis R. | 53.20% | 17.30% | 13 |
| Kennebecasis R. | 42.40% | 24% | 21 |
| Peticodiac R. | 36.70% | 24% | 16 |
| Palmers Cr. | 42.90% | 20% | 7 |
| NEWFOUNDLAND | | | |
| Waterford R. | 50% | 13% | 9 |
| Northeast Br. | 38% | 12.60% | 9 |
| Harrys' R. | 33.70% | 14.80% | 8 |
| Highlands R. | 36% | 20% | 5 |
| PRINCE EDWARD ISLAND | | | |
| North Br. | 81.80% | 15.40% | 15 |
| Wilmot Cr. | 53.50% | 20.20% | 15 |
| Emerald Br. | 95% | 20% | 7 |
| Brudenell R. | 51.40% | 24% | 12 |

Table 6.4: Coefficient of variation for sediment load (tonnes) and discharge (cumec) for selected stations in eastern Canada. Variation of sediment loads are consistently greater than variation of discharge.

the variations of discharge are consistently lower than the variations of sediment loads. Discharge is primarily influenced by meteorological conditions, while sediment loads, in addition to being influenced by meteorological conditions and discharge (transport conditions), are affected by land disturbance (supply conditions). Higher percentages of variability in the sediment loads can therefore be traced to larger numbers of factors influencing the loads than influencing the discharges. The variations in sediment loads cannot be attributed to geologic conditions, changes in soil characteristics or physiography as the time-scale is not long enough for significant changes to have been made. The higher percentages for sediment loads must therefore be attributed to climatological, hydrological and anthropogenic factors.

### 6.3.4 Human Factors Influencing Sediment Yield

In addition to the underlying geologic and natural hydrologic factors which can account for spatial and temporal patterns of sediment yields, humans, too, may influence the magnitude of yields. The removal of forest cover and conversion of land can accelerate the process of erosion tremendously (Stichling, 1973). Table 6.5 shows the population in 1986 at or near each of the gauging stations in the Atlantic provinces (McCalla, 1991; McManus & Wood, 1991).

| Site # | Population (#s of people) | Site # | Population (#s of people) |
|---|---|---|---|
| 1 | 1000 - 3499 | 15 | 1000 - 3499 |
| 2 | 3500 - 9999 | 16 | 0 - 100 |
| 3 | 0 - 100 | 17 | 25 000 - 74 999 |
| | 0 - 100 | 18 | 3500 - 9999 |
| 5 | 0 - 100 | 19 | 0 - 100 |
| 6 | 0 - 100 | 20 | 1000 - 3499 |
| 7 | 0 - 100 | 21 | 1000 - 3499 |
| 8 | 0 - 100 | 22 | 3500 - 9999 |
| 9 | 500 - 1500 | 23 | 0 - 100 |
| 10 | 20 000 - 25 000 | 24 | 3500 - 9999 |
| 11 | 5000 - 16 000 | 25 | 3500 - 9999 |
| 12 | 96 000 (St. John's) | 26 | 3500 - 9999 |
| 13 | 96 000 | 27 | 1000 - 3499 |
| 14 | 1000 - 3499 | 28 | 1000 - 3499 |

Table 6.5: Population of people (in 1986) at or near each of the gauging stations in eastern Canada.

The *magnitude* of the human influence on sediment yields will be discussed in Chapter Seven.

### 6.3.5 Other Factors Influencing Sediment Yields: Bank Erosion

Although difficult to quantify for the entire region, some examples of the potential magnitude of bank erosion can be provided for selected stations. Bank erosion along the Kennebecasis River, N.B. (Site #01AP004), for example, was deduced to be a primary source of the recorded sediment loadings (Pol, 1987). Stream bank erosion on a meandering stretch of the Annapolis River, N. S. (Site #01DC005) was also noted, with slumping and trampled soil primarily a result of cattle crossing the river (Environment Canada, 1988). Bank slumping was recorded along the Wilmot River, P.E.I. (Site #01CB004) as a result of the direct access to a relatively long portion of the bank of the Wilmot by cattle. Research in the relatively new field of "zoogeomorphology" has noted that trampling by animals can lead directly or indirectly to erosion. It can be a direct agent of erosion when trampling along the edge of a stream, pond, turf terrace, or erosion pan causes hoof or paw chiseling and bank sloughing and erosion (Butler, 1995). In fact, "...it is believed that most of the river sediments in the Wilmot basin are produced by the agricultural activities and by stream bank erosion" (Pol, 1988, p. 7).

## 6.4 Agriculture Canada: Parameters Outlined for Soil Erodibility

Agriculture Canada has produced *Water Erosion Risk Maps* of the Maritime Provinces (Coote et al.,1991), with polygons on each map corresponding to a database that contains attributes of its soils, crop cover, crop management, and the Universal Soil Loss Equation (USLE), which includes numerous parameters (e.g. erosivity of rainfall, soil erodibility, slope length and steepness, crop cover and management, and conservation practice).Spatial patterns of sediment yields, which indirectly give an indication of the patterns of erosion, were compared with the attributes of the database to determine the relationship between sediment yields and factors such as those just noted.

Data were collected from Agriculture Canada and the Canada Soil Inventory, compiled in a *Water Erosion Risk Map of the Maritime Provinces* (Coote et al.,1991) and in the *Soil Landscapes of Canada* map series (Hender & Woodrow, 1989). Each of the gauging stations in Nova Scotia, New Brunswick, and Prince Edward Island was located on the map sheets and information was obtained and recorded in Table 6.6. As a *Water Erosion Risk Map* has not been produced for Newfoundland, the *Soil Landscapes of Canada* (Newfoundland) map was utilized. Information on dominant and subdominant soils and slope angle was obtained from this map. Percentage of farmland was obtained from census data. The information in this table is not for the entire drainage basin of the gauged rivers, rather for polygon areas designated by Agriculture Canada. The polygons are indicative, however, of the physical and agricultural characteristics of the land area nearest to the gauging station in addition to being representative of the drainage basin (Shelton, 1998) as a whole.

### 6.4.1 Parameters of the Universal Soil Loss Equation (USLE)

The *Water Erosion Risk Map of the Maritime Provinces* (Coote et al.,1991) and *Soil Landscapes of Canada* map series (Hender & Woodrow, 1989) rely heavily on the Universal Soil Loss Equation (USLE), which is comprised of numerous parameters relating to physical and human attributes of given locations. The equation, developed by Wischmeier and Smith

| Station Number | Risk of Erosion | FL (%) | SL (%) | Management | DS | K | LS | SDS | Y |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Severe | 50-79.9 | 3.59 | Excellent | GS | 0.016 | 1.79 | SL | 9.19 |
| 2 | Severe | 10-29.9 | n/a | Excellent | GL | 0.032 | 3.14 | n/a | 5.87 |
| 3 | Severe-High | <10 | 3.21 | Excellent | GSL | 0.022 | 1.16 | GSL | 5.99 |
| 4 | Severe | 10-29.9 | n/a | Excellent | GL | 0.024 | 1.16 | GL | 20.47 |
| 5 | Severe-High | 10-29.9 | n/a | Excellent | GSL | 0.025 | 1.16 | GSL | 5.95 |
| 6 | Severe | <10 | 2.06 | Excellent | SL | 0.024 | 1.79 | SL | 5.64 |
| 7 | Severe-High | 30-49.9 | 0.76 | Good | GSL | 0.03 | 1.16 | GSL | 11.22 |
| 8 | Severe-Negligible | 50-79.9 | 0 | Excellent | GSL | 0.016 | 1.79 | SL | 34.81 |
| 9 | n/a | n/a | n/a | n/a | n/a | n/a | 16-30% | SL | 4.73 |
| 10 | n/a | n/a | n/a | n/a | SL | n/a | 4-9% | n/a | 10.5 |
| 11 | n/a | 30-49.9 | n/a | n/a | LFS | n/a | 1-4% | SL | 14.97 |
| 12 | n/a | 10-29.9 | n/a | n/a | SL | n/a | 16-30% | n/a | 3.5 |
| 13 | n/a | 50-79.9 | n/a | n/a | LS | n/a | 4-9% | n/a | 30.73 |
| 14 | Severe-Moderate | 30-49.9 | n/a | Good | GL | 0.03 | 1.63 | SICL | 69.38 |
| 15 | Severe-Moderate | 30-49.9 | n/a | Good | GL | 0.03 | 1.63 | SICL | 59.91 |
| 16 | Moderate-Severe | <10 | n/a | Excellent | SICL | 0.038 | 0.37 | GL | 19.57 |
| 17 | Severe | <10 | 1.5 | Excellent | GL | 0.042 | 1.12 | GSL | 6.39 |
| 18 | Severe | 10-29.9 | 0.7 | Excellent | CL | 0.043 | 5.29 | n/a | 30.73 |
| 19 | Severe | <10 | n/a | n/a | SL | 0.029 | 1.63 | GSL | 2 |
| 20 | Moderate-High | <10 | n/a | Excellent | SL | 0.034 | 0.4 | SL | 9.46 |
| 21 | Severe | 10-29.9 | 1.23 | Excellent | LFS | 0.018 | 5.29 | n/a | 14.25 |
| 22 | Severe | <10 | n/a | Excellent | CBSL | 0.026 | 8.53 | n/a | 15.14 |
| 23 | Severe | 80-100 | n/a | Good | FL | 0.05 | 3.14 | FL | 10.6 |
| 24 | High-Severe | 80-100 | 0 | Good | FL | 0.05 | 0.36 | FL | 40 |
| 25 | High-Low | 80-100 | 0 | Moderate | FL | 0.05 | 0.36 | L | 21 |
| 26 | Severe | 50-79.9 | n/a | Good | SL | 0.037 | 3.14 | SL | 28.9 |
| 27 | Moderate-High | 50-79.9 | 3.67 | Moderate | SL | 0.027 | 0.36 | FL | 19.7 |
| 28 | Moderate-High | 50-79.9 | 3.67 | Moderate | SL | 0.027 | 0.36 | FL | 13 |

**Table 6.6: Agriculture Canada: values of parameters for soil erodibility in the vicinity of each of the gauging locations**
(FL= farmland; SL= swampland; DS= dominant soil; K = soil erodibility; LS = slope length and steepness factor; SDS= subdominant soil; Y= sediment yield)

(1965) has been applied widely in the United States and Canada. Agriculture Canada (Coote et al.,1991) points out that these values should not be used quantitatively, but qualitatively to compare polygons by erosion risk class. In the Universal Soil Loss Equation:

$$A = R_t \cdot K \cdot LS \cdot C \cdot P \tag{6.1}$$

*A* is the predicted water erosion rate, $R_t$ is the erosivity of rainfall and snowmelt and winter runoff, *K* is soil erodibility, *LS* is a slope length and steepness factor, *C* is a crop cover and management factor and *P* is a conservation practice factor. The reliability of such an equation to estimate a risk of erosion may be questioned. When comparing sediment yields (an indirect measure of erosion) to risk of erosion, a relationship does not appear to exist. Some of the lowest yield regions are estimated by the Agriculture Canada maps as having a severe risk of erosion (e.g. sites 19, 6, 2). The sites with the highest sediment yields (sites 14, 15) have risks ranging from severe to moderate (Table 6.6). In fact, many of the parameters of the USLE do not correlate with the calculated values of sediment yields. The USLE indicates erosion on the plot level, whereas sediment yield indicates output from the drainage basin. Trimble (1981;1983) has also noted the difference between erosion rates (from the USLE) and sediment yields. The USLE parameters will be discussed briefly, followed by agricultural characteristics that were related to sediment yields.

#### 6.4.1.1 Land Management

The fifth column of Table 6.6 provides land management characteristics ranging from moderate to excellent. As outlined in the USLE, land management land management refers to a cropping practice factor (C) for each crop and crop group in each region. The C factor expresses the expected erosion under a given crop cover as a proportion of that expected on bare, unprotected soil. The weighted polygon mean C factor, grouped into five classes (excellent, good, medium, poor and inferior), indicates the effectiveness of cropping practices in protecting the soils from water erosion. A classification of excellent is indicative of a factor <0.10, with examples being hay, tree fruits, vines, grass, pasture and sod. A classification of good is 0.10 - 0.19, with similar land use as a classification of excellent. A moderate/ medium classification is 0.2 - 0.39, indicative of land uses such as spring and fall-sown cereals, potatoes, and nursery crops. Mean values for the Maritime Provinces are presented in Table 6.7. Absence of a classification for protection by crop management in Table 6.6 indicates too few crop data to make an estimate for that region. This situation often applies in forested areas, which are also usually indicated by a value of 1 (Coote, et al.,1991). Land management is a qualitative value, grouped into large categories that do not bear a relationship with sediment yield values alone. Management classifications of “excellent” might be expected to have lowest sediment yields. This, however, this is not the case.

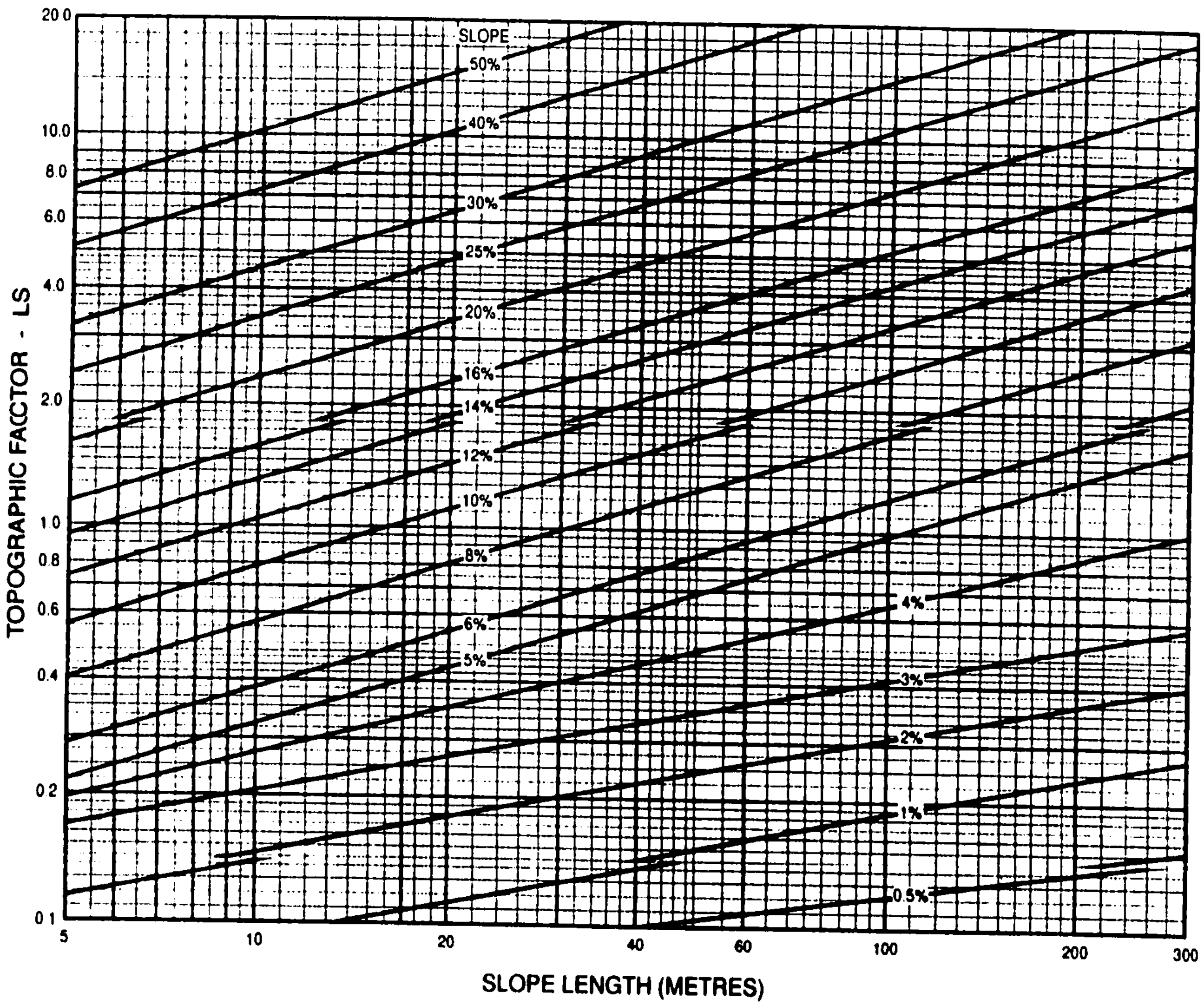



Figure 6.8: Slope Effect Chart (Wischmeier and Smith, 1978).

| Crop or crop group | Mean annual C factor |
|---|---|
| Grass hay, pasture | 0 |
| Sod | 0.02 |
| Hay (alfalfa) | 0.02 |
| Tree fruits, grapes | 0.05 |
| Small fruits | 0.10 |
| Nursery crops | 0.20 |
| Fall-sown cereals | 0.26 |
| Spring-sown cereals | 0.28 |
| Potatoes | 0.37 |
| Corn for grain | 0.41 |
| Corn for silage | 0.46 |
| Canola, peas, beans soybeans, buckwheat | 0.50 |
| Tobacco | 0.65 |
| Vegetables | 0.71 |
| Fallow | 1.00 |

Table 6.7: Mean annual C factor (expresses expected erosion under a given crop cover as a proportion of that expected on bare, unprotected soil) for various crop types (Coote et al., 1991).

### 6.4.1.2 Soil Erodibility

If the soil is more erodible, one would expect to find higher yields in areas of more erosive material. Estimates of soil erodibility for the polygon areas have been conducted by Agriculture Canada, based on Wischmeier and Smith (1978). The soil erodibility factor, K, represents the rate of soil loss per unit area. Calculation of a K value is based on five parameters: percent silt plus very fine sand (0.05 to 0.10 mm), percent sand greater than 0.10 mm, organic matter content, structure, and permeability (Wall, 1997). A K value is calculated for a specific soil, using the following equation

(Wischmeier & Smith, 1978):

$$K=27.66M^{1.14}(10^{-4})(12-a)+0.0043(b-2)+0.0033(c-3) \qquad (6.3)$$

where $M$ is percentage of (silt + very fine sand) x (100 - percentage of clay), $a$ is percentage of organic matter, $b$ is a soil structure code (varies from 1 to 4), and $c$ is a soil permeability code (varies from 1 to 6). The value and reliability of such an equation might also be questioned when comparing sediment yields to soil erodibility. Soil erodibility (K) values appear to have no relationship to sediment yields (Table 6.6). K values of 0.3, for example, have associated sediment yields of 5.87 to 69.38.

#### 6.4.1.3 Distribution of Slopes

Table 6.6 also provides a "slope factor" (LS) for the sites in Nova Scotia, Prince Edward Island and New Brunswick and slope percentage for sites in Newfoundland. The slope factor (LS), calculated in polygon areas for the three provinces, accounts for the effects of slope angle and length on erosion (Coote, 1997). The LS factor components have various effects on soil erosion and ultimately sediment loads. A slope's steepness may cause more runoff, with soil being rapidly removed. The relationship between steepness and runoff is influenced by a number of other factors, however, such as crop type, surface roughness, and soil saturation. Slope length is measured from the point where surface flow begins to where a) the runoff is concentrated into a channel, or b) the slope gradient decreases and deposition of eroded sediment occurs. Runoff and erosion generally increase with increasing slope length. A greater accumulation of runoff on longer slopes increases detachment and transport potential.

Type of slope also influences the amount of erosion and material that will be supplied to a river channel. Concave slopes generally have lower erosion rates (i.e. lower LS values) than a uniform slope of the same average gradient, since the gradient (and transport capability and erosion potential) will decrease with distance from the top of the slope. Convex slopes, on which gradient increases with distance from the top of the slope, on the other hand, will generally have a higher rate of erosion than uniform slopes (Coote, 1997). Figure 6.8 shows the graph that is used to obtain LS values. Generally, a larger LS value is indicative of higher slope angles and often shorter slope lengths. The higher the LS factor, the greater the erosion potential, however, there are numerous other factors which also require consideration when correlating sediment loads to slope angle and length. Similar slope factors do not necessarily mean similar sediment yields in the rivers draining those slopes. Crops located on the slope (e.g. corn vs. root crops) are likely to be even more significant (Shelton, 1998).

#### 6.4.1.4 Dominant Soil Cover

Dominant soil (DS) is that soil, if any, which occupies more than 40%

of the polygon area. Subdominant soil (SDS) occupies 15 - 40% of the polygon area. If there is no subdominant soil noted in Table 6.5, this means that the dominant soil type occupies at least 85% of the polygon area. Table 6.8 shows the major soil groups with the codes and classes for each of those soils.

| Soil Group | Surface texture class: Code | Class |
|---|---|---|
| Sands | S | Sand |
| | LS | Loamy sand |
| | GS | Gravelly sand |
| | LFS | Loamy fine sand |
| | GLS | Gravelly loamy sand |
| Sandy Loams | SL | Sandy loam |
| | FL | Fine sandy loam |
| | GSL | Gravelly sandy loam |
| | VGSL | Very gravelly sandy loam |
| | CBSL | Cobbly sandy loam |
| Loams | L | Loam |
| | CBL | Cobbly loam |
| | GL | Gravelly loam |
| | CBGL | Cobbly gravelly loam |
| | SIL | Silt loam |
| | GSIL | Gravelly silt loam |
| Clay loams | CL | Clay loam |
| | SCL | Sandy clay loam |
| | SICL | Silty clay loam |
| | GCL | Gravelly clay loam |

Table 6.8: Major soil groups and codes and classes for each of those soils (Coote et al., 1991).

Looking at Table 6.6, dominant soil type (DS) and subdominant soil (SDS) alone do not appear to have a strong relationship with sediment yield. A much more detailed investigation of the specific particle sizes, and seasonality of movement of various particle sizes would be required to draw conclusions regarding the actual relationship between yield and dominant soil cover. However, by looking at dominant soil cover and yield, a general relationship can not be found. Gravelly loam, for example, which is the dominant soil type in the highest yield locations (e.g. site 14, with a 69.4 $t\ km^{-2}\ a^{-1}$ yield and site15, with a 59.9 $t\ km^{-2}\ a^{-1}$ yield) is also the dominant soil in regions with lower yields (e.g. site 2 with a 5.9 $t\ km^{-2}\ a^{-1}$ yield). Generally, soils with a high percent content of silt and very fine sand particles will be most erodible *on the basis of soil characteristics alone* (Wall, 1997). This relationship was not observed for the dominant soil cover and sediment yields calculated in those regions. Each of these factors alone is actually unlikely to account for higher or lower yields; rather a combination of factors is likely to be responsible.

### 6.4.2 Influence of Crop Type on Sediment Yield

Farmland (FL %) was prepared from air photos taken between 1969 - 1974, which is a time period that generally falls within the period of suspended sediment data collection. Area of polygon covered by farmland ranges from less than 10% to 80 - 100%. By looking at column three in Table 6.6, an obvious relationship between percentage of farmland and sediment yield is not apparent. One might have expected to see larger yields in those areas with larger percentages of farmland cover. The regions with highest sediment yields are found in locations with only 30 - 49.9% farmland (FL) whereas low yields can be found in locations with 80-100% farmland. SL (%) is the percentage of swamps and lakes, or internal drainage in the region. A relationship between sediment yield and internal drainage can not be identified as a result of the lack of information at so many of the gauging sites.

It was hypothesized that if the *amount* of farmland is not immediately related to sediment yield, the *type* of crop dominating the drainage basin might be. To further investigate the relationship between type of crop and sediment yield, detailed information on crop types in the polygon areas was obtained from Agriculture Canada. The results of this compilation are presented in Table 6.9. The crop types are listed in columns ranging from those crops that are least likely to be susceptible to erosion (alfalfa) to those most likely to be susceptible to erosion (vegetables and summer fallow). The values are percentages of the polygon areas that are occupied by those crop types. The bold and enlarged values are the stations with the highest percentage of the given crop type. Total crop percentages (Table 6.9) and farmland percentages (Table 6.6) do not have the same values, as farmland will encompass that land owned by farmers, which may not necessarily be *crop*land. The stations with the highest percentages of both buckwheat and potatoes/beets also had the highest sediment yields.

| Site # | Area (HA) | Alfalfa | Hay | Pasture | Sod | Tree Fruits | Berries | Cereal | Pot/Beet | Corn | Buck | Tobacco | Veg. | S.Fallow | Crop % | Y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3706 | 0.43 | 4.13 | 8.8 | 0 | 1.5 | 0.24 | 1.21 | 0.3 | 0.7 | 0.03 | 0.13 | 0.4 | 0.27 | 9.34 | 9.19 |
| 2 | 2253.8 | 0.18 | 1.29 | 1.55 | 0 | 0.35 | 0 | 0.35 | 0 | 0.09 | 0 | 0 | 0.13 | 0.133 | 2.523 | 5.87 |
| 3 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 0 | 5.99 |
| 4 | 10708 | 0.34 | 2.56 | 4.31 | 0 | 0 | 0.16 | 0.32 | 0 | 0.04 | 0 | 0 | 0.02 | 0.28 | 3.72 | 20.47 |
| 5 | 38166 | 0.37 | 1.99 | 2.6 | 0 | 0 | 0.19 | 0.22 | 0 | 0.03 | 0 | 0 | 0 | 0.13 | 2.93 | 5.95 |
| 6 | 3741 | 0.03 | 0.29 | 0.5 | 0 | 0 | 0.35 | 0.05 | 0 | 0 | 0 | 0 | 0.03 | 0.08 | 0.83 | 5.64 |
| 7 | 8770 | 0.64 | 5.6 | 5.34 | 0 | 0 | 0.35 | 1.32 | 0 | 0.03 | 0 | 0 | 0.01 | 0.25 | 8.2 | 11.22 |
| 8 | 2173 | 0.09 | 0.87 | 2.12 | 0 | 0 | 0.04 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 1.05 | 34.81 |
| 9 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 0 | 4.73 |
| 10 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | 0 | 10.5 |
| 11 | 240.8 | 3.9 | 11.21 | 21.6 | 0.33 | 0.03 | 0.3 | 0.2 | 0.83 | 0 | 0 | 0 | 1.66 | 0.06 | 18.52 | 14.97 |
| 12 | 562 | 1.24 | 6.83 | 12.6 | 0.16 | 0 | 0.28 | 0.44 | 0.17 | 0 | 0 | 0 | 0.25 | 0 | 9.37 | 3.5 |
| 13 | 3635 | 1.84 | 28.5 | 16.91 | 1.3 | 0.02 | 0.36 | 0.76 | 0.5 | 0 | 0 | 0 | 1.17 | 0.22 | 34.67 | 30.73 |
| 14 | 93597 | 0.46 | 4.97 | 6.22 | 0 | 0 | 0.24 | 3.07 | 2.4 | 0.13 | 0.11 | 0 | 0.07 | 0.14 | 11.59 | 69.38 |
| 15 | 93597 | 0.46 | 4.97 | 6.22 | 0 | 0 | 0.24 | 3.07 | 2.4 | 0.13 | 0.11 | 0 | 0.07 | 0.14 | 11.59 | 59.91 |
| 16 | 26337 | 0.06 | 0.46 | 0.67 | 0 | 0 | 0 | 0.16 | 0 | 0.02 | 0.004 | 0 | 0.003 | 0 | 0.707 | 19.57 |
| 17 | 34991 | 0.06 | 0.52 | 0.57 | 0 | 0 | 0.002 | 0.06 | 0.002 | 0.03 | 0 | 0 | 0 | 0.01 | 0.684 | 6.39 |
| 18 | 10744 | 0.55 | 8.46 | 12.54 | 0 | 0 | 0 | 0.97 | 0.02 | 0.17 | 0 | 0 | 0.06 | 0.12 | 10.35 | 30.73 |
| 19 | 15693 | 0.01 | 0.12 | 0.29 | 0 | 0 | 0 | 0.006 | 0 | 0 | 0 | 0 | 0.01 | 0 | 0.146 | 2 |
| 20 | 43988 | 0.03 | 0.33 | 0.5 | 0 | 0 | 0 | 0.16 | 0 | 0 | 0 | 0 | 0.004 | 0.02 | 0.544 | 9.46 |
| 21 | 36434 | 0.2 | 2.08 | 2.53 | 0 | 0 | 0.002 | 0.32 | 0 | 0.06 | 0 | 0 | 0.005 | 0.02 | 2.707 | 14.25 |
| 22 | 33943 | 0 | 0.99 | 1.07 | 0 | 0 | 0 | 0.03 | 0 | 0 | 0 | 0 | 0.003 | 0 | 1.023 | 15.14 |
| 23 | 41883 | 0.005 | 0.06 | 0.07 | 0 | 0 | 0 | 0.14 | 0.005 | 0.002 | 0.002 | 0 | 0 | 0 | 0.214 | 10.6 |
| 24 | 16146 | 0.81 | 5.07 | 4.72 | 0 | 0 | 0 | 7.28 | 5.18 | 0.1 | 0 | 0 | 0.48 | 0.16 | 19.08 | 40 |
| 25 | 36335 | 0.68 | 6.78 | 8.89 | 0 | 0.02 | 0.07 | 10.78 | 1.28 | 0.23 | 0 | 0.73 | 0.15 | 0.43 | 21.15 | 21 |
| 26 | 29586 | 0.95 | 4.79 | 5.9 | 0 | 0.02 | 0.11 | 10.72 | 1.76 | 0.18 | 0 | 2.11 | 0.15 | 0.83 | 21.62 | 28.9 |
| 27 | 48596 | 1.02 | 7.92 | 9.08 | 0 | 0 | 0.11 | 13.91 | 2.32 | 0.58 | 0 | 0.43 | 0.28 | 0.31 | 26.88 | 19.7 |
| 28 | 48596 | 1.02 | 7.92 | 9.08 | 0 | 0 | 0.11 | 13.91 | 2.32 | 0.58 | 0 | 0.43 | 0.28 | 0.31 | 26.88 | 13 |

Table 6.9: Percentage of land covered by specific crop types

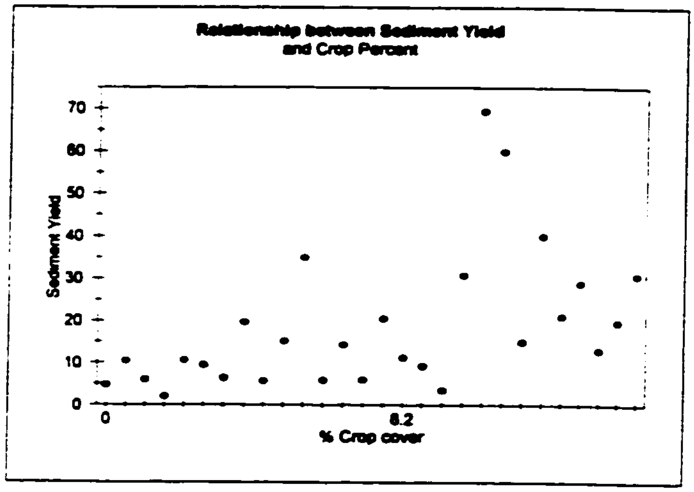



Figure 6.9: Relationship between sediment yield and % crop cover in eastern Canada

Total crop cover (per cent) was plotted against sediment yield values (Figure 6.9) to determine a relationship between % of total crop cover and sediment yield. No linear relationship between total crop cover and sediment yield was found ($r^2$ = 0.14). Coefficients of determination ($r^2$) between sediment yield and percentage of each crop cover are listed in Table 6.10.

| CROP | $r^2$ |
|---|---|
| Alfalfa | 0.004 |
| Hay | 0.06 |
| Pasture | 0.03 |
| Sod | 0.007 |
| Tree Fruits | 0.029 |
| Berries | 0.01 |
| Cereal | 0.04 |
| Potatoes/Beet | 0.355 |
| Corn | 0.0008 |
| Buckwheat | 0.578 |
| Tobacco | 0.006 |
| Vegetables | 0.003 |
| Summer Fallow | 0.033 |
| | |
| % Crop Cover | 0.14 |

Table 6.10: Crop type and $r^2$ indicating the significance of percentage of each crop cover and sediment yield.

It was concluded that no significant linear correlation between sediment yield and crop cover exists, with the exception of buckwheat. This means that as the % of buckwheat increases, so does sediment yield, although this relationship is not strong.

### 6.5 Summary and Discussion

The sediment yields of eastern Canada are often magnitudes lower than those of the eastern States. Patterns of suspended sediment yields in the Maritimes indicate that there are *local* highs and lows, however with myriad factors that account for these spatial variations. Sediment yields were found to be non-stationary in nature, with changing spatial patterns depending on the length of the time-averaged yield (Figures 6.2,6.3 & 6.4). Conditions which change in this time-scale (decades) to cause the changing patterns to emerge include meteorological conditions (changing precipitation from one year to the next), hydrological conditions (changes in discharge) and changes in land use or land disturbance (i.e. changes in crop cover). Conditions which remain relatively static over this length of time are geology, physiography, and soil type and availability. Comparisons between these potential causal factors and sediment yields were made throughout the Chapter and the factors which relate most strongly to sediment yields are hydrologic factors (discharge) and crop type (buckwheat).

Information was obtained from Agriculture Canada, but the USLE parameters could not be related directly to sediment yields. This is primarily a function of the USLE being rather arbitrary and quite general in scope, in addition, the relationship between soil erosion and sediment yield is not a straightforward one. Percentage of farmland was not directly related to sediment yield, but type of crop cover was found to have an influence. Both sites with highest yields in the Maritime provinces (Holmes Br. at Holmesville and at Moose Mtn.) have highest percentage of buckwheat and potatoes and beets.

The spatial patterns and temporal trends of sediment yields have been observed to change. The *magnitude* of sediment yields in the Atlantic Canadian provinces is consistently lower than those of the more southern United States (i.e. the latitudinal variation observed in Figure 3.2). These regional-scale variations in magnitudes of sediment yields are more likely to be due to large differences in climatic conditions as well as differences in numerous geologic factors (including soil availability). In a smaller regional setting, such as the eastern Canadian provinces alone, there are still large differences in geologic factors. The climatic variability within this regional setting, however, (similar lengths of seasons, similar amounts of mean annual precipitation) is less than that found across the larger regional setting of the whole of eastern North America.

Numerous factors contribute to the amount of sediment being carried by a river. The driving force is the discharge of the river. If wet meteorological conditions (whether days or years), the result of which is increased river flow, are co-incident at locations that have a large sediment availability, the ground is unfrozen and there is a disruptive dominant land use in the drainage basin (e.g. crop type or construction activity), then sediment yields will be high.

# CHAPTER 7

# DISCUSSION OF REGIONAL YIELDS

## 7.1 General Patterns of Suspended Sediment Yields from Eastern North America

Several maps depicting sediment yield patterns (Figures 3.3-3.6, 5.4-5.6,6.2-6.4) have been presented throughout this thesis. This section serves to summarize the general patterns of suspended sediment from eastern North America. In Chapters Three (eastern United States) and Six (eastern Canada), various maps were presented based on varying lengths of time-averaged sediment yields. The result was a notable shift in patterns from one location to another. In the eastern United States, for example, highest yields were found in the Washington, D.C. region and in the western corner of Virginia when a five-year time-averaged yield was used. A one-year record of sediment yields, however, produced a different pattern of high and low yields, with the highest yields situated on the coastal plain of North Carolina.

In the time series, moving averages indicated that there were oscillations between higher and lower yields. These trends were observed throughout the entire regional study area. Two conclusions can immediately be drawn from these results; sediment yields are non-stationary and sediment yields are sensitive to regional-scale driving forces (climate). Each of these conclusions will be discussed in the following sections.

## 7.2 Non-stationarity of Sediment Yields

While numerous authors (e.g. those listed in Table 1.1) have produced global, and to a lesser extent, regional maps of patterns of sediment yields, the results presented here lead to the conclusion that individual maps of yields are actually "snap-shots" in time. If the maps were produced with a different set of data spanning different years (e.g. different time-averaged yields), then the resulting patterns would be very different (Conrad & Saunderson, 1999). This leads to the conclusion that sediment yields are non-stationary, and as a result, factors which cause sediment yields to change from one year to the next need also to be discussed.

In the span of forty years (with most sites having even fewer years of record than this), geology, physiography, and soil availability remain relatively the same. As high yields move in space, shifting around the map, the characteristics of the underlying terrain are relatively unchanged. It was therefore concluded that yields must be sensitive to climatic conditions and changes in land use, since these phenomena do changeat the temporal scales considered. With patterns of yields shifting, climatological (precipitation) and hydrological (discharge) factors would account for a large degree of this non-stationarity. Comparisons of peak discharge and peak sediment loads indicated a correlation between peaks approximately 50% of the time.

Coefficients of variation of annual discharge and sediment loads indicated that the variability of loads was consistently greater than variability of discharge. There are more complex causal factors to drive changes in loads than changes in discharge, keeping in ind that the relationship between sediment loads and discharge is expected, to some degree. The changes in magnitudes of sediment yields are not solely attributed to changes in the magnitudes of discharge, however. The variability in sediment loads at individual sites over the span of a few decades could not be attributed to geologic characteristics of the underlying material since these features do not vary in the course of ten or twenty years. Other features that do change, however, are human uses of the land. In Chapter Five, urbanization and construction were noted to have an influence on sediment loads in rivers, and in Chapter Six, agriculture was discovered to have an influence on loads (with an increase in certain crop types, yields increased). The results of the time-series also pointed to questions concerning factors which could cause variations in yields through time, as well as space.

### 7.3 Temporal Patterns of Sediment Yields

In Chapter Four, common trends were noted in the moving-average time-series of sediment loads for stations spanning eastern North America. These sites all have very different geologic conditions, soil availability and physiographic conditions, in addition to differences in dominant land uses. It was apparent that climatic and consequently hydrologic conditions were forcing trends (a general peak in the 1960s followed by a dip into the 1970s and subsequent rise into the 1980s). Similar moving-average plots of discharge were produced, with the result being nearly identical patterns. This further emphasizes the important and intimate connection between precipitation, discharge, and ultimately sediment loads in rivers. Regardless of the *magnitude* of the load and discharge, the same trend emerged. This should not diminish the fact that there remain huge differences in the absolute yields, even though their behaviour through time is closely connected to larger-scale atmospheric conditions. The magnitude differences of the absolute yield values (i.e. Table 3.2) should still be considered and attributed to other factors, as will be discussed in the subsequent section.

## 7.4 Regional Sediment Yield Values

A general inverse relationship of decreasing sediment yield with increasing latitude was noted for the gauging sites included in this thesis (Figure 3.2). What could drive this relationship? In Chapter Five, the basins draining to Chesapeake Bay were used as an example of a generally high-yield area of eastern North America , and the eastern Canadian provinces (Chapter Six) a relatively low-yield area. The *magnitudes* of differences between the yields across the regional study area remain relatively constant, with numerous explanations for the magnitudes of variation:

- Eastern Canada has a smaller population, and therefore less potential for human disturbance to the land surface.
- Gauging stations are generally not located near or at major urban centres in

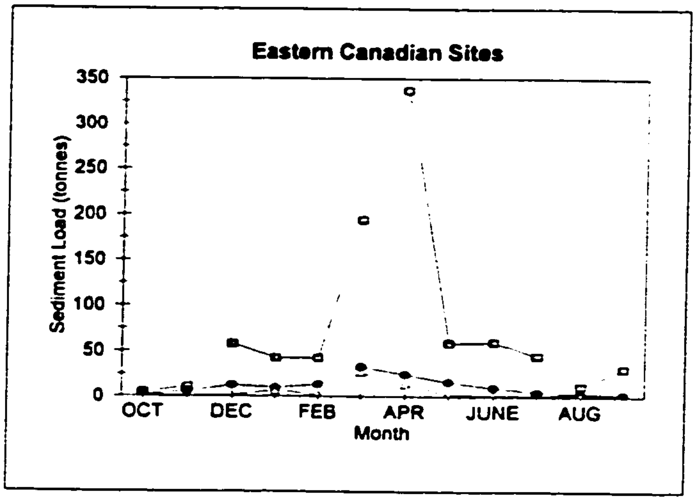
eastern Canada, but this is a common occurrence in the eastern U.S.

- During winter months, most basins in Canada are characterized by frozen and snow covered surfaces, a consequence of which is reduced surface sediment erosion for a large part of the year (Figure 7.1).
- Large expanses of thick, erodible soil are present throughout many of the eastern States (south of the glacial limit) whereas many regions in eastern Canada have thin soil horizons and bedrock surfaces.
- More land is affected by intensive agricultural and construction activities in some areas of the eastern States.

By some reports, the greatest source of sediment in many channels in the eastern States is the land which has undergone or is presently undergoing urbanization. When exposed to rainfall, earth laid bare during construction erodes easily and contributes sediment to waterways at rates that may approach 20 000 - 40 000 times the erosion rate of farms and woodlands.

## 7.5 Discussion and Summary

There are two ways that sediment yields can be investigated in the regional context of eastern North America: analysis of yields *through* time and space or *absolute* sediment yield values (that are compilations of entire lengths of record available). When yields are studied through contemporary lengths of time, trends in the data are attributed to changes in climatic conditions and consequently discharge,



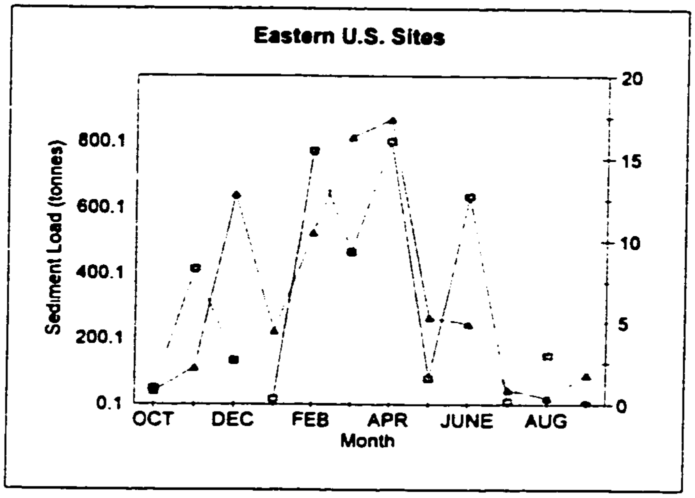




Figure 7.1: Mean monthly suspended sediment load (tonnes) trends for the period of 1982-86 for selected U.S. and Canadian sites

The top graph shows trends for the Kennebecasis River, New Brunswick (indicated with square symbols on the graph), the Annapolis River, Nova Scotia (round symbols) and the Northeast Brook, Newfoundland (triangle symbols). The bottom graph shows trends for the Rappahanock River, Virginia (square symbols) and the Choptank River, Maryland (triangle symbols).

and changes in magnitude additionally attributed to land use changes or land disturbance. When yields are analysed in a spatial context, patterns will shift as a result of the space-time dependency. As such, climate, discharge, and land use will also cause the spatial patterns of yields to shift.

The absolute values of sediment yields (i.e. as individually listed in Appendix A and summarized in Table 3.2) provide the ranges of magnitudes between yields calculated over various lengths of time. These differences in the absolute yields can additionally be affected by geology, physiography, and soil availability. A composite of natural and anthropogenic factors accounts for the varying magnitudes of yields across the study area. An erodible soil cover in a basin typified by high fluvial discharges and dominated by an urban or suburban environment undergoing intense construction activity would result in high sediment yields. The rivers draining to Chesapeake Bay flow across deposits that reach over 1000 m in depth, the ground is typically unfrozen for the large part of the year, and the sites where data are collected are often located in densely populated areas (e.g. the confluence of the Potomac and Anacostia Rivers in Washington, D.C. and Reston, VA). Conversely, the rivers draining the Atlantic provinces flow across thinner soil covers, and the ground is frozen for at least part of the year, with gauging stations located in more rural areas. The result is magnitudes of difference between sediment yields calculated for these geologically, geomorphologically and anthropogenically different environments.

# CHAPTER 8

# CONCLUSIONS

## 8.1 Contributions to Knowledge

This thesis has provided a regional study and analysis of spatial sediment yield patterns from eastern North America, temporal sediment yield trends, and factors which explain the spatial and temporal variations. The consequence is an enhanced understanding of both the patterns of regional-scale sediment yields in space and time. Detailed maps have been made of the eastern United States with the largest data set to-date. The first detailed maps of eastern Canada were produced. Issues of length of sediment yield record in generating maps were investigated. Given the theoretical and applied importance of sediment loads in rivers, this is a significant contribution to our knowledge of this regional environment. Through the investigation of the myriad factors which can affect sediment loads in rivers, an understanding of the natural and human impacts was developed. A time-series analysis of the temporal patterns of sediment loads as well as discharge has also shed new light on their universal change over this regional area, and perhaps extending to an even larger domain.

Through an investigation of the established research which had resulted in maps of patterns of suspended sediment yields, several observations were made:

- most of the research had been conducted at larger (global) or smaller (basin) scales than the present analysis

- many of the estimates of yields at the global scale are questionable
- small numbers of sites utilized in generating global maps have resulted in generalization over vast areas
- research conducted at the basin-scale might be considered to be more reliable, but yet that scale is too small to make conclusions over a larger region.

Before drawing conclusions about estimates of denudation based on such studies of sediment yields, numerous questions about the reliability of the sediment yield patterns (both temporal and spatial) remained. Therefore, this research was undertaken to investigate regional-scale yields, being both large enough to detect larger spatial and temporal patterns, as well as small enough to be able to manage the detail of the database. The end result would then be a better understanding of sediment yields in time and space, so that they might be used with more assurance and maps be viewed with some caution. In the case of the eastern Canadian provinces, the first detailed maps of sediment yield patterns were produced.

Sediment yield results for the fifteen states were found to range from 12.6 to 372.9 $t\ km^{-2}\ a^{-1}$. Maximum yields ranged from 18.4 to 3156.7 $t\ km^{-2}\ a^{-1}$. Sediment yields for the four provinces ranged from 12.4 to 25.4 $t\ km^{-2}\ a^{-1}$, while maximum yields ranged from 30.7 to 69.4 $t\ km^{-2}\ a^{-1}$. A general relationship of decreasing sediment yield with increasing latitude (Fig.3.2) was discovered. The values calculated indicate that the overall sediment yields of the eastern United States and Canada are, in some cases, much greater than previously determined. Reasons for this are the increased number of sites utilized in calculating sediment yields in this study and spanning a longer period of time. Over-generalization and smoothing of the data in former research (especially at the global scale) has been a problem. Sites on "major" rivers of the world had generally formed the basis of the dataset for such maps, with smaller rivers and tributaries excluded. The result has been a regional, and possibly world-wide underestimation of the world's sediment yields. Small rivers and tributaries, with smaller floodplain storage than larger rivers, can have greater sediment yields. It was found that a number of small rivers may contribute as much or more sediment than large ones. Stave Run, near Reston, VA, with a basin area of only 0.2 $km^2$, was found to have a sediment yield of 3157 $t\ km^{-2}\ a^{-1}$, whereas the Hudson River in New York State, with a basin area of 12 000 $km^2$ had a yield of only 20 $t\ km^{-2}\ a^{-1}$.

Results of the thesis (Chapters 3 and 6) indicate that the spatial patterns of suspended sediment will change depending on the number of years of record used. These maps are novel in that comparisons of patterns based on differing record lengths were compared. One might have suspected that spatial patterns of yields would vary, depending on the length of coverage, as a consequence of differences in climate, precipitation, and changes in land use. After the initial documentation of this phenomenon (e.g. Conrad & Saunderson, 1999), annual maps of yield were produced and relative highs and lows were observed to fluctuate from one area to another. This was attributed to gauging sites either opening or closing, as well as to meteorologically different conditions from one year to the next. Global maps of sediment yields are produced, however, as a point in time, and care and consideration must be taken when viewing such maps for other research purposes. The maps (as indicated from this research) would appear quite different if they were produced using either a different record length and/or spanning a different period of time, as a consequence of the non-stationarity of sediment yields.

Initially, (Chapter 1) several questions were posed, including:

- how different are sediment yields today (from the past) and
- how might they change in the future?

Ultimately, how representative are the sediment loads of the time period covered in this thesis of longer-term loads and would further data collection generate different results?

Standard deviations and standard errors of estimate were calculated (Chapter 3) for stations with at least five full years of record. Many of the stations in the database, however, had record lengths that were less than five full years, however. The station with the highest sediment yield included only one full year of record, so there was little way of knowing how representative the high yield at this site (>3000 $t\ km^{-2}\ a^{-1}$) was of yields that might be calculated at the same site in any other given year. Standard deviations of sediment yields were calculated and found to be high in many cases, increasing with increasing sediment yield (Figure 3.6). The standard error of estimate of the yields was also calculated, with values for a twenty-year and full-coverage average (30-42 years) being the same or very similar (Table 3.6). By calculating the standard error of estimate for the differing lengths of data collection for the sediment yields, it was found that it appeared to remain the same or closest to that of the full record length after a twenty year length of time. This might lead one to conclude that at least a twenty-year period of coverage is required for sediment yields to be representative of longer-term yields. The problem remains that most sites do not have at least a twenty-year record. In addition to this finding, and contrary to Walling's (1997b) findings for a number of rivers in eastern Europe, no general patterns of either increasing or decreasing loads could be discerned. After a twenty-year moving average was applied to the raw data at all of the sites with long record length, the noise in the time-series was removed (Figure 4.1). This observation, together with the standard error of estimate values after a twenty-year period, leads to the conclusion that perhaps a record length of twenty years is crucial for sediment yields to be representative of longer-term yields. Record lengths that are less than twenty-years would likely not be indicative of longer-term yields.

Several observations were made based on the graphs in Figures 4.2,4.3,4.4 and 4.5:

- there is an almost universal low yield around 1967
- the data does not indicate a random pattern
- the data is non-stationary, as shown by maxima that shift geographically over time
- the data may be illustrating a decadal cyclicity, however a sufficient length of continuous available data does not allow this to be conclusively determined
- the sites with data prior to 1970 show a drop in sediment yield that might have been interpreted as a declining *trend*

- the sites with data after 1970 show a rise in sediment yield that could have been interpreted as a rising *trend*.

The fact that three provinces and six states all show a similar temporal pattern of sediment yields and discharge points to climatic factors driving the behaviour of sediment loads.

Sediment yields vary in both time and space. The mean sediment yield for the eastern United States (96.7 $t\ km^{-2}\ a^{-1}$) is five-fold that of the eastern Canadian Provinces (18.2 $t\ km^{-2}\ a^{-1}$). The difference in magnitude of the maximum yield for the eastern United States (3156.7 $t\ km^{-2}\ a^{-1}$) is forty-five fold that of the eastern Canadian Provinces (69.3 $t\ km^{-2}\ a^{-1}$). The reasons that can account for the variations are numerous. Peak discharge and peak sediment load were found to correlate approximately half of the time, but the smoothed data showed astoundingly similar trends of both discharge and sediment loads in the time-series. Although meteorological conditions can explain the temporal trends as well as the fact that the highest and lowest relative yield locations change from one year to the next, other factors must be responsible for the magnitude differences between yields. A composite of natural (e.g. precipitation and discharge)and anthropogenic (e.g. population and land use factors) can explain the varying magnitudes of yields across the study area. An erodible and abundant soil cover in a basin with high discharge and situated in an urban location with intense construction activity or in a rural area with a crop cover (e.g. buckwheat) that increases sediment transfer to rivers will result in higher than average fluvial suspended sediment yields. A location with a human activity such as construction, occurring at a point in time where a peak in the time series exists may result in a *magnified* sediment yield. As was discussed in Chapter 6, it may also be that localized and unique events and characteristics in the immediate vicinity of the gauging station may be important in explaining the magnitudes of sediment yields. Bank erosion, both natural and as a result of cattle crossing a channel upstream of a gauging station, may also cause dramatic results. The explanations for the magnitude differences between sediment yields in eastern Canada versus much of the eastern United States were given in Chapter Seven.

## 8.2 Removal of Mass by Rivers in eastern North America

Previous studies of global sediment yields had many limitations in terms of providing a comprehensive and reliable basis for investigating the global denudation system. The present study has aided in our understanding of the regional-scale and in understanding the spatial and temporal behaviour of sediment yields. A map of sediment yields prepared with all of the available data from all stations provides us with an idea of sediment yields over a given area. It must be understood, however, that once more data are included or other data removed, the patterns may be very different. In addition, if sediment loads ultimately are to be used as indicators of rates of erosion and soil loss, improved knowledge of the processes of sediment delivery are required to understand the lag between on-site erosion and the sediment yield at the outlet of the drainage basin.

## 8.3 Future Research

Sediment yield data for the world's rivers can provide a valuable means of studying the global denudation system. A number of questions and concerns require further investigation:

- The eastern region of North America has been modified significantly by humans, making projection from post-colonial to geological time uncertain.
- The present study has considered only *suspended* sediment and should be compared with estimates derived from bed and solute loads to compare the relative amounts transported by the various means.
- Additional data should continue to be collected and added to the present database to monitor change in both time and space and to observe whether the present conclusions continue to hold true.
- Regional-scale investigations of sediment yields elsewhere should be studied to observe whether the conclusions drawn for this region are true of other regions.

It is important for data to continue to be collected and analysed if sediment loads in rivers are to be further related to factors such as climate, especially in light of recent concerns regarding the relationship between climate change and the terrestrial hydrologic environment. This thesis has contributed to such an understanding, which emerged through the regional analysis of sediment yields in space and time.

## CHAPTER 9

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## Appendix A:

## Eastern United States and Canada Compiled Data Sets

| STATION ID | STATION NAME | LATITUDE | LONGITUDE | ELEVATION (ft.) | Total Sed. Load (tonnes) | MEAN ANNUAL STREAM FLOW |
|---|---|---|---|---|---|---|
| 01125415 | MUDDY BROOK AT CHILDS HILL RD NR WOODSTOCK, CT. | 415756 | 0715745 | N/A | 28.576899792 | 34.73 |
| 01127500 | YANTIC R AT YANTIC, CT | 413331 | 0720719 | 94 | 17769.19032 | 181.69 |
| 01184500 | SCANTIC R AT BROAD BROOK, CT. | 415442 | 0723348 | 26.23 | 7785.1368 | 191.25 |
| 01192883 | COGINCHAUG RIVER AT MIDDLEFIELD, CT | 413112 | 0724323 | N/A | 5041.691424 | 62.29 |
| 01193500 | SALMON RIVER NEAR EAST HAMPTON, CT | 413253 | 0722659 | 63.71 | 28425.2976 | 184.77 |
| 01199000 | HOUSATONIC R AT FALLS VILLAGE,CT. | 415726 | 0732211 | 529.06 | 47675.110896 | 1008.99 |
| 01200500 | HOUSATONIC R AT GAYLORDSVILLE, CT | 413911 | 0732925 | 236.78 | 70310.67624 | 1415.28 |
| | **STATE MEAN** | | | | | |
| 01480000 | RED CLAY C AT WOODDALE, DE | 394552 | 0753808 | 81.46 | 21063.1908816 | 63.66 |
| 01481500 | BRANDYWINE C AT WILMINGTON DE | 394609 | 0753425 | 68.23 | 1736181.470016 | 478.10 |
| | **STATE MEAN** | | | | | |
| 02190200 | TOMS CREEK TRIB (NFBR SWS NO. 14) NR AVALON, GA. | 342935 | 0831323 | 735.33 | 117.30096 | 1.96 |
| 02192000 | BROAD RIVER NEAR BELL, GA. | 335827 | 0824612 | 357.16 | 566115.48 | 1784.03 |
| 02193500 | LITTLE RIVER NEAR WASHINGTON, GA. | 333646 | 0824433 | 353.88 | 75637.4171616 | 264.34 |
| 02198000 | BRIER CREEK AT MILLHAVEN, GA. | 325600 | 0813905 | 95.88 | 30504.2389344 | 635.96 |
| 02202500 | OGEECHEE RIVER NEAR EDEN, GA. | 321129 | 0812458 | 19.64 | 55877.2585056 | 2350.49 |
| 02213000 | OCMULGEE RIVER AT MACON, GA. | 325019 | 0833714 | 269.8 | 339621.2064 | 2706.79 |
| 02218500 | OCONEE RIVER NEAR GREENSBORO, GA. | 333452 | 0831622 | 409.82 | 288616.608 | 1441.75 |
| 02223500 | OCONEE RIVER AT DUBLIN, GA. | 323240 | 0825341 | 149.08 | 409769.5392 | 4900.38 |
| 02317500 | ALAPAHA RIVER AT STATENVILLE, GA. | 304214 | 0830200 | 76.77 | 5530.8373344 | 1079.46 |
| 02347500 | FLINT RIVER NEAR CULLODEN, GA. | 324317 | 0841357 | 334.54 | 333777.024 | 2332.31 |
| 02352500 | FLINT RIVER AT ALBANY, GA. | 313539 | 0840839 | 150.03 | 124351.7038848 | 6159.29 |
| 02383500 | COOSAWATTEE RIVER NEAR PINE CHAPEL, GA. | 343351 | 0844959 | 616.16 | 881428.44384 | 1498.50 |
| 02387000 | CONASAUGA RIVER AT TILTON, GA. | 344000 | 0845542 | 622.28 | 149827.7088 | 1207.24 |
| | **STATE MEAN** | | | | | |
| 01491000 | CHOPTANK R NR GREENSBORO, MD | 385950 | 0754710 | 3.51 | 20033.761104 | 131.43 |
| 01578310 | SUSQUEHANNA R AT CONOWINGO, MD | 393926 | 0761031 | 5 | 7932161.89584 | 41436.29 |
| 01594440 | PATUXENT R NR BOWIE, MD | 385721 | 0764136 | 13.1 | 141734.71368 | 363.70 |
| 01597000 | CRABTREE C NR SWANTON, MD | 393000 | 0790935 | 1529.06 | 1844.890992 | 28.96 |
| 01603000 | NB POTOMAC R NR CUMBERLAND, MD | 393719 | 0784624 | 585.22 | 2233620.47664 | 1286.78 |
| 01614500 | CONOCOCHEAGUE C AT FAIRVIEW, MD | 394257 | 0774928 | 391.85 | 821348.0996112 | 594.76 |
| 01638500 | POTOMAC R AT POINT OF ROCKS, MD | 391625 | 0773235 | 200.54 | 34933502.1950208 | 9371.98 |
| 01643000 | MONOCACY R AT JUG BRIDGE NR FREDERICK, MD | 392316 | 0772248 | 231.92 | 967940.8420752 | 937.06 |

| YRS. OF COVERAGE | Drainage Area (sq km) | tonnes/sq km/a |
|---|---|---|
| 3 | 52.32059 | 12.8619243243243 |
| 5 | 231.28959 | 15.3663567567568 |
| 1 | 254.338 | 30.6101189189189 |
| 7 | 77.18459 | 9.3312 |
| 7 | 259.00259 | 15.6780972972973 |
| 1 | 1642.06259 | 29.0339027027027 |
| 1 | 2579.64259 | 27.2545297297297 |
| | | 20 |
| 1 | 121.73259 | 173.030010810811 |
| 32 | 813.26259 | 66.7124756756757 |
| | | 119.9 |
| 1 | 3.11059 | 37.7416216216216 |
| 1 | 3703.70259 | 152.850940540541 |
| 1 | 753.69 | 100.355935135135 |
| 1 | 248.3292 | 18.2315675675676 |
| 1 | 6863.50259 | 8.14028108108108 |
| 1 | 5801.60259 | 58.5371675675676 |
| 1 | 2823.10259 | 102.233383783784 |
| 1 | 11396 | 35.958745945946 |
| 1 | 3626.00259 | 1.52367567567568 |
| 1 | 4791.50259 | 69.6617513513514 |
| 1 | 13752.9 | 4.52198918918919 |
| 3 | 2152.29259 | 136.510832432432 |
| 1 | 1779.33259 | 84.204972972973 |
| | | 62.3 |
| 11 | 292.67259 | 5.7059027027027 |
| 8 | 70189 | 10.273427027027 |
| 7 | 901.32259 | 22.4663351351351 |
| 1 | 43.25559 | 42.6524108108108 |
| 16 | 2266.25259 | 62.5582702702703 |
| 14 | 1279.46259 | 45.8538810810811 |
| 32 | 24996.09 | 43.6752 |
| 9 | 2116.03259 | 50.8242162162162 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 01647685 | WILLIAMSBURG RN NR OLNEY, MD | 390832 | 0770548 | 390 | 1810.9580832 | 2.80 |
| 01647740 | NB ROCK C NR ROCKVILLE, MD | 390609 | 0770712 | 270 | 5447.9736864 | 16.02 |
| 01650085 | NURSERY RN AT CLOVERLY, MD | 390705 | 0770024 | 400 | 95.1525792 | 0.47 |
| 01650500 | NW B ANACOSTIA R NR COLESVILLE, MD | 390355 | 0770148 | 264.85 | 174751.3305216 | 22.60 |
| | **STATE MEAN** | | | | | |
| 01100000 | MERRIMACK RIVER BL CONCORD RIVER AT LOWELL, MA | 423845 | 0711756 | 5.18 | 1107697.82256 | 7632.38 |
| 01197500 | HOUSATONIC RIVER NEAR GREAT BARRINGTON, MA | 421355 | 0732119 | 683.04 | 6727.758912 | 525.72 |
| | **STATE MEAN** | | | | | |
| 01379500 | PASSAIC RIVER NEAR CHATHAM NJ | 404331 | 0742323 | 193.51 | 28790.7776352 | 174.18 |
| 01387500 | RAMAPO RIVER NEAR MAHWAH NJ | 410551 | 0740948 | 253.1 | 2067.23664 | 229.90 |
| 01389500 | PASSAIC RIVER AT LITTLE FALLS NJ | 405305 | 0741335 | 120 | 11248.3728 | 1150.10 |
| 01397000 | SB RARITAN R AT STANTON NJ | 403421 | 0745210 | 125.01 | 25026.9264 | 248.05 |
| 01400932 | BALDWINS CREEK AT BALDWIN LAKE NR PENNINGTON NJ | 402026 | 0744648 | 150 | 672.1472016 | 2.73 |
| 01401000 | STONY BROOK AT PRINCETON NJ | 401959 | 0744056 | 62.23 | 73940.7118464 | 65.70 |
| 01410787 | GREAT EGG HARBOR R TR AT SICKLERVILLE NJ | 394331 | 0745739 | 121 | 215.632368 | 2.04 |
| 01410810 | FOURMILE BRANCH AT NEW BROOKLYN NJ | 394147 | 0745625 | 101.04 | 96.20856 | 13.49 |
| 01411000 | GREAT EGG HARBOR RIVER AT FOLSOM NJ | 393542 | 0745106 | 53.32 | 1640.163168 | 85.98 |
| 01411500 | MAURICE RIVER AT NORMA NJ | 392942 | 0750438 | 46.94 | 974.3328 | 165.43 |
| 01442750 | DELAWARE R AT DUNNFIELD NJ | 405840 | 0750810 | N/A | 1373192.4309264 | 7322.84 |
| 01463500 | DELAWARE RIVER AT TRENTON NJ | 401318 | 0744642 | N/A | 21138442.48656 | 11662.27 |
| 01464500 | CROSSWICKS CREEK AT EXTONVILLE NJ | 400815 | 0743602 | 24.94 | 18182.156832 | 136.03 |
| 01467150 | COOPER RIVER AT HADDONFIELD NJ | 395411 | 0750119 | 9.29 | 1819.6581312 | 34.59 |
| 01477120 | RACCOON CREEK NEAR SWEDESBORO NJ | 394428 | 0751533 | N/A | 3490.5354624 | 40.34 |
| | **STATE MEAN** | | | | | |
| 01331095 | HUDSON RIVER AT STILLWATER NY | 425608 | 0733908 | 78.99 | 100422.9576 | 6599.42 |
| 01335770 | HUDSON RIVER AT WATERFORD NY RT 4 BRIDGE | 424719 | 0734028 | N/A | 946606.22784 | 8217.56 |
| 01357500 | MOHAWK RIVER AT COHOES NY | 424707 | 0734229 | 49.13 | 1958782.96656 | 5687.36 |
| 01359150 | MILL CREEK NR EAST GREENBUSH NY | 423645 | 0734145 | N/A | 2214.148608 | 15.45 |
| 01520500 | TIOGA RIVER AT LINDLEY NY | 420143 | 0770757 | 964.5 | 1826180.545392 | 802.13 |
| 01527050 | SWITZER CREEK NEAR COHOCTON NY | 422928 | 0772910 | 1320 | 892.18584 | 4.05 |
| 01531000 | CHEMUNG RIVER AT CHEMUNG NY | 420008 | 0763806 | 778.63 | 2485160.491968 | 2574.04 |
| 04221000 | GENESEE RIVER AT WELLSVILLE NY | 420720 | 0775727 | 1470 | 88096.676976 | 390.44 |
| 04223000 | GENESEE RIVER AT PORTAGEVILLE NY | 423413 | 0780233 | 1080 | 2167412.74848 | 1257.30 |
| 04227000 | CANASERAGA CREEK AT SHAKERS CROSSING NY | 424413 | 0775027 | 545.52 | 444779.285328 | 296.52 |
| 04227500 | GENESEE RIVER NEAR MOUNT MORRIS NY | 424600 | 0775021 | 540.12 | 1977059.5992 | 1666.79 |

| | | |
|---|---|---|
| 2 | 5.83009 | 155.379891891892 |
| 10 | 32.37759 | 16.8269837837838 |
| 2 | 0.90909 | 52.4844972972973 |
| 13 | 54.65159 | 245.977297297297 |
| | | 62.9 |
| 5 | 12004.65 | 18.4557405405405 |
| 1 | 730.38259 | 9.21210810810811 |
| | | 13.8 |
| 5 | 259.00259 | 22.2316540540541 |
| 1 | 310.80259 | 6.64812972972973 |
| 1 | 1973.58259 | 5.6988972972973 |
| 3 | 380.73259 | 21.9129081081081 |
| 7 | 6.52939 | 14.7113513513514 |
| 11 | 115.25759 | 58.3235027027027 |
| 4 | 4.2476 | 12.6902918918919 |
| 1 | 20.04919 | 4.7987027027027 |
| 5 | 147.889 | 2.21721081081081 |
| 1 | 290.08259 | 3.35909189189189 |
| 10 | 10748.5 | 12.7743567567568 |
| 32 | 17560.2 | 37.619027027027 |
| 4 | 211.08759 | 21.5346162162162 |
| 1 | 44.03259 | 41.3283891891892 |
| 3 | 69.67359 | 16.7008864864865 |
| | | 18.8 |
| 1 | 9772.07259 | 10.2769297297297 |
| 4 | 11965.8 | 19.7762594594595 |
| 5 | 8935.50259 | 43.8433297297297 |
| 1 | 25.22919 | 87.7602162162163 |
| 6 | 1996.89259 | 152.416605405405 |
| 2 | 9.01579 | 49.4931891891892 |
| 3 | 6490.54259 | 127.631481081081 |
| 2 | 745.92259 | 59.0555675675676 |
| 2 | 2548.56259 | 425.224605405406 |
| 2 | 867.65259 | 256.313772972973 |
| 2 | 3688.16259 | 268.026810810811 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 04228500 | GENESEE RIVER AT AVON NY | 425504 | 0774527 | 500.11 | 2461794.15888 | 1955.68 |
| 04230500 | OATKA CREEK AT GARBUTT NY | 430036 | 0774730 | 560.86 | 21791.733264 | 216.61 |
| 04232000 | GENESEE RIVER AT ROCHESTER NY | 431050 | 0773740 | 246.24 | 2075544.05184 | 2798.61 |
| 04240145 | SPAFFORD CREEK AT BROMLEY RD NR SPAFFORD NY | 424715 | 0761149 | 1020 | 500.266368 | 5.53 |
| 0424015305 | RICE BROOK AT MOUTH AT RICE GROVE NY | 425107 | 0761533 | 800 | 4615.316496 | 14.79 |
| 04240150 | SPAFFORD CR AT OTISCO VALLEY NY | 424933 | 0761408 | 800 | 192.308256 | 3.18 |
| 0424016205 | WILLOW BROOK AT LADER POINT NY | 425231 | 0761821 | 800 | 496.165824 | 4.30 |
| 0424016825 | AMBER BROOK AT AMBER NY | 425322 | 0761751 | 800 | 419.026608 | 5.03 |
| 0424016975 | VAN BENTHUYSEN BROOK AT MOUTH AT AMBER NY | 425340 | 0761808 | 800 | 290.957184 | 5.80 |
| | **STATE MEAN** | | | | | |
| 02077300 | HYCO RIVER AT MCGHEES MILL N C | 363102 | 0790142 | 349.78 | 33976.064304 | 133.86 |
| 02083500 | TAR RIVER AT TARBORO, N. C. | 355338 | 0773200 | 10.37 | 791776.0368 | 2222.94 |
| 02084160 | CHICOD CR AT SR 1760 NEAR SIMPSON N C | 353347 | 0771343 | N/A | 23908.040352 | 50.08 |
| 02084557 | VAN SWAMP NEAR HOKE N C | 354349 | 0764449 | N/A | 121167.881856 | 26.09 |
| 02084558 | ALBEMARLE CANAL NEAR SWINDELL N C | 353818 | 0764319 | N/A | 20623.813056 | 92.52 |
| 02085220 | LITTLE RIVER NEAR ORANGE FACTORY N C | 360820 | 0785424 | 333.98 | 116690.169456 | 73.01 |
| 02116500 | YADKIN RIVER AT YADKIN COLLEGE N C | 355124 | 0802310 | 638.65 | 35400103.5050208 | 3032.92 |
| 02118000 | SOUTH YADKIN RIVER NEAR MOCKSVILLE N C | 355041 | 0803934 | 663.62 | 529245.0576 | 342.64 |
| 02119400 | THIRD CREEK NR. STONY POINT, N. C. | 355204 | 0810400 | 976 | 4945.0437792 | 6.36 |
| 03448000 | FRENCH BROAD RIVER AT BENT CREEK N C | 353007 | 0823533 | 1950.28 | 772712.95248 | 1689.78 |
| | **STATE MEAN** | | | | | |
| 01440200 | DELAWARE RIVER NEAR DELAWARE WATER GAP PA | 410042 | 0750509 | 293.64 | 309423.42144 | 6283.29 |
| 01481000 | BRANDYWINE CREEK AT CHADDS FORD, PA. | 395209 | 0753535 | 150.45 | 706635.9082944 | 397.72 |
| 01515050 | SUSQUEHANNA R AT SAYRE, PA. | 415852 | 0763026 | N/A | 794064.26736 | 8245.25 |
| 01516500 | COREY CREEK NEAR MAINESBURG, PA. | 414727 | 0770054 | 1337.5 | 8209.07136 | 12.64 |
| 01517000 | ELK RUN NEAR MAINESBURG, PA. | 414854 | 0765755 | 1385.05 | 16202.68272 | 11.05 |
| 01531500 | SUSQUEHANNA RIVER AT TOWANDA, PA | 414555 | 0762628 | 694.38 | 1711414.656 | 10654.65 |
| 01539000 | FISHING CREEK NEAR BLOOMSBURG, PA. | 410441 | 0762553 | 543.84 | 17050.0855392 | 480.84 |
| 01539200 | APPLEMANS RUN ABOVE LIGHT STREET, PA. | 410153 | 0762513 | N/A | 7737.844464 | 1.89 |
| 01539210 | APPLEMANS RUN BELOW LIGHT STREET, PA. | 410155 | 0762539 | N/A | 14812.498512 | 2.52 |
| 01540500 | SUSQUEHANNA RIVER AT DANVILLE, PA | 405729 | 0763710 | 431.29 | 4330490.1696 | 15258.00 |
| 01541000 | WEST BRANCH SUSQUEHANNA RIVER AT BOWER, PA | 405349 | 0784038 | 1207.14 | 40660.97616 | 561.32 |
| 01544000 | F.FORK, SINNEMAHONING, PA | 412406 | 0780128 | 878.71 | 18034.110864 | 399.58 |
| 01545600 | YOUNG WOMANS CREEK NEAR RENOVO, PA. | 412322 | 0774128 | 780 | 1731.146256 | 74.39 |

| | | |
|---|---|---|
| 2 | 4333.07259 | 284.069189189189 |
| 2 | 518.00259 | 21.0337297297297 |
| 2 | 6389.53259 | 162.416821621622 |
| 2 | 8.13519 | 30.7572324324324 |
| 2 | 6.32219 | 110.545297297297 |
| 2 | 20.87799 | 4.60605405405406 |
| 2 | 9.66329 | 25.6783135135135 |
| 2 | 9.55969 | 21.9234162162162 |
| 2 | 15.1256 | 9.61842162162162 |
| | | 108.5 |
| 3 | 494.69259 | 22 8936648648649 |
| 8 | 5653.97259 | 17.5065081081081 |
| 9 | 116.55259 | 22.7920864864865 |
| 2 | 59.57259 | 1017.02023783784 |
| 2 | 176.12259 | 58.5511783783784 |
| 15 | 208.23859 | 37.3563243243243 |
| 42 | 5905.20259 | 142.731632432432 |
| 9 | 792.54259 | 74.1977513513514 |
| 12 | 12.53819 | 32.8728648648649 |
| 3 | 1750.84259 | 147.113513513514 |
| | | 157.3 |
| 2 | 9971.50259 | 15.516972972973 |
| 15 | 743.33259 | 63.3744 |
| 1 | 12354.30259 | 64.2745945945946 |
| 6 | 31.598 | 43.3004108108108 |
| 13 | 26.418 | 47.1779027027027 |
| 2 | 20194.23 | 42.3721945945946 |
| 2 | 709.66259 | 12.0142702702703 |
| 2 | 4.45739 | 867.980237837838 |
| 2 | 5.15669 | 1436.24121081081 |
| 2 | 29059.8 | 74.5094918918919 |
| 2 | 815.85259 | 24.918227027027 |
| 2 | 634.55259 | 14.2101145945946 |
| 1 | 119.658 | 14.4661621621622 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 01547500 | BALD EAGLE CREEK AT BLANCHARD, PA | 410306 | 0773617 | 579.79 | 15329.8656 | 464.42 |
| 01547700 | MARSH CREEK AT BLANCHARD, PA. | 410334 | 0773622 | 586.16 | 7230.02112 | 59.53 |
| 01548408 | WILSON CREEK ABOVE SAND RUN NEAR ANTRIM, PA | 413851 | 0771826 | N/A | 13430.542608 | 13.83 |
| 01548417 | BASSWOOD RUN NEAR ANTRIM, PA | 413706 | 0771840 | N/A | 97.596576 | 0.16 |
| 01548422 | RATTLER RUN NEAR MORRIS, PA | 413636 | 0771809 | N/A | 19.722528 | 0.16 |
| 01549100 | BLOCKHOUSE CR TRIB AT LIBERTY, PA. | 413404 | 0770606 | N/A | 1436.269968 | 1.72 |
| 01549300 | BLOCKHOUSE CR AT BUTTONWOOD, PA. | 412943 | 0770902 | N/A | 29124.313344 | 35.38 |
| 01549350 | STEAM VALLEY RUN AT BUTTONWOOD, PA. | 412939 | 0770903 | N/A | 3175.853184 | 10.83 |
| 01549500 | BLOCKHOUSE CREEK NEAR ENGLISH CENTER, PA. | 412825 | 0771352 | 1041.85 | 46529.262864 | 59.03 |
| 01553500 | WEST BRANCH SUSQUEHANNA RIVER AT LEWISBURG, PA | 405803 | 0765236 | 428 2 | 1118918.34432 | 10955.69 |
| 01567000 | JUNIATA RIVER AT NEWPORT, PA. □NEWPRT□ | 402842 | 0770746 | 363.93 | 9145718.6165856 | 4297.42 |
| 01567500 | BIXLER RUN NR LOYSVILLE, PA. | 402215 | 0772409 | 601.22 | 14477.206464 | 19.28 |
| 01569980 | CONODOGUINET CR AT WILLOW ML BRG NR HOGESTOWN, | 401510 | 0770208 | N/A | 43477.931952 | 662.94 |
| 01570100 | CONODOGUINET CREEK TRIB NO. 1 NR ENOLA, PA. | 401727 | 0765938 | 418.56 | 814.701888 | 1.06 |
| 01570200 | CONODOGUINET CR. TRIB. NO. 2 NR. ENOLA, PA. | 401721 | 0765835 | N/A | 1027.884816 | 1.15 |
| 01570230 | CONODOGUINET CR. TRIB. NO. 2A NR. ENOLA, PA. | 401744 | 0765755 | N/A | 617.902992 | 1.08 |
| 01570260 | CONODOGUINET CR. TRIB. NO. 2B NR. ENOLA, PA. | 401747 | 0765751 | N/A | 1193.46696 | 1.04 |
| 01570300 | CONODOGUINET CREEK TRIB NO. 3 NR ENOLA, PA. | 401805 | 0765657 | 416.56 | 989.61912 | 0.59 |
| 01570500 | SUSQUEHANNA RIVER AT HARRISBURG, PA. | 401517 | 0765311 | 290.01 | 39906594.9072 | 34384.62 |
| 01571827 | SWATARA CR BELOW RAVINE, PA | 403347 | 0762353 | N/A | 6398.780976 | 68.21 |
| 01571919 | SWATARA CR AB HWY BRIDGE 895 AT PINE GROVE, PA | 403243 | 0762251 | 500 | 48331.025568 | 164.54 |
| 01572000 | LOWER LITTLE SWATARA CR AT PINE GROVE, PA | 403215 | 0762240 | 500 | 15599.585232 | 57.57 |
| 01572030 | SWATÀRA CREEK NR SUEDBERG, PA | 403129 | 0762724 | N/A | 14272.941312 | 181.55 |
| 01573000 | SWATARA CREEK AT HARPER TAVERN, PA. □HARPER□ | 402409 | 0763439 | 356.68 | 377491.118256 | 573.49 |
| 01575000 | SOUTH BRANCH CODORUS CREEK NEAR YORK, PA. | 395514 | 0764457 | 373.03 | 26716.5981936 | 112.23 |
| 01576085 | LITTLE CONESTOGA C.,PA | 400841 | 0755920 | 410 | 2272.58136 | 7.26 |
| 01576500 | CONESTOGA RIVER AT LANCASTER, PA. | 400300 | 0761639 | 245.63 | 87390.21312 | 397.36 |
| 01576787 | PEQUEA CREEK AT MARTIC FORGE, PA | 395421 | 0761943 | N/A | 270739.977984 | 219.93 |
| 03015500 | BROKENSTRAW CREEK AT YOUNGSVILLE, PA. | 415109 | 0791903 | 1186.92 | 14489.290368 | 595.62 |
| 03020500 | OIL CREEK AT ROUSEVILLE, PA. | 412854 | 0794144 | 1028.32 | 34995.140208 | 543.57 |
| 03024000 | FRENCH CREEK AT UTICA, PA. | 412615 | 0795722 | 1019.44 | 105174.32688 | 1857.61 |
| 03029500 | CLARION RIVER AT COOKSBURG, PA. | 411950 | 0791233 | 1147 | 101473.63128 | 1487.79 |
| 03032500 | REDBANK CREEK AT ST. CHARLES, PA. | 405940 | 0792340 | 973.14 | 346936.703904 | 877.00 |
| 03033222 | BEAVER RUN NR TROUTVILLE, PA | 410033 | 0784749 | N/A | 192.652992 | 2.28 |

| | | |
|---|---|---|
| 1 | 878.01 | 17.460972972973 |
| 2 | 114.219 | 31.6504216216216 |
| 3 | 32.634 | 137.183351351351 |
| 2 | 1.4763 | 33.0550054054054 |
| 1 | 0.8288 | 23.7973621621622 |
| 5 | 2.7972 | 64.1835243243244 |
| 5 | 57.757 | 100.849816216216 |
| 5 | 13.8306 | 45.9239351351352 |
| 5 | 97.643 | 95.3046875675676 |
| 2 | 17733.73 | 31.5488432432432 |
| 40 | 8686.86 | 26.3193081081081 |
| 16 | 38.85 | 23.2894702702703 |
| 1 | 1155.14 | 37.6400432432433 |
| 6 | 1.9943 | 68.0855351351351 |
| 4 | 1.9684 | 130.549232432432 |
| 4 | 1.813 | 85.2032432432433 |
| 4 | 1.6835 | 217.645686486487 |
| 7 | 0.9842 | 143.642335135135 |
| 14 | 62419 | 45.6682378378378 |
| 1 | 119.917 | 53.360172972973 |
| 3 | 188.034 | 85.6761081081081 |
| 3 | 88.837 | 58.5336648648649 |
| 1 | 321.16 | 44.4422918918919 |
| 4 | 872.83 | 108.121427027027 |
| 2 | 303.03 | 44.0815135135135 |
| 1 | 15.0738 | 150.76332972973 |
| 1 | 839.16 | 104.138854054054 |
| 1 | 383.32 | 706.302486486487 |
| 1 | 831.39 | 17.4294486486487 |
| 1 | 777 | 45.0377513513514 |
| 1 | 2662.52 | 39.5034810810811 |
| 2 | 2090.13 | 24.2737297297297 |
| 4 | 1367.52 | 63.4234378378379 |
| 1 | 5.7239 | 33.6574702702703 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 03033225 | EB MAHONING CR NR BIG RUN, PA | 405749 | 0785058 | N/A | 8187.098976 | 44.48 |
| 03040000 | STONYCREEK RIVER AT FERNDALE, PA. | 401708 | 0785515 | 1184.06 | 144825.081408 | 684.14 |
| 03049625 | ALLEGHENY R AT NEW KENSINGTON, PA. | 403352 | 0794622 | N/A | 3907769.4432 | 21860.77 |
| 03070415 | STONY FORK NEAR FARMINGTON, PA | 394651 | 0793431 | N/A | 156.183552 | 5.09 |
| 03070420 | STONY FORK TRIB NR GIBBON GLADE, PA (67) | 394551 | 0793514 | N/A | 2663.820432 | 1.80 |
| 03070455 | STONY FORK NEAR ELLIOTTSVILLE, PA (51) | 394608 | 0793634 | N/A | 12738.367152 | 13.08 |
| 03072670 | WHITELEY CREEK NEAR KIRBY, PA # 311 | 394739 | 0800810 | N/A | 6070.556016 | 7.56 |
| 03073030 | CASTILE RUN AT CLARKSVILLE, PA # 111 | 395744 | 0800312 | N/A | 3122.237664 | 6.08 |
| 03082020 | INDIAN CR AT JONES MILLS, PA--SITE #3 | 400521 | 0792004 | N/A | 2422.160496 | 39.35 |
| 03082120 | CHAMPION CR AT MELCROFT, PA--SITE #6 | 400355 | 0792355 | N/A | 2626.398432 | 30.83 |
| 03082190 | POPLAR RUN NR NORMALVILLE, PA SITE 16 | 400109 | 0792539 | 0 | 4466.499408 | 19.08 |
| 03082237 | INDIAN CREEK AT WHITE BRIDGE--SITE #23 | 395940 | 0792559 | N/A | 40787.730144 | 209.49 |
| 03085000 | MONONGAHELA RIVER AT BRADDOCK, PA. | 402328 | 0795130 | 707.16 | 6664122.4608 | 12629.46 |
| 03111585 | ENLOW FORK NEAR WEST FINLEY, PA # 503 | 395806 | 0802653 | N/A | 49821.65496 | 43.28 |
| | **STATE MEAN** | | | | | |
| 02131000 | PEE DEE RIVER AT PEEDEE, SC | 341215 | 0793255 | 24.73 | 2489387.653872 | 10000.78 |
| 02175000 | EDISTO RIVER NR GIVHANS S.C. | 330140 | 0802330 | 20.46 | 122124.243024 | 2602.27 |
| | **STATE MEAN** | | | | | |
| 01631000 | S F SHENANDOAH RIVER AT FRONT ROYAL, VA | 385450 | 0781240 | 469.38 | 611275.896 | 1572.55 |
| 01634000 | N F SHENANDOAH RIVER NEAR STRASBURG, VA | 385836 | 0782011 | 494.03 | 6491.9232 | 593.47 |
| 01644291 | STAVE RUN NEAR RESTON, VA | 385656 | 0772216 | 367.25 | 1308.155184 | 0.12 |
| 01644295 | SMILAX BRANCH AT RESTON, VA | 385710 | 0772204 | 356.59 | 1148.01624 | 0.41 |
| 01645784 | SNAKEDEN BRANCH AT RESTON, VA | 385548 | 0772043 | N/A | 4096.153152 | 0.76 |
| 01646580 | POTOMAC R AT CHAIN BRIDGE, AT WASH, DC | 385546 | 0770702 | N/A | 4040326.332 | 12769.12 |
| 01663500 | HAZEL RIVER AT RIXEYVILLE, VA | 383530 | 0775755 | 2088.3 | 178825.4496 | 338.35 |
| 01664000 | RAPPAHANNOCK RIVER AT REMINGTON, VA | 383150 | 0774850 | 252.53 | 3766520.3890608 | 686.81 |
| 01667500 | RAPIDAN RIVER NEAR CULPEPER, VA | 382101 | 0775831 | 241.36 | 335818.224 | 533.36 |
| 02019500 | JAMES RIVER AT BUCHANAN, VA | 373150 | 0794045 | 802.9 | 898108.9488 | 2464.18 |
| 02029000 | JAMES RIVER AT SCOTTSVILLE, VA | 374750 | 0782930 | 253.18 | 2829085.9632 | 5225.38 |
| 02060500 | ROANOKE RIVER AT ALTAVISTA, VA | 370616 | 0791744 | 503.1 | 1284901.8336 | 1814.90 |
| 02066000 | ROANOKE (STAUNTON) RIVER AT RANDOLPH, VA | 365454 | 0784428 | 307.59 | 10519365.169152 | 3080.63 |
| 02075500 | DAN RIVER AT PACES, VA | 363832 | 0790523 | 322.48 | 14941454.31576 | 2756.60 |
| 03207500 | LEVISA FORK NEAR GRUNDY, VA | 371752 | 0820734 | 988.5 | 54216.394848 | 287.88 |
| 03207800 | LEVISA FORK AT BIG ROCK, VA | 372113 | 0821145 | 866.37 | 4007990.27664 | 377.48 |
| 03207805 | CONAWAY CREEK AT CONAWAY, VA. | 372045 | 0821229 | N/A | 33324.467904 | 13.06 |
| 03490000 | N F HOLSTON RIVER NEAR GATE CITY, VA | 363631 | 0823405 | 1197.56 | 563403.22416 | 905.13 |
| 03527000 | CLINCH RIVER AT SPEERS FERRY, VA | 363855 | 0824502 | 1196.52 | 760192.14096 | 1593.49 |
| | **STATE MEAN** | | | | | |

| | | |
|---|---|---|
| 2 | 76.664 | 53.3952 |
| 1 | 1168.09 | 123.985167567568 |
| 3 | 29785 | 43.734745945946 |
| 1 | 6.475 | 24.1196108108108 |
| 13 | 2.4087 | 85.0701405405406 |
| 8 | 19.2696 | 88.9371243243243 |
| 2 | 15.4105 | 196.960475675676 |
| 1 | 16.0839 | 194.123286486487 |
| 1 | 45.066 | 53.7454702702703 |
| 1 | 35.742 | 73.4832 |
| 4 | 22.8697 | 48.824172972973 |
| 1 | 236.208 | 172.676237837838 |
| 6 | 19002.83 | 58.4496 |
| 5 | 98.679 | 100.975913513514 |
| | | 114.4 |
| 5 | 22869.7 | 21.7692972972973 |
| 5 | 7070.7 | 3.45366486486487 |
| | | 12.6 |
| 3 | 4252.78 | 47.9134702702703 |
| 1 | 1989.12 | 3.26451891891892 |
| 2 | 0.2072 | 3156.74425945946 |
| 4 | 0.8288 | 346.287697297297 |
| 5 | 2.0461 | 400.386940540541 |
| 3 | 29966.3 | 44.9431783783784 |
| 4 | 743.33 | 60.1449081081081 |
| 42 | 1605.8 | 55.8470918918919 |
| 5 | 1222.48 | 54.9398918918919 |
| 5 | 5374.25 | 33.4227891891892 |
| 5 | 11872.56 | 47.657772972973 |
| 3 | 4633.51 | 92.4363243243243 |
| 26 | 7710.43 | 52.4739891891892 |
| 26 | 6604.5 | 87.0106378378379 |
| 1 | 608.65 | 89.0772324324325 |
| 9 | 769.23 | 578.933708108108 |
| 1 | 19.166 | 1738.72761081081 |
| 3 | 1740.48 | 107.900756756757 |
| 3 | 2916.34 | 86.8880432432433 |
| | | 372.9 |

| STATION NO. | STATION NAME | LAT | LONG | DRAINAGE AREA (sq. km) | PERIOD OF CONT. SED. RECORD | MEAN DISCHARGE CUBIC M/SEC | TOTAL SUSP. SED. (tonnes) | SED. YIELD (t/sq. km/yr) |
|---|---|---|---|---|---|---|---|---|
| NFLD | | | | | | | | |
| 02YD002 | NORTHEAST BROOK NEAR RODDICKTON | 505544 | 560644 | 200 | 1982-1987 | 4.9 | 5678 | 4.73 |
| 024JO01 | HARRYS R. BELOW HIGHWAY BRIDGE | 483431 | 582148 | 640 | 1980-1987 | 24.86 | 53840 | 10.5 |
| 02ZA002 | HIGHLANDS R. AT TRANS-CANADA HWY | 480633 | 584704 | 72 | 1982-1986 | 2.68 | 5389 | 14.97 |
| 02ZM006 | NORTHEAST POND R. AT NORTHEAST POND | 473806 | 525014 | 3 63 | 1970-1978 | 0.128 | 114.87 | 3.5 |
| 02ZM008 | WATERFORD RIVER AT KILBRIDE | 473145 | 524443 | 52 7 | 1979-1987 | 2.29 | 14576 | 30.73 |
| NS | | | | | | | | |
| 01DC005 | ANNAPOLIS RIVER AT WILMOT | 445659 | 650147 | 546 | 1968-1985 | 12.95 | 90360 | 9.19 |
| 01DD004 | SHARPE BROOK AT LLOYDS | 450130 | 6438 | 8.81 | 1969-1974 | 0.22 | 310.5 | 5.87 |
| 01DG018 | PEMBROKE RIVER AT GLENBERVIE | 451554 | 625629 | 73.3 | 1978-1986 | 2.26 | 3950 | 5.99 |
| 01DH002 | SALMON RIVER AT MURRAY | 452209 | 631255 | 363 | 1968-1972 | 10.89 | 37150 | 20.47 |
| 01DH003 | FRASER BROOK NEAR ARCHIBALD | 452035 | 631005 | 10.1 | 1967-1975 | 0.24 | 541.1 | 5.95 |
| 01DL001 | KELLEY R. (MILL CREEK) AT EIGHT MILE FORD | 453510 | 642705 | 63.2 | 1975-1986 | 1.99 | 4279.8 | 5.64 |
| 01DP004 | MIDDLE RIVER OF PICTOU AT ROCKLIN | 452950 | 624651 | 92.2 | 1970-1980 | 2.89 | 11376 | 11.22 |
| 01FB005 | APRIL BROOK AT GILLISDALE | 461353 | 610830 | 6.22 | 1969-1978 | 0.25 | 2165 | 34.81 |
| NB | | | | | | | | |
| 01AJ007 | HOLMES BROOK NEAR HOLMESVILLE | 463434 | 673543 | 31.3 | 1972-1973 | 0.28 | 4343 | 69.38 |
| 01AJ006 | HOLMES BROOK AT MOOSE MTN | 463646 | 673638 | 7.77 | 1972-1973 | 1.02 | 931 | 59.91 |

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|---|---|---|---|---|---|---|---|---|
| 01AJ010 | BECAGUIMEC STREAM AT COLDSTREAM | 462027 | 672758 | 350 | 1976-1978 | 8.15 | 20550 | 19.57 |
| 01AK005 | MIDDLE BR. NASHWAKSIS NR. ROYAL ROAD | 460206 | 664205 | 26.9 | 1966-1978 | 0.52 | 2235.8 | 6.39 |
| 01AP004 | KENNEBECASIS R. AT APOHAQUI | 454207 | 653605 | 1100 | 1967-1987 | 26.11 | 709900 | 30.73 |
| 01BO001 | SW MIRAMICHI R. AT BLACKVILLE | 464410 | 654936 | 5050 | 1985 | 72.8 | 10100 | 2 |
| 01BS001 | COAL BRANCH R. AT BEERSVILLE | 462637 | 650355 | 166 | 1985-1986 | 2.89 | 3140 | 9.46 |
| 01BU002 | PETICODIAC RIVER NR. PETICODIAC | 455637 | 651013 | 391 | 1968-1983 | 8.54 | 89160 | 14.25 |
| 01BU004 | PALMERS CREEK NR. DORCHESTER | 455314 | 643059 | 34.2 | 1968-1974 | 0.9 | 3625 | 15.14 |
| PEI | | | | | | | | |
| 01CA004 | SMELT CREEK NR. ELLERSLIE | 463606 | 635614 | 17.3 | 1968-1972 | 0.38 | 917.5 | 10.6 |
| 01CB004 | WILMOT R. NEAR WILMOT VALLEY | 462335 | 633935 | 45.4 | 1972-1986 | 0.95 | 27240 | 40 |
| 01CB005 | NORTH BROOK NEAR WALL RD. | 462049 | 633758 | 12.9 | 1972-1986 | 0.26 | 4068.2 | 21 |
| 01CB006 | EMERALD BROOK NEAR EMERALD | 462134 | 633329 | 5.59 | 1975-1981 | 0.1 | 1130.9 | 28.9 |
| 01CE003 | BRUDENELL R. NEAR BRUDENELL | 461202 | 623858 | 36 | 1967-1978 | 0.76 | 8496 | 19.7 |
| 01CE004 | BRUDENELL R. AT BRUDENELL | 461207 | 623923 | 33.1 | 1980-1987 | 0.78 | 3430 | 13 |