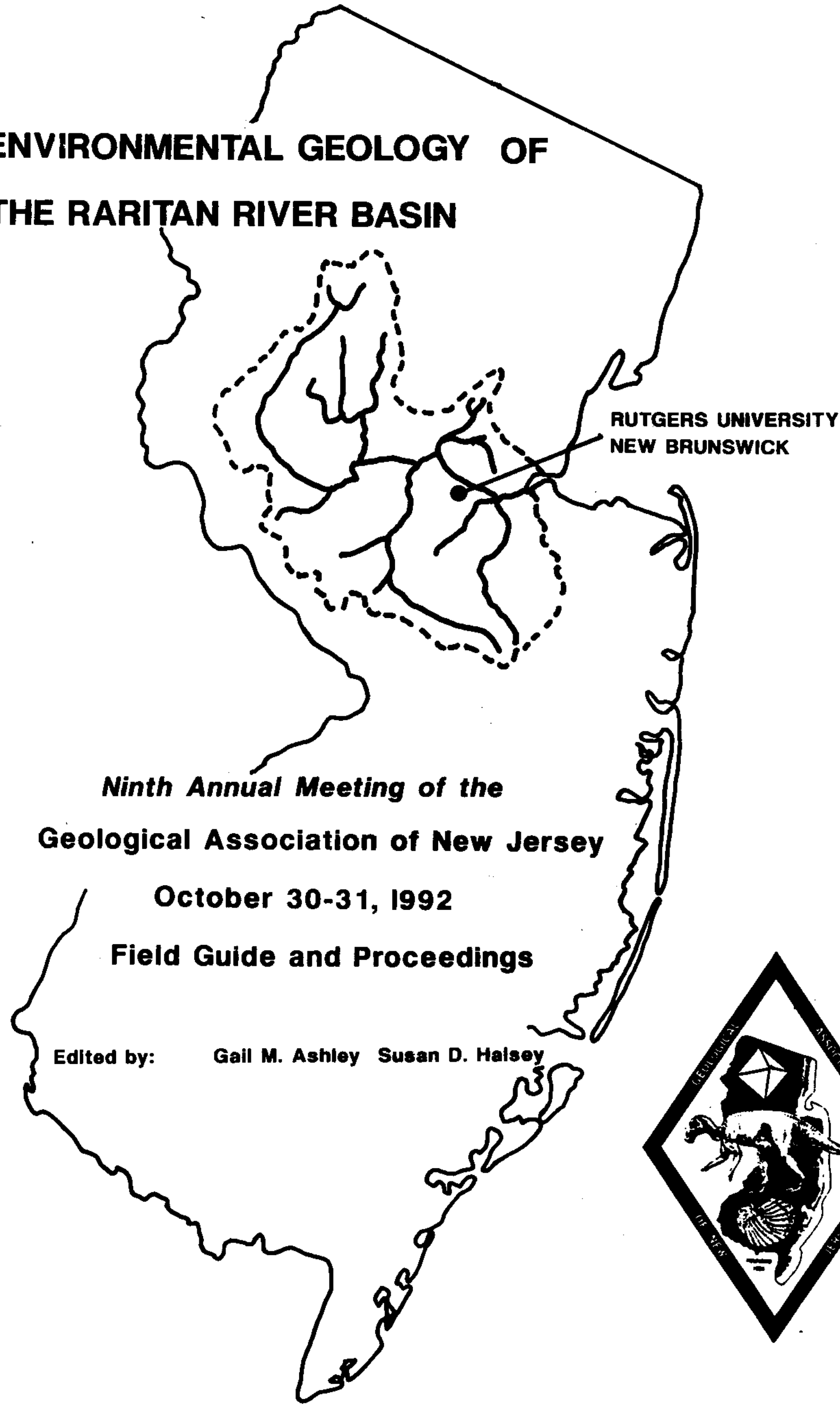
ENVIRONMENTAL GEOLOGY OF THE RARITAN RIVER BASIN



Ninth Annual Meeting of the

Geological Association of New Jersey

October 30-31, 1992

Field Guide and Proceedings

Edited by: Gail M. Ashley Susan D. Halsey

ENVIRONMENTAL GEOLOGY OF THE RARITAN RIVER BASIN

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Ninth Annual Meeting of the

GEOLOGICAL ASSOCIATION OF NEW JERSEY

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Hosted by: **Rutgers University, New Bruswick, NJ 08903**

Field Trip Leaders: **Gail M. Ashley**

William H. Renwick

Supported, in part by: **Jersey City State College**

Rutgers University

IN 1609 HENRY HUDSON IN THE HALF-MOON DISCOVERED THE RARITAN RIVER WHILE EXPLORING THE COAST BETWEEN SANDY HOOK AND THE HUDSON.

FOREWARD

The Raritan watershed was first occupied by native americans approximately 10,000 years ago. They fished the river and estuary, hunted in the woodlands, left little record, and made virtually no environmental impact. The river was "rediscovered" in 1609 when Henry Hudson sailed into Raritan Bay. Humans have had an ever increasing impact on the river system. Many studies have been conducted on the geology, surface hydrology, and water quality by federal, state, and county agencies, as well as academics. However, all have been focused on specific topics or localities within the drainage basin. This field guide represents the first synthesis on a basin-wide scale. Research was conducted by the Geological Sciences and Geography Departments of Rutgers University between 1978-1988 and was supported by: (1) NJDEPE (Office of Science and Research) with project coordinators Thomas Belton and Robert Mueller; (2) U.S. Geological Survey, Water Resources Div.; and (3) Rutgers University. Our findings include contributions from a large number of individuals. Four M.S. theses were produced: Gary Haag (1982), Christopher Motta (1984), Franklin McLaughlin (1988), and Robert Pavlowsky (1989). In addition, contributions were made by 11 undergraduate research projects. Independent studies were conducted by: Eric Barkmeyer, John Boersma, Laura Brachfeld, Shawn Dilles, Peter Harrison, Marcy McKinley, Herbert Koenig, James Van Nest, Darren Vogel, Diane Werbin, and Michael Whalen. As is typical of most research, we answered many questions but raised many more. We hope this synthesis will provide the background for future work on the environmental geology of the Raritan River Basin as the challenges presented by the most densely populated state in the nation continue into escalate into the 21st century.

Gail M. Ashley William H. Renwick

Mules pulling barges were a common sight on the Delaware and Raritan Canal during the last half of the 19th century. Now the canal brings us Delaware River water and gives us a long narrow park for recreation.

ENVIRONMENTAL GEOLOGY OF THE RARITAN RIVER BASIN
FIELD GUIDE AND PROCEEDINGS

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Field Guide

Field Trip

Note:
The art work used throughout the field guide is from the **Raritan River Children's Book Vol. #1** produced for the Raritan River Festival in cooperation with the HOME NEWS by M.J. Babcock, M.G. Blackwell, and E.B. Paulus.

Art work by: Robert J. Albrecht
Robert A. Albrecht
Claire G. Albrecht
George A. Bradshaw

Digging Clay in the Dreary Sand Hills: A Preliminary Overview of the Historical Development and Economic Geology of the Middlesex County Clay Products Industry.

The New Jersey clay products industry was at its height in 1902 with 157 establishments producing $10,786,673 worth of products. New Jersey was the leading producer of hollow brick, fireproofing, terra cotta, flue linings, gas retorts, and raw clay, and ranked 3rd in overall national production. However, unlike the larger producers, Ohio and New York, the vast majority of the New Jersey clay products industry was highly concentrated within a 68 square mile area in northeastern Middlesex County. Blessed with extensive clay deposits on both sides of the Raritan River, direct access to the New York market, and the presence of enterprising individuals and businesses, a vast clay products industry emerged in this area during the 19th century. Clay was mined and sold in either its raw form, or as one of a diverse range of finished products, which included common building brick, fire brick, hollow brick, pressed brick, face brick, paving brick, wall tiles, terra cotta, fireproofing, conduits, pipes, and pottery. The purpose of this paper is to give a preliminary overview of the unique development of the clay products industry in northeastern Middlesex County, and to discuss the extent that the geology of the region affected the location of specific industries and the methods and technology used to extract and process the clay.

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THE HEALTH OF THE SOUTH BRANCH WATERSHED
MONITORING AND PROTECTING OUR WATERWAYS

By Marie Kneser, Administrator, SBWA

ABSTRACT OF PRESENTATION FOR OCTOBER 30, 1992

As a local, non-profit, environmental organization, the South Branch Watershed Association works to protect and preserve the clean water in the South Branch Raritan River Watershed. We work with citizens, students, technical experts and all levels of government to create an awareness of the environmental pressures and issues in our watershed.

The water in this watershed is greatly impacted by non-point source pollution. As you know, the sources of this pollution are difficult to identify and ameliorate. Therefore, we have initiated a monitoring program to establish a baseline water quality index for our waterways. We work closely with trained volunteers and dedicated students from area high schools and middle schools.

Throughout the year, well-water testing is available through our facilities through a New Jersey licensed laboratory. Information about maintaining your wells and septic systems is provided to the participants.

The Association has sponsored several workshops designed to address the gamut of non-point source pollution problems and the karst geology which exists in the northern portion of our watershed. These workshops are geared primarily toward technical experts and municipalities to provide manageable alternatives for these people.

This summer the SBWA has initiated a project known as "Water Waves" which works with various recreation and camp sites in the watershed to provide water-related activities for children. We have also carried out a pilot Natural Resource Inventory Project for middle-school students.

For the past 30 years, The SBWA has administered community service projects such as bi-annual stream clean-ups, and community well-testing. It has also served as a clearinghouse for environmental questions, and worked with municipalities to create environmental inventories of natural resources, and protected open space.

THE IMPORTANCE OF WATER QUALITY TO FISHERY RESOURCES OF THE HUDSON-RARITAN ESTUARY

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Pollutants in the form of toxic chemicals, pathogens, and nutrients are entering the coastal zone from a variety of point and nonpoint sources threatening the vitality and quality of marine ecosystems and marine organisms, and impairing use of these resources by the public. These pollutants can degrade the marine environment and result in adverse health effects, ecological damage, and economic damage.

The Hudson-Raritan estuary, including New York Harbor, is one of the greatest natural harbors in the world. It is also one of the busiest ports in the nation, playing a crucial role in the regional economy. During the past century, the Hudson-Raritan estuary has been subjected to serious pollution and other modification which have resulted in a number of changes to the environment and biota of the estuary.

To the casual observer, the wide-scale shoreline development, discharges of industrial wastes and sewage, and destruction of tidal marshes as a result of dredging and filling that have taken place in the estuary are all incongruous with the concept of sustaining a healthy biota. As a result of the region's long-standing history of environmental abuse, the estuary projects an image of harboring little in the way of important living marine resources. Therefore, it is not surprising that many people have an erroneous concept of the importance of Newark Bay, the lower Hudson River, Raritan Bay, and the other waterways within this estuarine system.

However, despite the multitude of factors that have had a serious deleterious effect on the aquatic resources of the area, the Hudson-Raritan estuary continues to provide important habitat for a variety of commercially and recreationally important fish and shellfish. Among the more important species are striped bass, bluefish, weakfish, white perch, winter flounder, and summer flounder. All of these fish utilize portions of the estuary as either nursery or feeding grounds. Other marine resources of importance include blue claw crabs, lobsters, hard clams, soft clams, and fish such as shad, herring, and tomcod.

The important consideration that must be realized and understood is that, despite its compromised environmental status, the Hudson-Raritan estuary continues to serve as an essential habitat for many important marine and estuarine fishery resources.

STORMWATER/WETLANDS MANAGEMENT AND CHANGES WITH TIME IN THE URBAN WATERSHED

by
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The urban watershed is a complex hydrologic and biologic system that is understudied and misunderstood. Historically, the urban watershed has been channelized, piped, and filled to where the normal hydrological patterns no longer exist. As the impervious surfaces increased within the watershed, the objective has been to transport stormwater to the nearest outlet as soon as possible with no concern for instream and downstream impacts. In the 1970's, a new stormwater management concept developed requiring the stormwater facility to meet the objectives of water quality, erosion, and flood control problems in the developing watershed.

Today, we have thousands of stormwater management facilities affecting the stormwater flow through the watershed with no understanding of their overall impact to the system. Many of these facilities are failures in that they are not meeting their designed stormwater discharge criteria. The end result is thousands of small semi-isolated wetlands creating a variety of nuisances. The answer to the restoration and protection of our urban watersheds is not just the construction of more isolated facilities but the reconstruction of the entire watershed from both the hydrologic and biologic standpoints. The regulatory process has developed a major problem by the implementation of ineffective urban watershed and stormwater management projects.

FRACTURE FLOW VELOCITIES IN THE PASSAIC FORMATION IN LIGHT OF INTERWELL TRACER TESTS

Andrew Michalski and Todd Gerber
The Whitman Companies, Inc., East Brunswick, NJ

ABSTRACT

Interwell tracer tests were performed at two locations within the Passaic Formation in central New Jersey. Each test involved the release of a small amount of salt tracer into one well and subsequent repeated logging of electrical conductivity in the nearest downgradient observation well(s) for the detection of tracer breakthrough.

At one location, a natural-gradient tracing was successfully completed between two bedrock wells installed 63.5 feet apart and along the strike of beds. The tracer was found to migrate along a bedding plane separation at an average rate of 8.9 feet per day. This bedding separation provided a dominant aquifer unit within the open intervals of the two wells. Hydraulic tests yielded a transmissivity value of 1,000-1,500 gpd/ft for this discrete unit; a typical value obtained for major water-bearing units at several sites within the region.

At another site, a positive trace was obtained along a minor bedding plane (transmissivity of less than 35 gpd/ft) intersected by two wells placed 10.3 feet apart. The tracer introduced to the shallower of the two wells was found to travel with a velocity greater than 100 feet per day. Most of the injected tracer mass was recovered in the deeper well. The high velocity of tracer migration through a relatively minor bedding fracture was due to crossflows through open intervals of the wells. The occurrence of downward flows within these intervals was documented by conducting an in-well flow tracing prior to the interwell tracing.

The tracing results demonstrate the discrete character of ground-water flow and the major role of bedding plane separations in the flow and tracer transport through the Passaic Formation. The results imply that a single major bedding separation can provide a preferential pathway for contaminant migration from a site, with rates greater than one-half mile per year. Unless such a pathway is identified, accurate delineation of a plume may not possible. In addition, improper placement of monitoring wells can induce or accelerate the contaminant migration from the source area into the preferential pathways.

INTRODUCTION

Tracer tests are often recommended and used to determine migration pathways and rates for ground water in karst terrains (e.g. Quinlan and Ewers, 1985). Interwell tracing is seldom used for non-karstic fractured aquifers. If used, various injection-withdrawal schemes are applied (e.g. Davis et al., 1985;) to overcome uncertainties associated with tracer reappearance and long travel times for interwell testing conducted under natural hydraulic gradients.

This paper describes natural-gradient, interwell tracing experiments conducted at two sites in central New Jersey. These sites were located within fractured bedrock of the Passaic Formation, a part of the Triassic Newark Basin. At each of these sites, an adequate understanding of hydrogeology and migration pathways was attained prior to embarking on the tracing experiments. These tracing experiments were undertaken to verify important aspects of the hydrogeology of each site, particularly the role of bedding plane separations for ground water and contaminant transport.

TEST NO. 1

At a site in Piscataway, NJ, a natural-gradient tracing experiment was conducted between two bedrock wells (Figure 1). A downgradient well, SK-R, was installed 63.5 feet from the upgradient and injection well DW-1. Both wells were six inches in diameter and had open intervals approximately 30 and 40 feet long. The static water level in both wells was found within the cased-off intervals. The average difference of water level elevations between these wells during the test period was 0.10 feet, indicating an average hydraulic gradient of 0.0016. These two wells were installed along the general direction of strike of mudstone and shale beds at the site, but the downgradient well was slightly offset in the downdip direction.

Prior to the test, a major transmissive fracture was identified at an elevation of about +15 feet above msl in well DW-1 and at about +12.5 feet in well SK-R (Figure 1). Based upon the position of these two wells with respect to the strike and dip of beds, the fractures identified were interpreted to represent intersections of wells with the same major bedding separation, as shown in Figure 1. The identification of fracture locations was based primarily upon electrical conductivity (EC) logs obtained for these two wells. An inflection apparent on each of the baseline EC logs (Figure 2 and 4) usually correspond to a major fracture with an active ground-water flow at this depth (e.g. Michalski and Klepp, 1990).

The tracing experiment was conducted to verify whether the interpreted major bedding separation (Figure 1) provided a preferential migration pathway of ground water flow between the wells and also to determine associated tracer migration rates. Using a modified Kemmerer sampler, 158 grams of NaCl dissolved in 2.2 liters of water was introduced into well DW-1. This slug of saline solution was released below the bottom of the casing and just above the interpreted position of the major bedding-plane separation (Figure 1).

The fate of the injected tracer was tracked through a repeated logging of electrical conductivity (adjusted for temperature) in the injection and downgradient wells. A YSI downhole conductivity probe (Model 3000 TLC) was used for the logging. The EC values above the background (baseline) level were indicative of the saline tracer concentration at a given depth within the water column of the wells.

As evidenced by the tracer concentration (EC) profiles for injection well DW-1 (Figure 2), the fate of the tracer was influenced by two major processes. Due to a significant density contrast, the denser tracer solution was observed to sink into the lower portion of the water column until an equalization of tracer concentrations was attained approximately one day later (right-hand graph on Figure 2). At the same time, the tracer solution was swept into the major bedding separation at a depth of 63 feet below the top of casing (elevation +15) by a prevailing, preferential flow of ground water through this bedding fracture.

The amount of tracer remaining in well storage and the amount swept away was estimated by integrating the area between the current and the baseline EC plots and assuming that a linear relationship existed between temperature-adjusted EC readings and tracer concentrations. Figure 3 presents a plot of tracer mass swept from the injection well as a function of time elapsed after the tracer injection. Nearly 50% of the injected tracer mass was swept away within the first two days. Thereafter, the sweeping rate significantly decreased, as diffusion became a principal mechanism for tracer removal from the lower segment of the well. At the completion of the experiment 10 days after the tracer release, high concentrations of injected salt were still detectable in the lower portion of the injection well. The concentration profiles obtained (Figure 2) and tracer mass balance for the injection well (Figure 3) suggest that the lower segment of the well was hydraulically inactive.

In the downgradient well, SK-R, logs of EC were taken usually twice a day to detect tracer breakthrough. On the seventh day after tracer injection into well DW-1, a measurable departure of EC log from the baseline log (Figure 4) was observed. An increase of EC readings at the depth of the major transmissive bedding separation (Figure 1) indicated the tracer breakthrough. The preexisting inflection of the baseline log at the fracture depth was enhanced by a contribution from the saline tracer. This contribution was discernible on EC logs over several days before it dissipated to the baseline levels.

Figure 5 shows a tracer breakthrough curve based upon EC readings obtained at a depth of 67 feet (elevation +12 feet) in a series of EC logs taken in well SK-R. This curve is asymmetrical; its recession portion is flattened, possibly even bimodal. This shape might be the result of a prolonged tracer input into the bedding fracture at the injection well, and also of a possible channelling of flow within this fracture. The peak value of tracer concentration in well SK-R was observed approximately 7.1 days after the tracer injection into the upgradient well. This travel time indicated an average tracer migration velocity of 8.9 feet per day between the two wells under a flow condition undisturbed by any pumping.

The results of this tracing experiment have confirmed earlier concepts on the principal role of bedding separation for ground-water flow and contaminant transport in the Passaic Formation (Michalski, 1990; Carswell, 1976). The bedding separation tested at the Piscataway site is believed to represent a water-bearing unit which is typically encountered at most sites in the Passaic Formation within a stratigraphic interval of no more than about 50-100 feet. Therefore, one can expect that unretarded contaminants can migrate at velocities in excess of 3,000 feet per year, once they have entered such a major bedding separation.

For cases involving more transmissive fractures or hydraulic gradients increased by pumping, the migration rates may even be higher than obtained in this tracing experiment. Slug permeability tests and a pump test indicated a transmissivity range of 1,000-1,500 gal/day/ft for the bedding separation along which a positive tracing was obtained. There is at least one documented case of an areally extensive bedding fissure in the Passaic Formation with a transmissivity of approximately 15,000 gal/day/ft (Michalski et al., 1992). A fast migration rate, on the order of one thousand feet per month, can be anticipated for such an extreme case.

TEST NO. 2

At another site located in Bridgewater, NJ, a tracing test was conducted between two wells located only 10.3 feet apart (Figure 6). The deeper well (MW-4) and the shallow well (MW-15) were installed as a well cluster several years earlier. The shallow well was found to be completed within a mudstone unit (a confining unit). Results of slug testing indicated a low transmissivity (35 gpd/ft) for the saturated section of well MW-15. In contrast, a relatively high transmissivity value of greater than 2,000 gpd/ft obtained for well MW-4 suggested that the deep well intersected a major aquifer unit in its lower portion. The elevation of water level in the shallow well (MW-15) was consistently 0.30-0.55 feet higher than in the deeper well.

Before the interwell tracing was attempted, the presence of measurable downward flows in each of these wells (Figure 6) was ascertained using an in-well tracing methodology described by Michalski and Klepp (1990). These flows were produced because open well intervals bridged water-bearing zones with different hydraulic heads. Analytical sampling revealed that the highest levels of contaminants (dissolved chlorinated hydrocarbons) occurred at the top of the water column in well MW-15. It became apparent that the occurrence of downward flows induced contaminant migration from a surficial source.

The interwell tracing was conducted to track the fate of the grossly contaminated ground water entering well MW-15. The interwell tracer test involved an injection of saline tracer (59 grams of NaCl in 2.2 liters of water) into a lower portion of well MW-15 (Figure 6). Well MW-4 and other adjacent wells were repeatedly logged using the EC probe to detect a breakthrough of the tracer.

Relatively rapid reappearance of the injected tracer was observed in well MW-4. As indicated by a series of successive EC profiles obtained for this well (Figure 7), the tracer appeared in MW-4 at an elevation of 8.7 feet within less than two hours after tracer injection into well MW-15. A minor bedding plane separation must have provided the pathway for tracer migration from MW-15 to MW-4 (Figure 6). The baseline profile (0 hours in Figure 7) also showed an inflection at this depth, implying that slightly more mineralized water (higher EC) entered well MW-4 through this bedding fracture. The tracer arrival time of less than 2 hours suggested a migration rate of more than 100 feet per day, considering a 10.3 feet distance between wells MW-15 and MW-4. The estimated arrival time is conservative, as it incorporates downward tracer travel inside well MW-15 before the minor bedding fracture was reached by the tracer.

Successive EC profiles indicate that tracer concentration in MW-4 was increasing until about 80 hours after the tracer injection (Figure 7). Thereafter, the concentrations declined. An estimate of tracer mass recovered in well MW-4 was performed, based upon the concentration profiles shown in Figure 7 and the measured downward flow within this well at the depth of interest. The estimate indicated that most of the tracer mass injected into well MW-15 reappeared in well MW-4. This high recovery rate confirmed that contaminated ground water entering the shallow well MW-15 was subsequently entrapped by well MW-4 and then transported into the lower portion of MW-4.

The results of the tracing experiment performed at the Bridgewater site illustrate how monitoring wells themselves can provide short-circuiting pathways for an accelerated contaminant migration in a complex, multiunit fracture aquifer system in the Passaic Formation. If this aspect is ignored, an erroneous picture of ground-water flow and contaminant distribution can be obtained.

CONCLUSIONS

The results of interwell tracing conducted at the Piscataway site provide additional evidence of the discrete character of ground-water flow in the Passaic Formation and for the dominant role of bedding plane separations in ground-water flow and contaminant transport. It follows that the concept of equivalent porous medium should not be used for the hydrogeologic characterization of sites located within the Passaic Formation.

The typical major bedding separation can provide a preferential pathway for contamination migration with velocities in excess of one-half mile per year. Unless such a pathway is identified and monitored, an accurate plume delineation and effective aquifer remediation may not be possible.

The length of open intervals of monitoring wells and their position respective to the internal aquifer structure are of primary importance. As indicated by tracing at the Bridgewater site, an improper placement of these intervals can induce and accelerate the contaminant migration from the source area into a major bedding fracture which constitutes a local aquifer unit and preferential migration pathway. Specialized techniques, including in-well tracing or flowmeter testing, should be used to identify wells with significant crossflows within the Passaic Formation.

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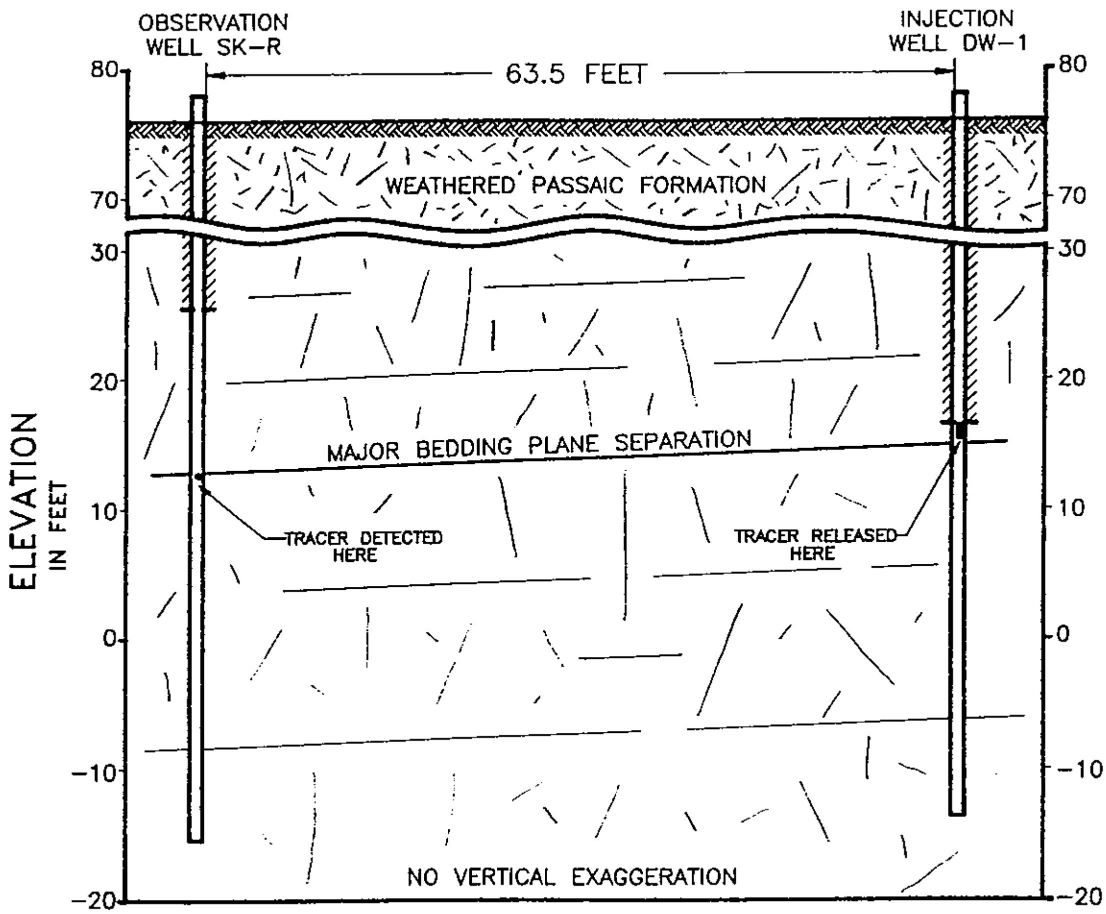

Figure 1. Geologic cross-section and setup for interwell tracing test No. 1

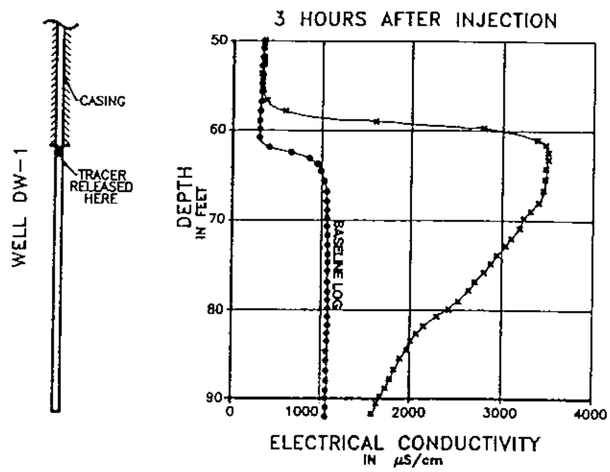

Figure 2. Electrical conductivity (tracer concentration) profiles in the injection well 3 hours and 26 hours after tracer injection

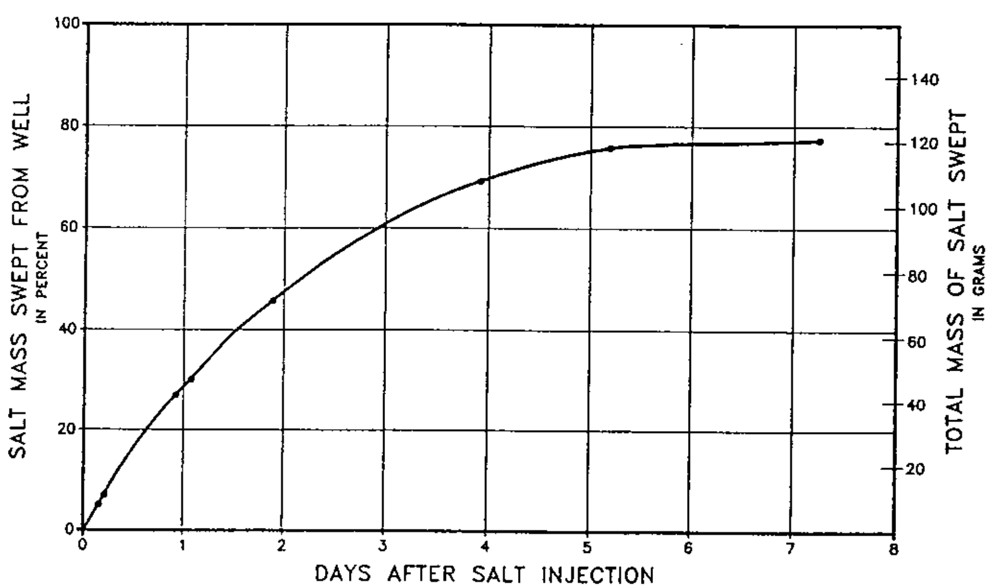

Figure 3. Estimated tracer mass swept from the injection well as a function of time

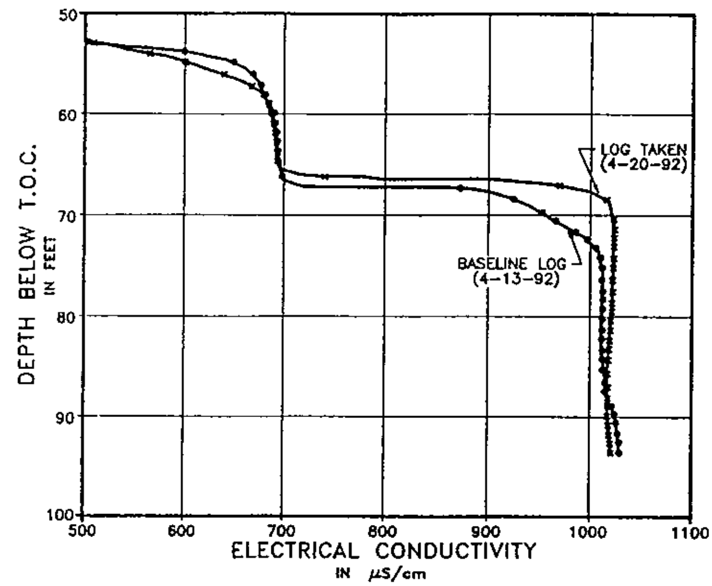

Figure 4. Baseline EC log for observation well SK-R and and example of a log taken during tracer breakthrough to this well

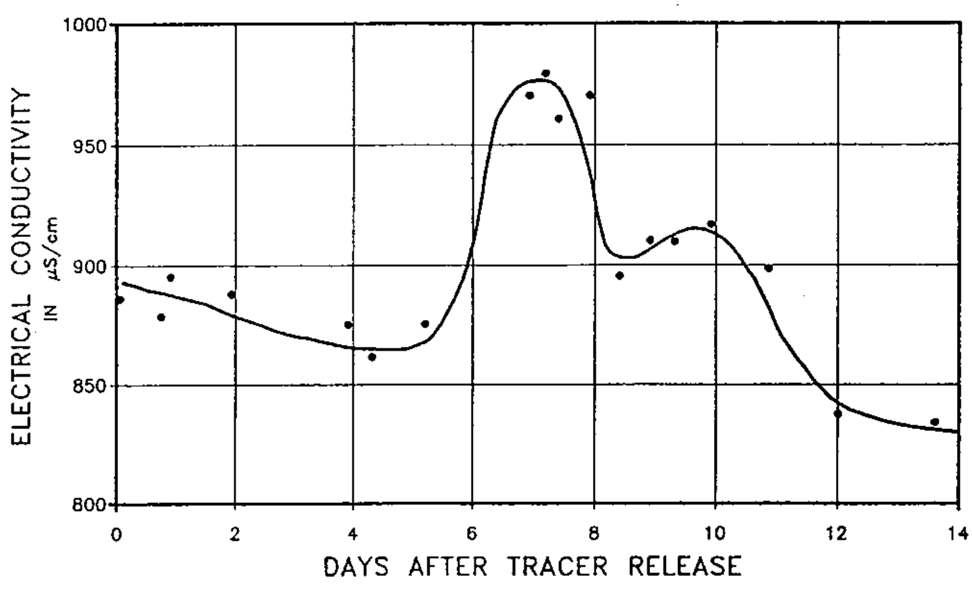

Figure 5. Tracer breakthrough curve based on EC readings obtained at a depth of 67 feet in well SK-R, where the major bedding separation intersects the well

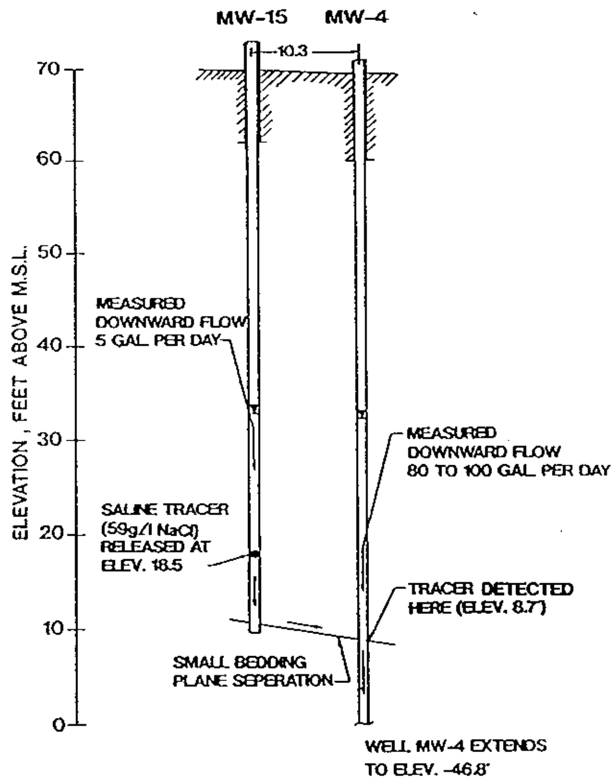

Figure 6. Test setup for interwell tracer test No.2

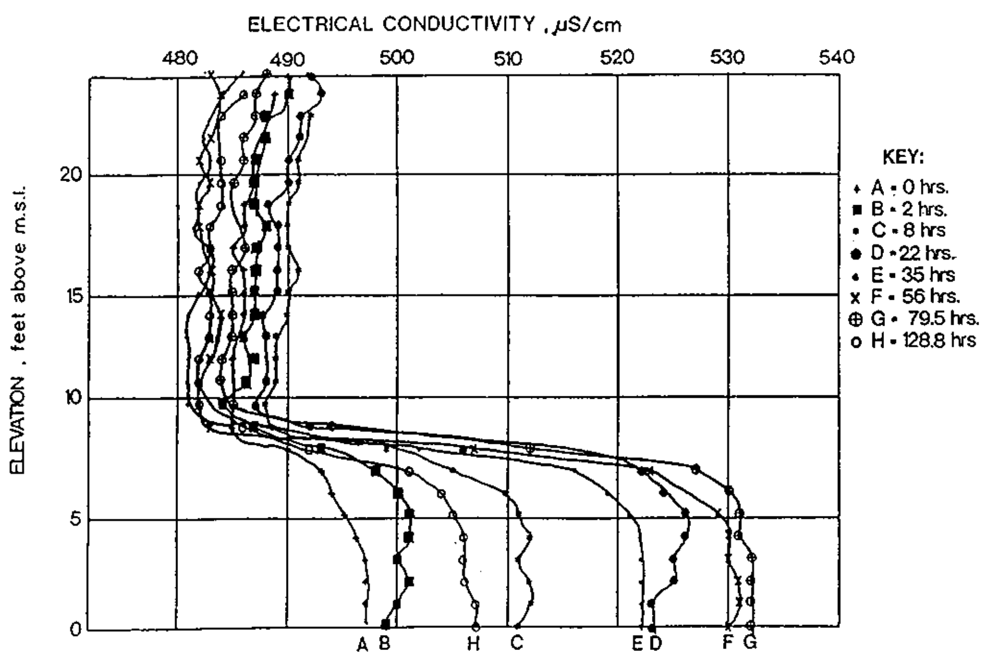

Figure 7. EC logs in a section of well MW-4, obtained at various times after tracer injection into well MW-15

BEDROCK HYDROGEOLOGY OF THE MANVILLE-BRIDGEWATER SECTION OF THE RARITAN RIVER VALLEY

Andrew Michalski, Richard Britton and Alan H. Uminski
The Whitman Companies, Inc., East Brunswick, NJ

ABSTRACT

Two temporary test holes, each 200 feet in length, were drilled into the Passaic Formation bedrock within the Raritan River valley in Bridgewater, NJ. In order to identify major zones for water quality monitoring, video surveys, electrical conductivity logging, and tracing of vertical crossflows were performed in these test holes. Two clusters of monitoring wells were subsequently installed near the test hole locations. Pumping tests were conducted in the clusters to determine the degree of hydraulic connection between these wells and wells located at an industrial site north of the river valley.

The results obtained have been integrated into a hydrogeologic cross-section extending for over 3,000 feet from the Manville municipal wellfield to the industrial site at the northern side of the river valley. The mudstone and siltstone beds of the Passaic Formation strike subparallel to the river valley and dip to the northeast at 7°-9°. Major bedding plane separations provide the principal pathways for ground-water flow which is predominantly along-the-strike direction. Some vertical leakage occurs across intervening mudstone beds. Due to its limited thickness (15-20 feet) and moderate permeability, the alluvial cover on the bedrock plays a minor hydrologic role.

The two specific hydrogeologic features encountered in the valley include the presence of mineralized ground water ascending into the river valley, and the occurrence of large bedding fissures at the contact of the fresh and mineralized ground water. A single major open bedding fissure was found to extend for a distance of at least 1,500 feet, and to exhibit transmissivity of about 15,000 gpd/ft. This value is an order of magnitude greater than typical transmissivity values for major bedding separations measured elsewhere in the Passaic Formation. This open bedding fissure serves as a dominant aquifer unit channeling the flows from the fresh water zone above it and from the mineralized ground water zone below.

Many enlarged bedding fissures and other fractures, which are now completely or partially infilled with gypsum, were observed beneath the open fissure zone. It is hypothesized that these enlargements have resulted from stress changes that accompanied glacial cycles.

INTRODUCTION

The concern that ground-water contamination found at an industrial site might have an adverse impact on water supply wells for the Borough of Manville prompted an area-wide hydrogeologic investigation. Water supply for Manville is furnished by several deep wells located adjacent to the Raritan River (Figure 1), and the suspect industrial site is located approximately 3,000 feet north of these wells. The hydrogeologic investigation was conducted at the industrial site and in an area between the site and the Manville supply wells. Results of the latter investigation are presented in this paper.

The study area in central New Jersey is located within the Triassic Newark Basin and is underlain by the Passaic Formation (Olsen, 1980). This formation, formerly referred to as the Brunswick Formation, consists of alternating sequence of fractured reddish-brown mudstones, siltstones and shales. The formation hosts a complex, multiunit leaky aquifer system with larger bedding plane separations serving as principal aquifer units (Michalski, 1991). Measurements taken at outcrops indicate that the strike of Passaic beds is subparallel to the river valley in the study area and dip is to the northeast at 6°-11° (Figure 1).

As part of the investigation, pilot holes and well clusters were installed in-between the industrial site and the Raritan river (Figure 1). Various techniques were utilized to characterize the hydrogeology of this area. They revealed interesting hydrogeologic features, including the presence of unusually transmissive bedding fissures and the occurrence of mineralized water ascending into the river valley. The results obtained from the pilot holes and well clusters were integrated with hydrogeologic data available for the industrial site and the Manville supply wells. This integration resulted in preparation of a cross-section depicting the bedrock hydrogeology along the 3,000 feet distance across the Raritan valley from Manville to Bridgewater.

INVESTIGATIVE TECHNIQUES USED

Drilling of Temporary Pilot Holes

Two temporary pilot holes (TH-18 and TH-19) were drilled on the floodplain of the Raritan river (Figure 1). The purpose of these pilot holes was to identify the position of major bedding separations (or other major water-bearing zones) which would become target zones for monitoring by subsequently installed well clusters. Each of these holes was cased-off within alluvial overburden and then drilled to a total depth of 200 feet using an air-rotary method. The holes were six inches in diameter. Significant discharges of ground water (up to about 200 gpm) were observed during drilling of these holes. The two test holes were grouted upon completion of planned tests.

Video Survey

A downhole video survey was performed to evaluate the lithology and fractures intersected by the pilot holes. In the amount and quality of hydrogeologic information obtained, this color video survey surpassed conventional coring techniques.

The survey confirmed that thick and massive mudstone units were the dominant lithologic type in both test holes, with subordinate beds of thin shale and siltstone. These thin beds were more densely fractured and could be recognized by their tendency to appear on the screen as "rough" segments of the holes. Bedding plane separations and fissures commonly occurred within such segments. These segments were separated by intervals of thick mudstone beds.

The most striking feature observed on the video screen was the presence of whitish infilling in numerous bedding fissures and occasional high-angle fractures. This infilling of bedding fissures appeared as white rings and were found only below a depth of 168 feet in Hole 18T and 116 feet in TH-19. Some of the rings attained a thickness of over two inches (e.g. at 196 ft in TH-19). Infilling mineral exhibited fibrous structure, low hardness and a negative reaction to hydrochloric acid typical of gypsum.

While large bedding fissures in the lowermost sections of both holes appeared completely filled with gypsum, they were only partially filled within the uppermost portion of the zone containing gypsum infillings. Open bedding fissures with the largest apertures were encountered just above the gypsum infilling zone. For example, a very distinct bedding fissure was observed in hole TH-18 at a depth of 165 feet. Particles of suspended matter were seen moving into this fracture, implying its large transmissivity. This fissure created problems during sealing of the temporary pilot hole by accepting an unusually large amount of grout.

One can speculate that these bedding plane separations and fissures were probably enlarged due to stress relief associated with deglaciations and earlier erosional unloading. Freezing of weathered bedrock under permafrost conditions, together with shearing exerted by advancing glaciers might have contributed to the formation of these bedding fissures. The enlargement of bedding plane separations due to erosional removal of compressional stress is described in literature (e.g. Wyrick and Borchers, 1981).

The occurrence of white infillings predominantly along bedding separations provides an additional indication that the bedding separations have provided primary pathways for ground water flow through the Passaic Formation at this location.

Electrical Conductivity (EC) Logging

Logging of electrical conductivity (EC) in the pilot holes was conducted using a downhole commercial probe (YSI Model 3000 TLC Meter). The logging is aimed at detection of effects associated with mixing of waters at major fractures intersecting wellbore. Such mixing often produces a distinct inflection of the EC plot at the major fracture locations. The position of dominant fractures can thus be identified for each wellbore. EC logging has been a useful tool for characterization of fracture flow (e.g. Key 1989; Michalski 1989).

The EC logging was repeated on three different dates. Figure 2 shows EC plots for each of three logs performed in test hole TH-19. In order to extend EC data beyond the 150-foot depth range of the logging device used, discrete water samples were collected from depths of 160, 170, 180, 190 and 200 feet using a Kemmerer sampler. A two-inch rainfall event which occurred 2.5 days prior to the logging on 8-12-91, is believed to account for the shape of the EC log obtained for that date.

The EC profiles obtained for the two test holes indicated unusually high variation of EC values, ranging from about 200 to nearly 5,500 uS/cm. An abrupt increase in water salinity occurred below depths of 170 ft in TH-18 and 140 feet in TH-19 (Figure 2). This abrupt change appears to mark a transition between the zones of fresh and mineralized (brackish) water circulations. The occurrence of mineralized water at a relatively shallow depth can be expected in a setting where a major river valley creates a large sink for a regional flow. Although analyses of major ions were not performed for samples of this mineralized water, the presence of gypsum infillings suggests that sulfate may be a dominant anion. High sulfate concentrations were reported in some areas within the Passaic Formation (Cook, 1885, p. 115-117; Carswell and Rooney, 1976), but at much greater depths than the depth of 140-170 feet at which mineralized water was encountered in the Raritan River valley.

Results of EC logging were used to select open intervals for monitoring well clusters which replaced the pilot holes. Since the zone of mineralized water was likely associated with a deeper, regional circulation originating from distant recharge areas, this brackish zone was not included in monitoring of effects of the relatively recent contamination possibly emanating from the industrial site. Consequently, open intervals of the deepest well of each cluster were positioned at the transition between the two zones. The strong EC gradient in the transition zone near a depth of 140 feet (Figure 2) corresponded to a depth at which a major bedding fissure was observed on the video log. This fissure was located just above the zone of gypsum-infilled fractures. At Cluster 18, the deepest well (MW-18C) straddled the large fissure found at 165 feet in hole TH-18.

In-Well Flow Tracing

Tracing of internal flows was performed in each of the pilot holes in order to measure the amount and direction of vertical crossflows and to obtain more information on the locations of major inflow and exit zone within each hole. A crossflow develops in a hole when fractures with different heads or permeabilities are connected by the hole.

In-well tracing was performed using methodology described by Michalski and Klepp (1990). Each test involved an injection of a 2.2 liter slug of saline solution (concentration of salt 15 g/l) into the water column. A modified Kemmerer sampler was used to release the tracer slug at a predetermined depth. The position of the tracer slug over time was tracked through repeated logging with the downhole EC probe. Several in-well flow tracing tests were performed, and the tracer slug was released at multiple depths.

Figure 3 presents an example of results of an in-well flow tracing performed within an upper segment of test hole TH-19. The tracer slug was released at a depth of 72 feet. A sequence of curves plotted represented consecutive images of the injected tracer slug, which were obtained through EC logging at different times after the tracer release. An analysis of these curves indicate that an upward flow occurred within the interval tested. Upward velocity and flowrate could be estimated (Figure 3) based on the slug migration data and the diameter of the hole. The positions of fluid exit zones (fractures) could also be ascertained. Such zones were recognized by the reduction of the remaining tracer mass (area under the curves) accompanied by the diminished vertical flow.

All four tests conducted in hole TH-19 indicated the occurrence of an upward flow. This flow originated below a depth of 118 feet (which was the lowest depth of tracer injection in this hole). The presence of upward flows in hole TH-19 pointed to the presence of a higher head in the zone of mineralized water intercepted by the lower segment of this hole. This higher head and an upward hydraulic gradient were produced by the location of the test hole in a regional discharge zone.

The hydraulics of Hole TH-18 was more complex and variable over time, possibly due to the influence of pumping at one of the Manville wells (Figure 1). Downward flow was measured in this hole below a depth of 140 feet, indicating that the highly transmissive fracture at 165 feet exerted a dominant influence on the hydraulics of this hole. While conducting one of the in-well flow tracings in this hole at depths 70-80 feet, a decrease in the amount of upward flow was noticed. This decrease was accompanied by a noticeable drop of water level in this hole. These effects suggest that the bedding fracture at 165 feet in Hole TH-18 might be hydraulically connected to one of the Manville wells. No such effects were observed for TH-18.

Installation of Monitoring Well Clusters MW-18 and MW-19

Upon sealing the two pilot holes, two clusters of monitoring wells (MW-18 and 19) were installed. Each cluster consisted of three monitoring wells, labelled A, B and C. Positions of open intervals for each well were selected based on analysis of video logs, the results of EC logging (Figure 2) and in-hole flow tracing (Figure 3). The length of open interval was less than 20 feet in each well. Six-inch casing was grouted in place above the open interval. Because an unusually high intake of grout occurred during sealing of test hole TH-18, the location of Cluster 18 was moved about 60 feet along the strike of beds from the former Test Hole location.

Short-Term Pump Tests in Deep Wells MW-19C and MW-18C

Concurrently with purging required as part of a standard sampling protocol, a short-term pump test was conducted in well MW-19C. No other well was purged prior to this test or during the pumping; thus, the pumping of well MW-19C was the only known hydraulic stress applied at that time. Similar short-term pumping (purging) was performed in well MW-18C.

During the first test, well MW-19C was pumped at a constant rate of 38 gpm using a submersible pump. The pumping lasted for 60 minutes. Water levels were monitored manually in the remaining five wells of the two clusters (MW-19B, MW-19A, MW-18C, MW-18B, and MW-18A). In addition, continuous, automated water level monitoring using pressure transducers was in effect in wells at the industrial site during the period of test pumping.

Graphical results of this short-term pump testing in MW-19C are presented in Figure 4, using standard semilogarithmic plots of drawdown versus time (Driscoll, 1989).

The principal objective of this testing was to determine the presence or absence of direct hydraulic connection between the pumped well and the observation wells. The presence of a direct hydraulic connection is inferred if an observation well responded to pumping with little delay and exhibited a significant drawdown. A delayed response to pumping stress, accompanied by a small drawdown, would be indicative of an indirect hydraulic connection (typical of "leaky" systems). The length of delay itself would be related to the degree of hydraulic connection and leakage.

During pumping in well MW-19C, the fastest responses were observed in observation wells MW-18C and the former production well PW-1 located at the industrial site (Figure 1). While MW-18C was located "only" 240 ft from the pumped well MW-19C (Figure 1), well PW-1 was about 1,500 ft away from the pumped well. A record of water levels in PW-1 on the day of pump testing is shown on Figure 5. This record indicates that the water level in PW-1 began to drop within several minutes after pumping in MW-19C had started. At the end of pumping in MW-19C, drawdown in PW-1 reached over 0.6 ft. This was a significant amount of drawdown, considering that drawdown measured in the pumped well was only 3.4 ft (Figure 4). The recovery of water level in PW-1 began as soon as pumping in MW-19C was terminated.

The fast response of PW-1 to pumping in MW-19C, coupled with significant drawdown produced in PW-1 during pumping and a fast response to the termination of the pumping, indicate the presence of a direct hydraulic connection between these two wells. Most likely, this connection is provided by a single bedding plane separation, as interpreted on the regional hydrogeologic section (Figure 6).

The hypothesis that a direct, single-fracture hydraulic connection exists between wells MW-19C and PW-1 is consistent with a very low value of storage coefficient obtained from analysis of the pump test data for observation well PW-1 (Figure 4; this well is located on the industrial site). In addition, video logs showed the presence of very large bedding fissures at the very bottom of well PW-1 and within an open interval of well MW-19C. The interpreted bedding fracture connecting wells MW-19C and PW-1 has an apparent dip of 7° to NE (Figure 1).

In contrast, the pumping results indicate that an indirect hydraulic connection exists between the pumped deep well (MW-19C) and the middle (MW-19B) and shallow (MW-19A) wells of this cluster. The responses observed in the latter wells (Figure 4) are indicative of a leaky type of vertical connection between open intervals of this cluster. These results are consistent with the notion of the Passaic Formation as a heterogeneous, multiunit and leaky aquifer system (Michalski, 1990).

Despite the short duration of the test pumping, the test results could be used to determine the aquifer parameters (transmissivity and storage coefficient) using the Jacob method of analysis (Figure 4). While approximating the test data by straight lines, early data were disregarded as being affected by casing storage effects. The transmissivity values obtained from Figure 4 are an order of magnitude larger than transmissivity values obtained for monitoring wells installed at the industrial site using data from slug tests and a 24-hour pump test.

The transmissivity values obtained for wells MW-19C, MW-18C and PW-1 (Figure 4) are nearly the same as an average transmissivity of 14,500 gpd/ft for well 10D in the Manville wellfield, as computed by Demicco and Schmidt (1987) based on results of their 72-hour pump test. However, while open intervals in wells MW-18C and 19C were less than 20 feet long, the length of open interval in Manville well 10D was more than 200 ft. This comparison of transmissivity values and lengths of open intervals between the two sets of wells provides a numerical confirmation that the deep well of Cluster MW-19 intercepts the most transmissive bedding fractures ever identified in the Raritan Valley in this area.

The second short-term pump test was conducted in well MW-18C a few hours after the first test. This well was pumped at the same constant rate of 38 gpm. The second test produced a drawdown of 0.15 ft in well PW-1 (Figure 5). The response of PW-1 to the second test was less pronounced than the response to the earlier pumping in well MW-19C. Therefore, one can infer an indirect character of hydraulic connection between MW-18C and PW-1, as illustrated on Figure 6.

With an exception of deep well PW-1, no other well located on the industrial site responded to the pumping in wells MW-19C and MW-18C. The lack of response in the shallow wells is indicative of a poor hydraulic connection between the shallow and deep zones at the industrial site.

Interpretation of Regional Hydrogeology and Contaminant Migration Pathways

The hydrogeologic section (Figure 6) was prepared to illustrate the dominant hydrogeologic features of the area. The section line selected (Figure 1) runs subparallel to Finderne Avenue from the Raritan River near the Manville well C-1 through well cluster MW-19 and well PW-1 on the industrial site. The total length of the section is over 3,000 ft. The section line is nearly perpendicular to the strike of the Passaic beds as measured in outcrops located along the river bank near the Finderne Avenue bridge and at a scarp near Historical Society House (Figure 1).

All major bedding plane separations indicated on the section were interpreted based on results of tests conducted in wells installed in the Raritan valley and at the industrial site. These tests included EC logging, in-well flow tracing and pump tests. The most transmissive bedding separations (discrete aquifer units) are identified on the section as Units 18 and 19 (named after well clusters they intersect). These aquifer units appear to be associated with bedding separations enlarged by stress-relief phenomena. No data on locations of major water-bearing zones were available for the Manville wells.

In the area of clusters 18 and 19, aquifer units 18 and 19 mark the transition between zones of fresh and brackish water circulation. Water in these highly transmissive units was found to be more mineralized than water in the overlying units. This was indicated by large differences in EC measurements between the deepest wells (MW-18C and MW-19C) and the remaining wells making up the 18 and 19 clusters (Figure 2).

It is postulated that aquifer units 18 and 19 in the vicinity of the clusters act as principal collectors of ground water flows from two geochemical regimes: the fresh water regime characterized by a shallow circulation and the regime of brackish waters ascending into the valley. An updip flow component along bedding separations may carry brackish water into the valley from large distances. In general, however, the dominant direction of ground water flow under non-pumping conditions is anticipated to be along the strike of beds and towards the viewer of the section (Figure 6). Ground water from Units 18 and 19 is thought to discharge into the river south of an island shown on Figure 1.

Data on the vertical gradient acquired from the well clusters appear to confirm the postulated hydraulic role of Units 18 and 19 as major interceptors of flows from both the fresh and the brackish zones. Water level elevations measured in the two well clusters on several occasions indicated the presence of a downward vertical gradient for both clusters. As the deepest wells in these clusters (MW-18C and MW-19C) were completed within the major discrete Units 18 and 19 at an upper boundary of the brackish zone (Figure 6), these wells did not penetrate into the brackish zone as the test holes did. The apparent reversal of vertical gradient in the clusters in relation to the pilot holes is explained by the different completion depth of the pilot holes and the well clusters.

CONCLUSIONS

The investigation conducted in the Raritan River valley indicate that ground-water flow in the Passaic Formation is of a highly discrete character. A few bedding plane fissures provide tabular conduits which attract the bulk of ground-water flow from adjoining beds. These major discrete aquifer units are found to be areally extensive and exhibit transmissivity values that are among the highest reported for bedrock aquifers within the Newark Basin.

The occurrence of mineralized ground water at relatively shallow depth is another distinct hydrogeologic feature of the area. The Raritan River valley provides a sink for regional ground water flow. The ascendancy of mineralized water into this sink is facilitated by the high transmissivity associated with major bedding plane fissure and by the subparallel alignment of the river valley with the strike of the Passaic beds.

The interpreted hydraulic connections between the contaminated industrial site and the Manville wellfield are poor and of indirect character. This indirect character results from the multiunit, heterogeneous structure of the bedrock aquifer system and its overall anisotropic behavior. While the preferential ground-water flow occurs along major bedding plane separations, a poor hydraulic connection and large dispersivity are characteristic for the direction normal to the strike. Together with the occurrence of a ridge of mineralized water ascending into the valley in-between the Manville wellfield and the industrial site, these factors appear to prevent any significant migration of contaminants from the industrial site toward the Manville wellfield.

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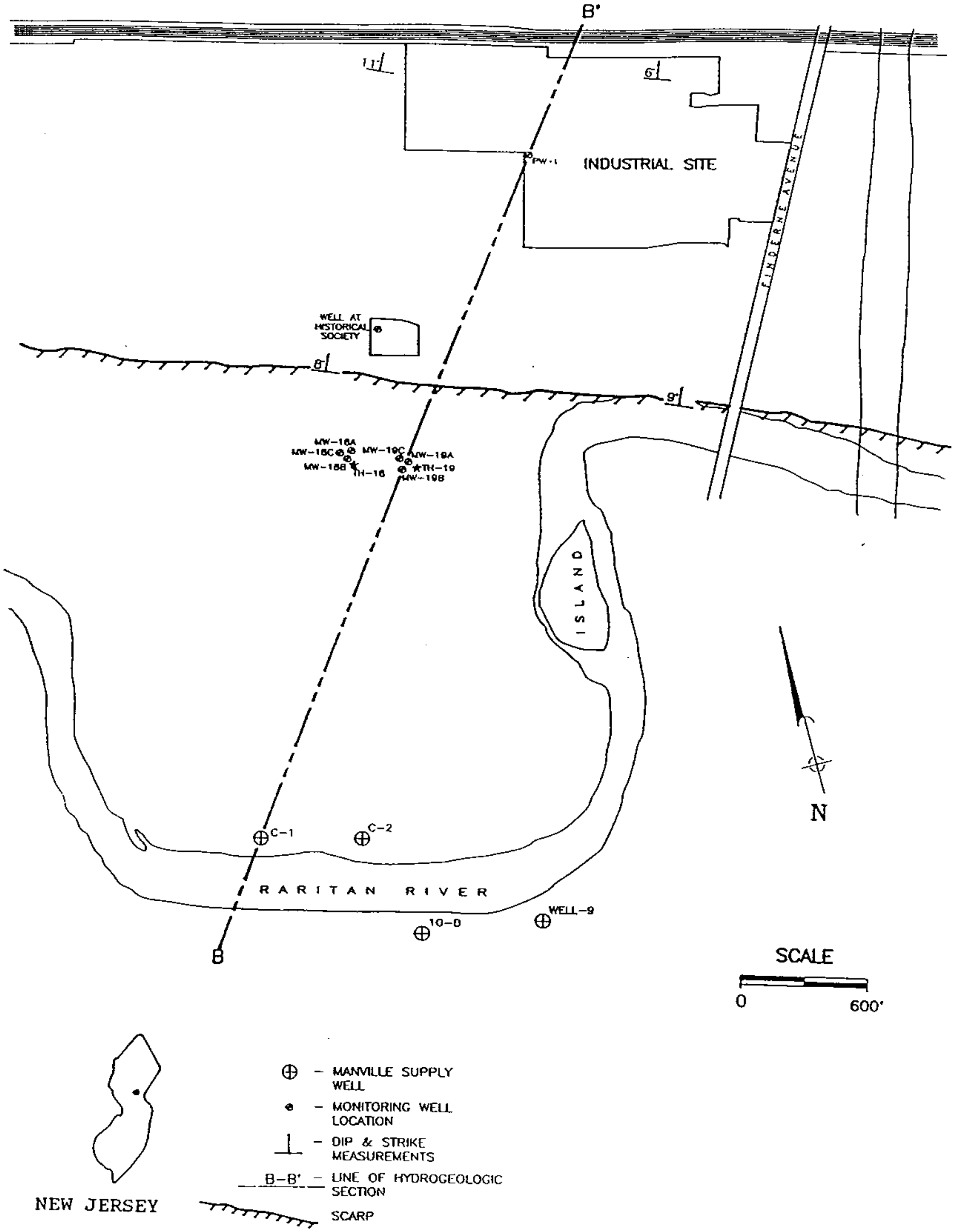


Figure 1. Site Location Map

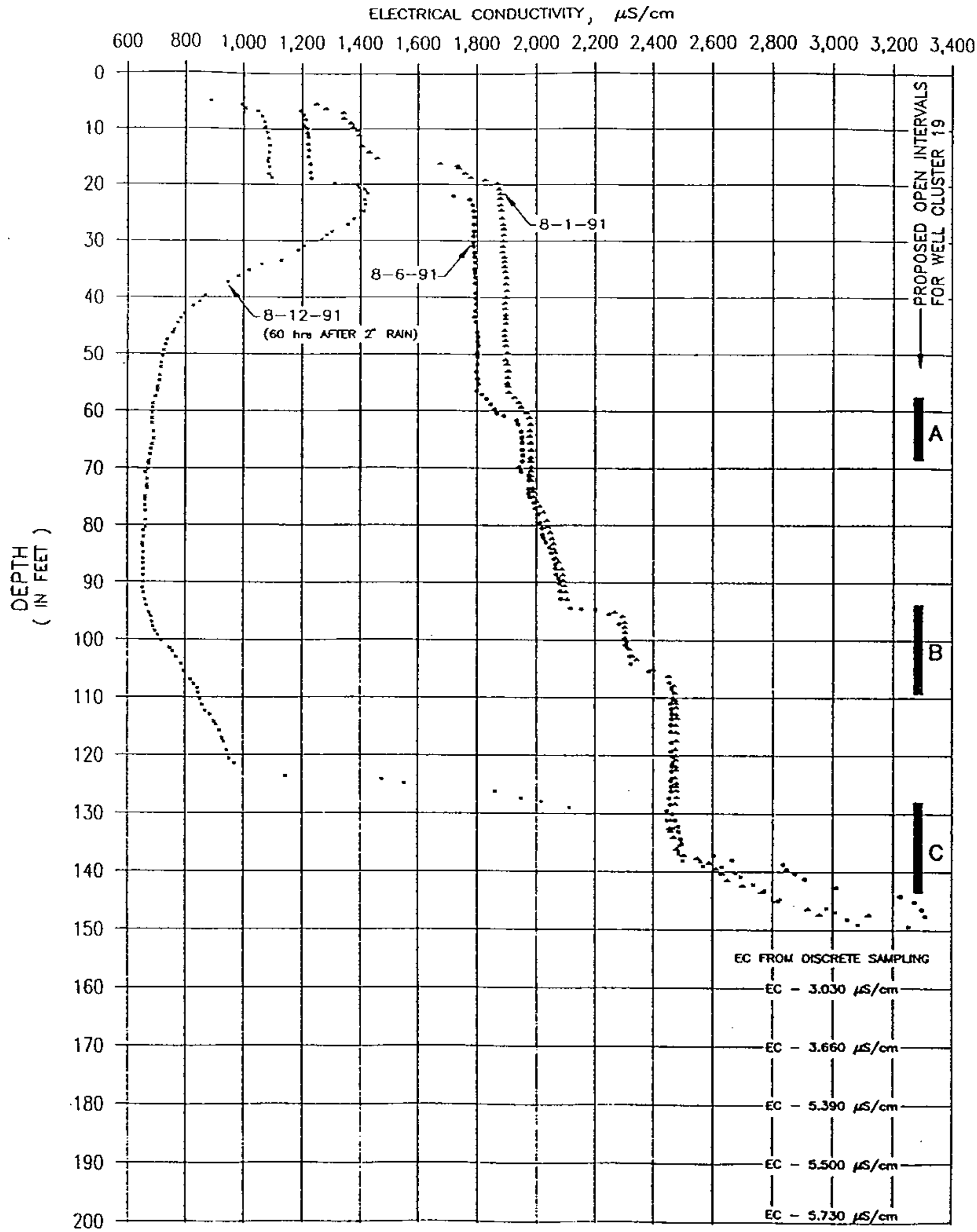
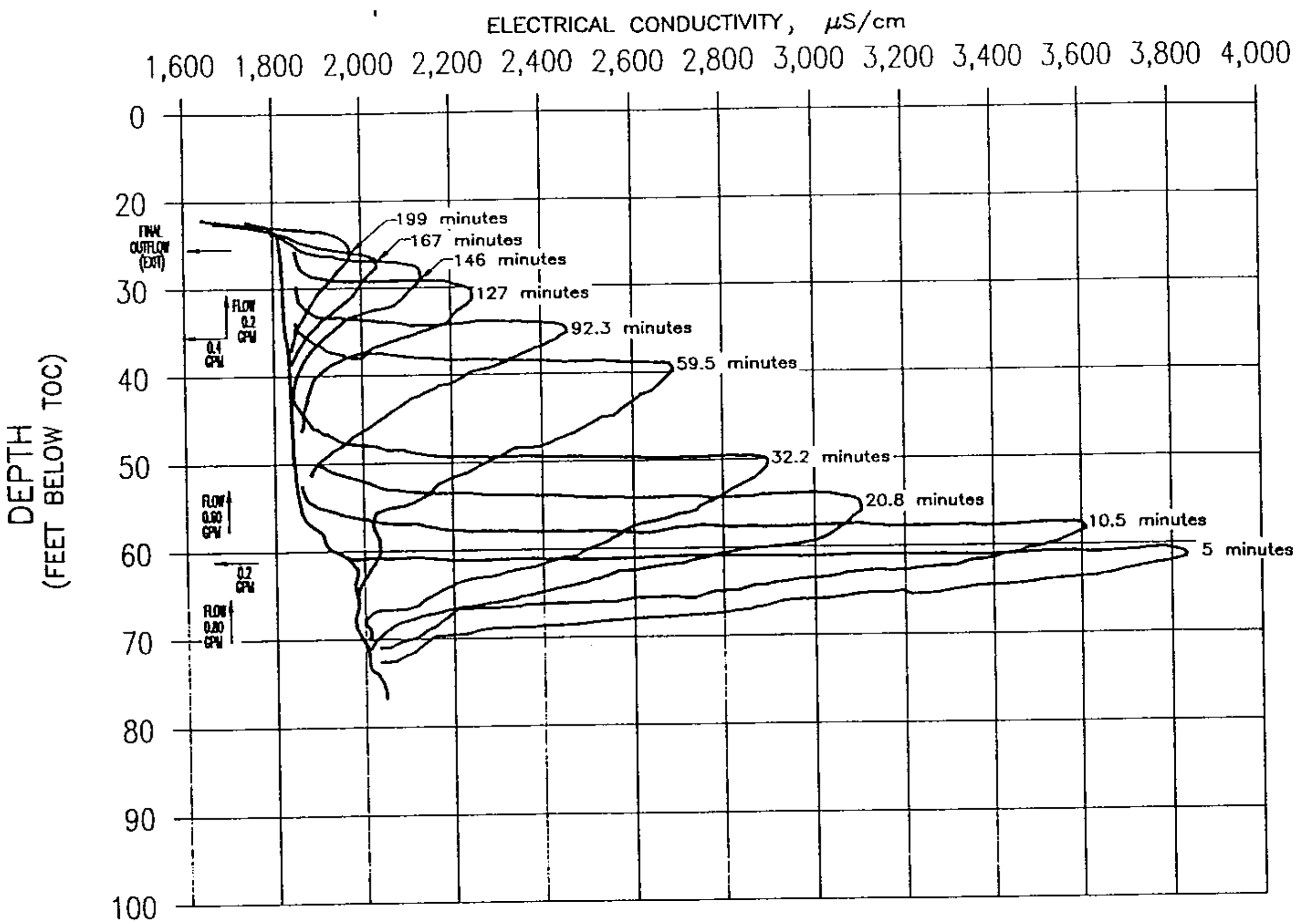


Figure 2. Electrical Conductivity (EC) logs for three dates in test hole TH-19. EC values below 150 feet were obtained through discrete sampling.



UPWARD VELOCITY AND FLOW COMPUTATIONS

TIME INTERVAL (MINUTES)	SLUG MIGRATION (FEET)		VELOCITY (FEET/MINUTE)	FLOW (GPM)
5.0 - 10.5	3.0		0.55	0.80
10.5 - 20.8	4.0	average	0.39	
20.8 - 32.2	5.0	0.41	0.44	0.60
32.2 - 59.5	11.0		0.40	
59.5 - 92.3	5.0	average	0.15	
92.3 - 127.0	5.0	0.15	0.14	0.22
127.0 - 146.0	3.0		0.16	

Figure 3. A sequence of images of the injected slug for various times after injection. In this test, the slug was released at a depth of 72 feet in test hole TH-19.

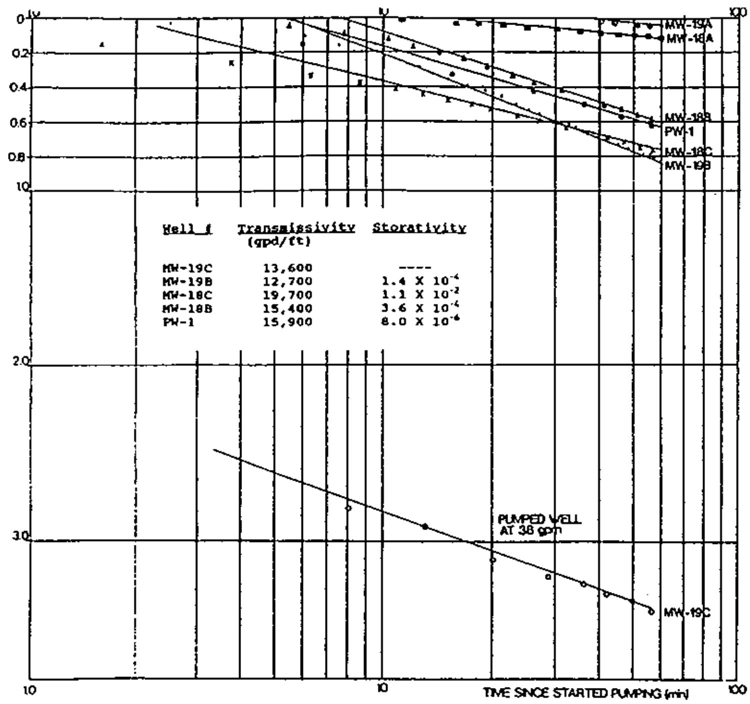


Figure 4. Semilog plots of drawdown in observations wells versus time for a short-term pumping test in well MW-19C.

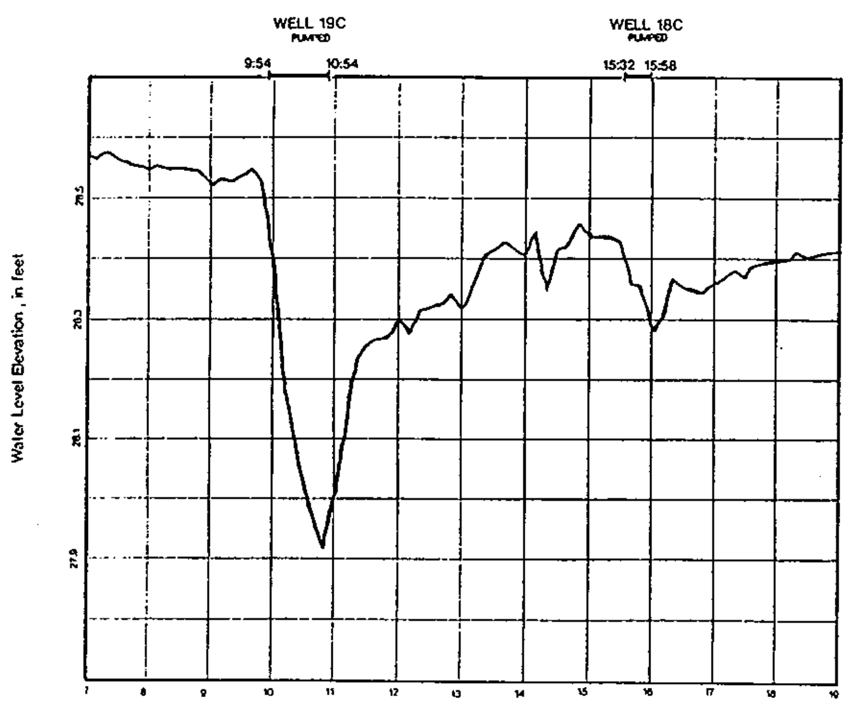


Figure 5. Record of water level elevations in observation well PW-1 for the day pumping tests were conducted in well MW-19C and MW-18C.

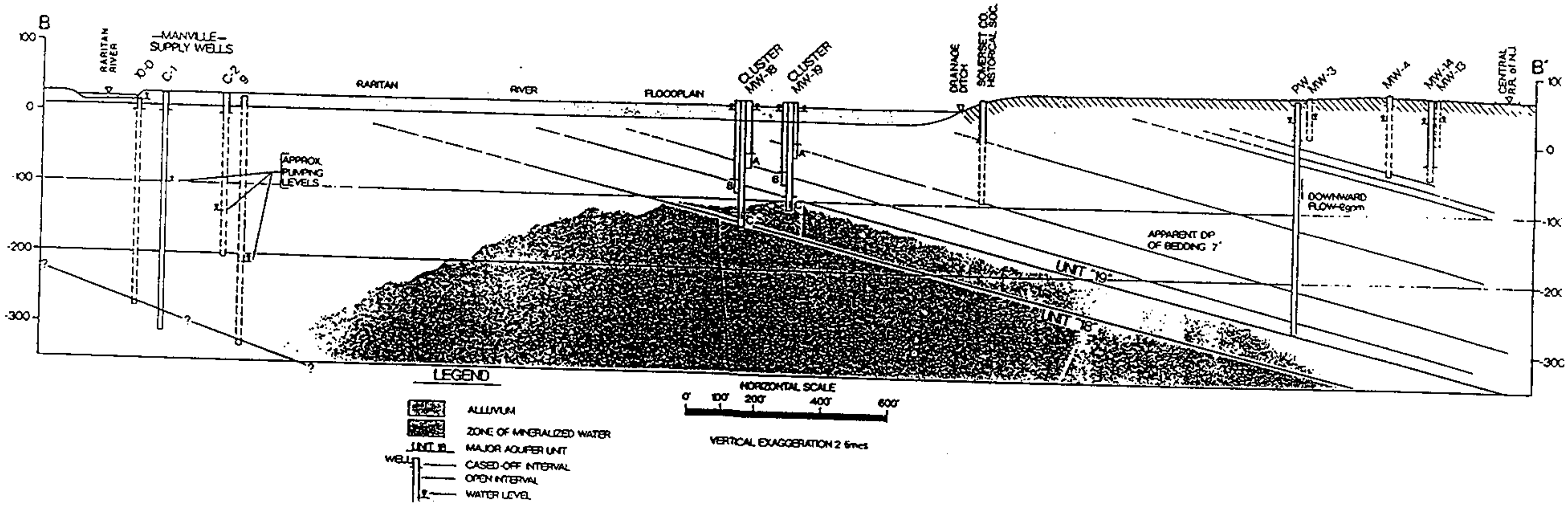


Figure 6. Regional Hydrogeologic Cross-section B-B′. Refer to Figure 1 for the location of the cross-section line.

EXERCISE

1) Draw a Pace Map of your permanent residence in the space below. Include the fractional scale, verbal scale and true north.

TOPOGRAPHIC MAP ANALYSES
BY DR. FRED GOLDSTEIN
PHYSICS DEPARTMENT
TRENTON STATE COLLEGE

A "HANDS-ON" SEMINAR INCLUDING THE FOLLOWING TOPICS:

1) Map Scales
2) Latitudes and Longitudes
3) Magnetic Declinations
4) Contour Intervals
5) Profiles
6) Gradients
7) Vertical Exaggerations
8) Drainage Patterns
9) Glacial Deposits
10) Shoreline Features

Maps of the Raritan River Basin will be used to illustrate these features.

(Presented at the Ninth Annual Meeting of the Geological Association of New Jersey
October 30, 1992)

TOPOGRAPHIC MAPS

There are three types of information that are ascertained through a study of topographic maps: *distance, location* and *elevation.*

DISTANCE

Distance on a map may be determined through the use of a *map scale.*

The *Map Scale* is the ratio of the distance on the map to the corresponding distance on the earth's surface.

The *Map Scale* may be expressed as a:

1) Verbal Scale: one inch on the map equals one mile on the earth's surface.

*2) Fractional Scale: 1/63,360 (where one inch on the map equal 63,360 inches, or one mile, on the earth's surface.)

*3) Proportional Scale: 1:63,360 (where one inch on the map equal 63,360 inches, or one mile, on the earth's surface.)

4) Graphic Scale: 0 1 2 3 4

(where one inch on the map equals one mile on the earth's surface.)

Exercises

1) Convert the following fractional scales into verbal scales.

FRACTIONAL SCALE		VERBAL SCALE	
a)	1/31,680	a)	______________________
b)	1/62,500	b)	______________________
c)	1/125,000	c)	______________________
d)	1/250,000	d)	______________________
e)	1/500,000	e)	______________________
f)	1/1,000,000	f)	______________________

*Sometimes the fractional scale of 1/62,500 and the proportional scale 1:62,500 are used in order to more easily facilitate the use of smaller scale maps.

2) Convert the following verbal scales into fractional scales.

VERBAL SCALE		FRACTIONAL SCALE	
a)	One inch equals ten feet	a)	__________
b)	One inch equals one hundred feet	b)	__________
c)	One inch equals one thousand feet	c)	__________
d)	One inch equals two thousand feet	d)	__________
e)	One inch equals one mile	e)	__________
f)	One inch equals sixteen miles	f)	__________

LOCATION

Location on a map may be ascertained through the use of longitude lines (meridians) and latitude lin (parallels).

Meridians run in a north-south direction, diverging at the equator and meeting at the geographic nor and south poles.

Parallels run in an east-west direction and are everywhere equidistant from each other.

Longitude is measured in degrees east and west of the Prime Meridian.

Latitude is measured in degrees north and south of the Equator.

Degrees of longitude and latitude are divided into minutes (60 minutes per degree) and seconds (60 secon per minute).

Topographic Maps are issued in 7½ and 15 minute series.

Maps in the 7½ minute series have dimensions of 7½ minutes of longitude by 7½ minutes of latitud

Maps in the 15 minute series have dimensions of 15 minutes of longitude by 15 minutes of latitude

This exercise is from "Introduction to Geology Workbook" by Fredric R. Goldstein, 1992, published by Kendall/Hunt Publ. Co., Dubugue, Iowa, 134p.

MAPPING EXERCISE

Locate the following National Parks on a map of the United States. Indicate the location, latitude and longitude of each area.

National Park	Location	Latitude and Longitude
Acadia	____________	________________________
Big Bend	____________	________________________
Bryce Canyon	____________	________________________
Carlsbad Caverns	____________	________________________
Crater Lake	____________	________________________
Everglades	____________	________________________
Glacier	____________	________________________
Grand Canyon	____________	________________________
Grand Teton	____________	________________________
Hawaii Volcanoes	____________	________________________
Hot Springs	____________	________________________
Katmai	____________	________________________
Mammouth Cave	____________	________________________
Mesa Verde	____________	________________________
Petrified Forest	____________	________________________
Redwood	____________	________________________
Rocky Mountain	____________	________________________
Yellowstone	____________	________________________
Yosemite	____________	________________________
Zion	____________	________________________

(Additional Mapping Exercises are located in Appendix A)

EXERCISE

1) Draw a Pace Map of your permanent residence in the space below. Include the fractional scale, verbal scale and true north.

ELEVATION

Elevation on a map may be indicated by colors or *contour lines*.

Maps that use colors to indicate changing elevations provide a *legend* that is used to match particular colors with specific intervals of elevation.

Shades of blue indicate depths below sea level; the darker the shade of blue, the greater the depth.

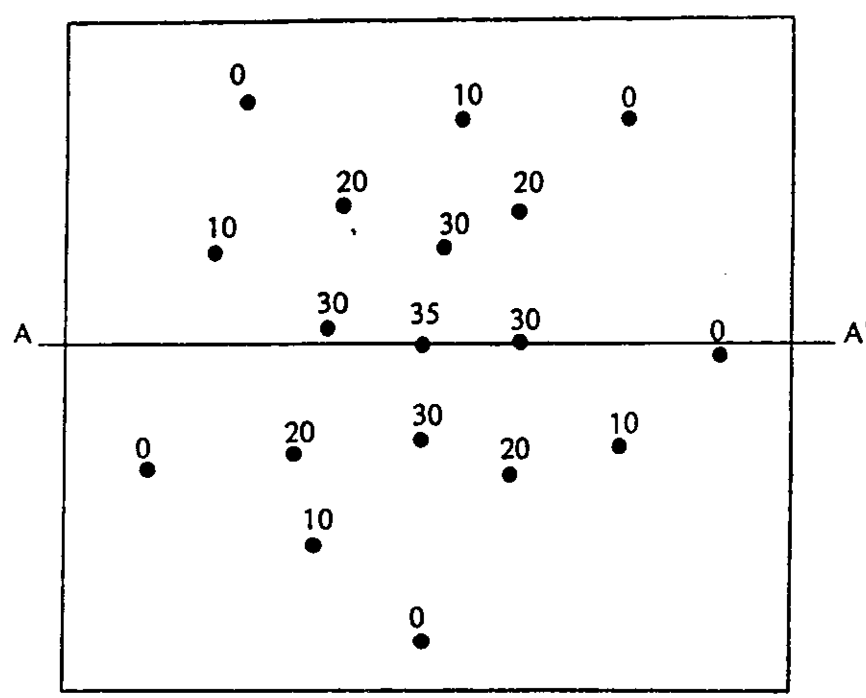
Increasing elevations above sea level are indicated by shades of green, yellow, orange, brown and finally red which indicates the highest area above sea level.

A *contour line* is an imaginary line on the earth's surface, every point on which is at the same elevation.

The *contour interval* is the vertical distance between two adjacent contour lines.

EXERCISE

Create a contour map of the area below by connecting points of equal elevation. Use a contour interval of ten feet.



There are a number of rules to keep in mind when working with contour maps.

1) Contour lines must be multiples of the contour interval.

2) Every fifth contour line is darkened and numbered.

3) Closely spaced contour lines represent steep slopes.

4) Widely spaced contour lines represent gentle slopes.

5) The area within a circular contour line is higher than the line itself.

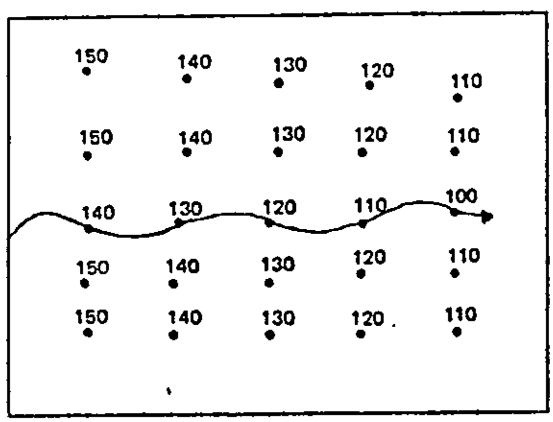
6) Depressions are indicated by hachured contour lines.

7) The area within a hachured contour line is lower than the line itself.

8) The elevation of a hachured contour line is the same as the regular line that surrounds it.

9) The elevation of a hachured contour line is one contour interval less than the hachured contour line that surrounds it.

10) Where contour lines cross a stream of a valley, they bend in the upstream or uphill direction.



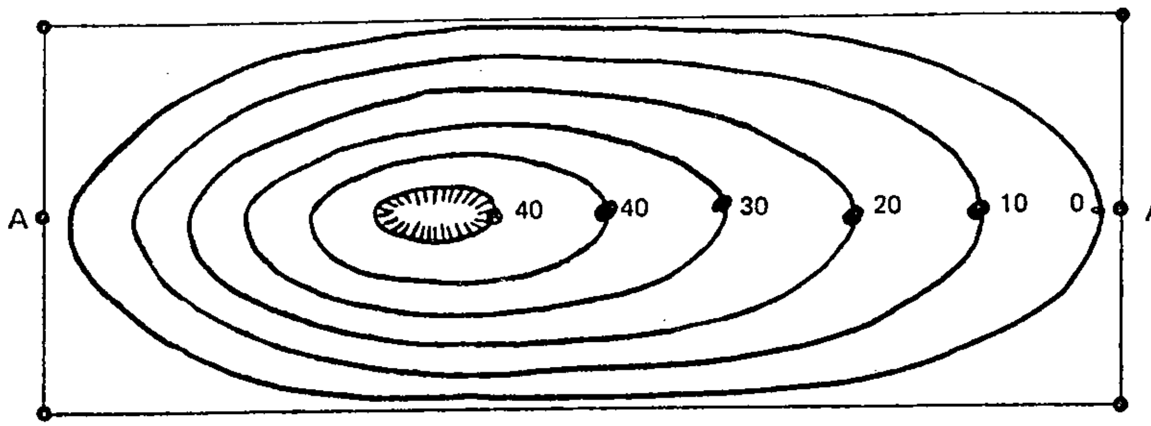
1) Draw a contour map of the above area, using a contour interval of 10 feet.

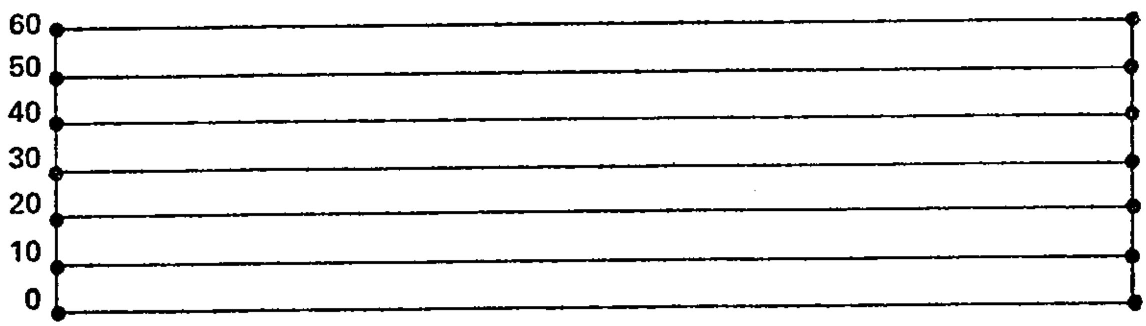
2) Which would be an appropriate contour interval for a map of the Rocky Mountains....
___ 5 feet, ____ 20 feet, or ____ 100 feet?

3) Which would be an appropriate contour interval for the Bonneville Salt Flats....
____ 5 feet, ____ 20 feet, or ___ 100 feet?

4) Which would be an appropriate contour interval for Trenton, New Jersey....
____ 5 feet, ____ 20 feet, or ____ 100 feet?

CONSTRUCTING PROFILES FROM TOPOGRAPHIC MAPS





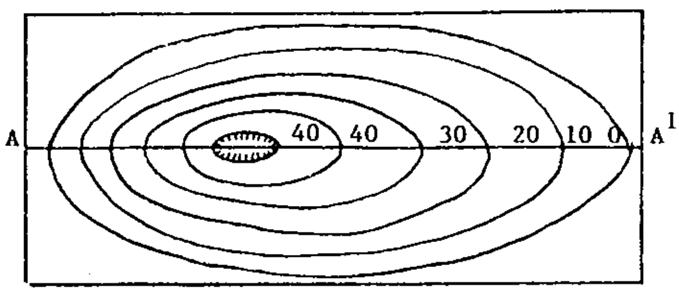
Construct a profile of the contour map above by following the instructions below.

1) Draw a straight line (profile line) from A to A'.

2) Mark each intersection of the straight line (profile line) and contour lines with a small "x".

3) Draw a light construction line connecting each "x" with a point on the grid *directly below the* "x" at the corresponding elevation.

4) Connect the dots on the grid following the rules on page 40.


A
40
40
30
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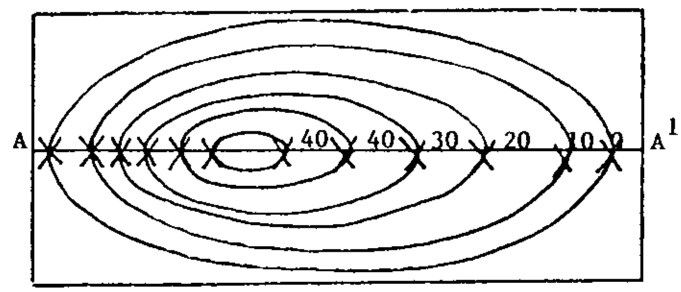
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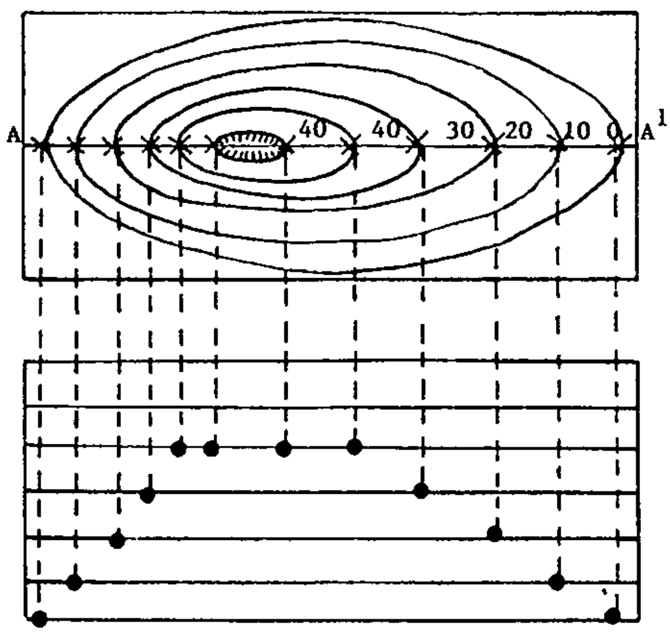
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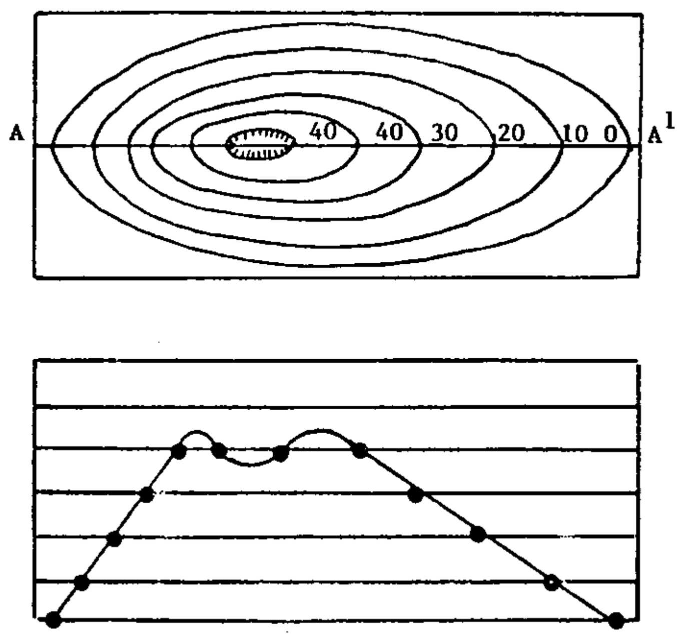
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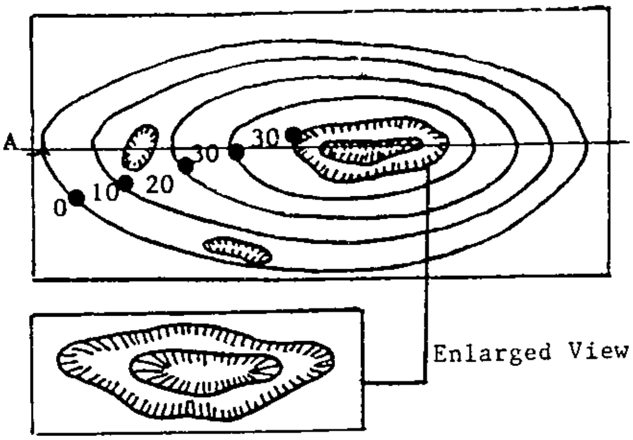
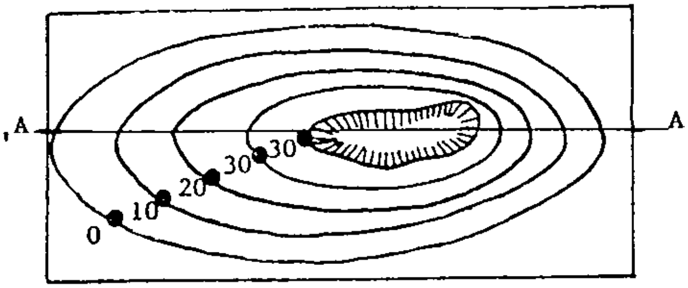
EXERCISES

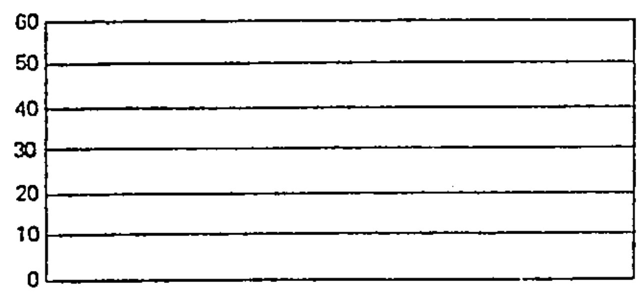
Construct profiles on the maps below from A to A'.





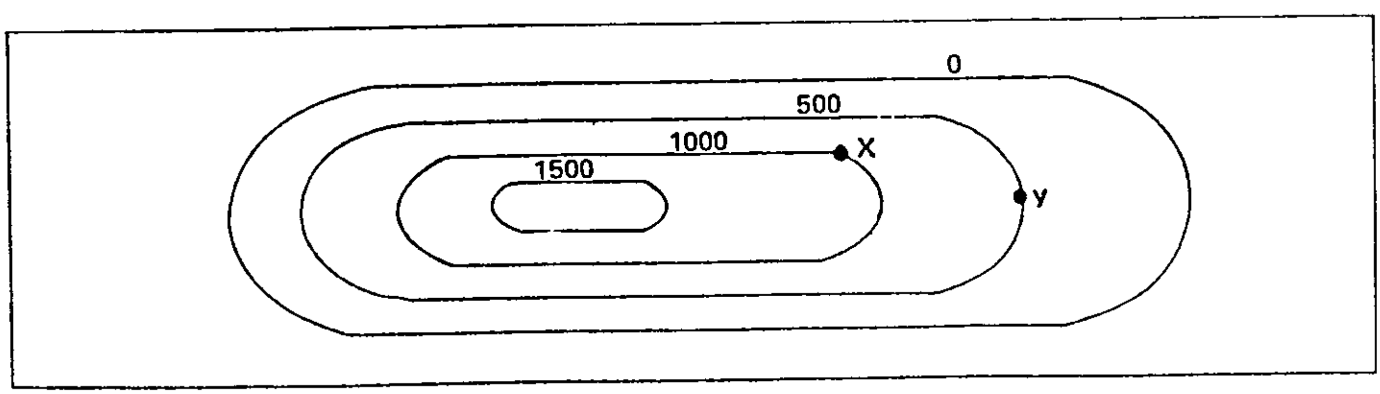
CI = 10 feet

CI = 10 feet



Gradient

The change in elevation between two points as compared to the distance that separates those same two points is referred to as the *gradient*. The gradient may be reported in *feet per mile*, as a *percentage* or in *angular degrees*. Your instructor will indicate and illustrate the method for reporting gradient for your class.

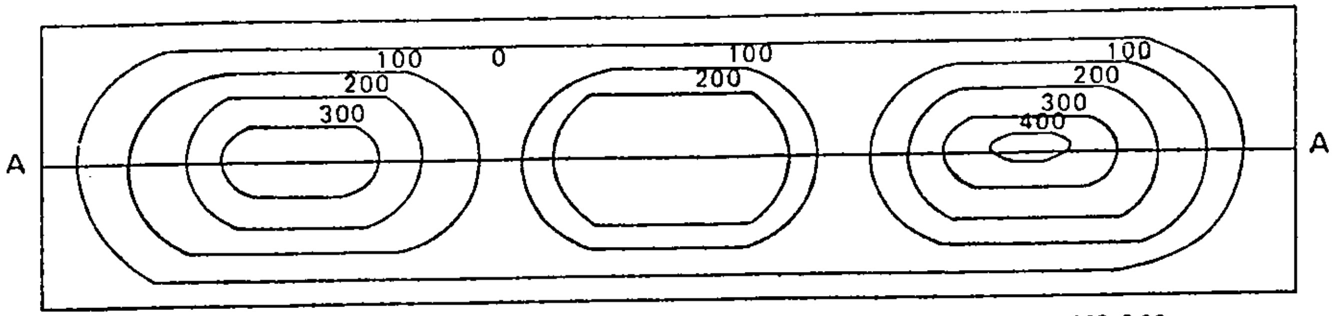


The gradient from "x" to "y" is: Fractional scale 1/63,360

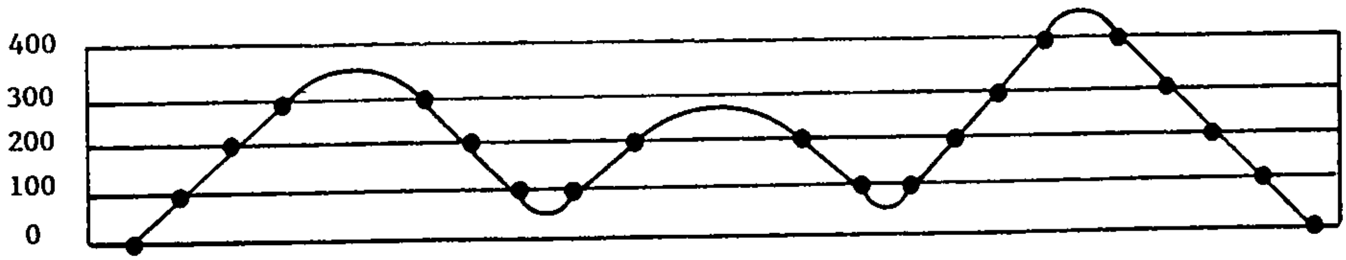
a) 1,000 feet - 500 feet/1 mile = 500 feet per mile
b) 1,000 feet - 500 feet/1 mile = 500 feet/5280 feet = 9.47 percent
c) 1,000 feet - 500 feet/1 mile = 500 feet/5280 feet = .0947
The angle whose tangent is .0947 is approximately 5½ degrees

Vertical Exaggeration

The ratio between the vertical scale on the grid and the horizontal scale on both the map and the grid is called the *vertical exaggeration* of the profile.



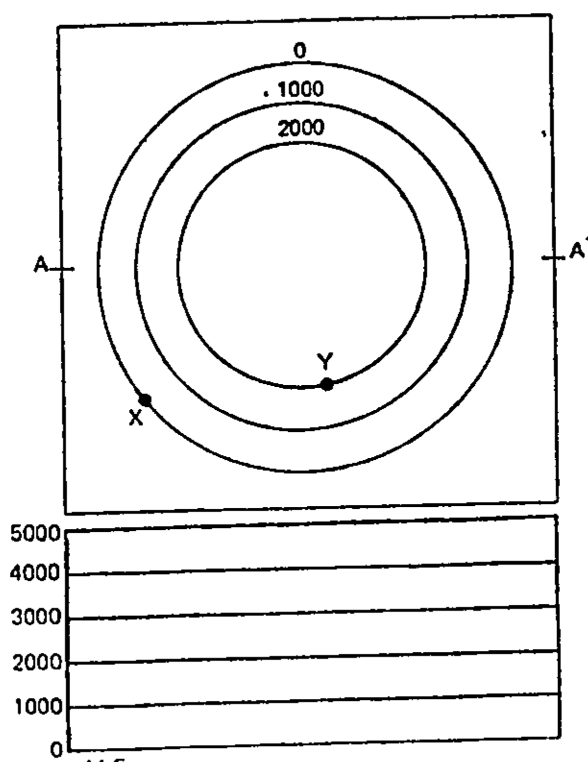
Fractional scale 1/63,360



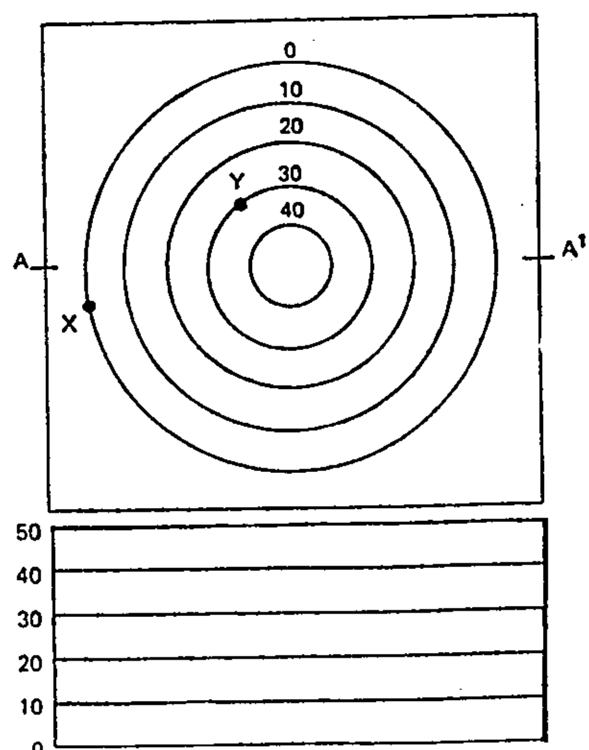
The vertical scale of the profile above is 1 inch=400 feet. The horizontal scale of the profile is 1 inch 5,280 feet. The *vertical exaggeration* is (1/4,800) ÷ (1/63,360) = 13.2.

EXERCISES

Construct profiles of the maps that appear below. Compute the vertical exaggeration of each profile and the gradient from "x" to "y" on each map using a verbal scale of one inch equals two miles.



V.E. =
Gradient (x-y) =



V.E. =
Gradient (x-y) =

CAMPUS QUADRANGLE
TOPOGRAPHIC MAP EXERCISES

GENERAL INFORMATION

1. What is the name of this map?

2. In which year was this map published?

3. What is the verbal map scale?

4. How many square miles are included in this map?

5. What is the magnetic declination of this map?

6. What does that mean?

LATITUDE

7. What is the latitude of the northern parallel of this map?

8. What is the latitude of the southern parallel of this map?

9. How can you determine if these parallels are northern or southern latitudes?

10. How many minutes of latitude does this map contain?

LONGITUDE

11. What is the longitude of the eastern meridian of this map?

12. What is the longitude of the western meridian of this map?

13. How can you determine if these meridians are east or west longitude?

14. How many minutes of longitude does this map contain?

LOCATION

15. Where in this state is this map located?

16. Which areas are located adjacent to your map? (Please use the diagram below to complete this answer.)

N.W.	N.	N.E.
W.		E.
S.W.	S.	S.E.

17. Your map may be divided into 9 sections, each section will measure 2' 30" of latitude by 2' 30" of longitude. (Use a pencil and ruler to divide your map.)

18. What is the contour interval of this map?

19. What is the highest possible elevation on this map?

20. In which section is it located?

21. What is the lowest possible elevation on this map?

22. In which section is it located?

23. Locate a major river or stream in this area. In which section is it located?

24. In which direction is it flowing?

25. How can this be determined?

ESSAY:

Discuss the geological and environmental features that are located on this map.

HOMETOWN QUADRANGLE
TOPOGRAPHIC MAP EXERCISES

GENERAL INFORMATION

1. What is the name of this map?

2. In which year was this map published?

3. What is the verbal map scale?

4. How many square miles are included in this map?

5. What is the magnetic declination of this map?

6. What does that mean?

LATITUDE

7. What is the latitude of the northern parallel of this map?

8. What is the latitude of the southern parallel of this map?

9. How can you determine if these parallels are northern or southern latitudes?

10. How many minutes of latitude does this map contain?

LONGITUDE

11. What is the longitude of the eastern meridian of this map?

12. What is the longitude of the western meridian of this map?

13. How can you determine if these meridians are east or west longitude?

14. How many minutes of longitude does this map contain?

LOCATION

15. Where in this state is this map located?

16. Which areas are located adjacent to your map? (Please use the diagram below to complete this answer.)

N.W.	N.	N.E.
W.		E.
S.W.	S.	S.E.

17. Your map may be divided into 9 sections, each section will measure 2' 30" of latitude by 2' 30" of longitude. (Use a pencil and ruler to divide your map.)

18. What is the contour interval of this map?

19. What is the highest possible elevation on this map?

20. In which section is it located?

21. What is the lowest possible elevation on this map?

22. In which section is it located?

23. Locate a major river or stream in this area. In which section is it located?

24. In which direction is it flowing?

25. How can this be determined?

ESSAY:

Discuss the geological and environmental features that are located on this map.

GEOLOGY, GEOMORPHOLOGY, AND LAND USE

Gail M. Ashley

Dept. of Geological Sciences

Rutgers University

The Raritan River, located in central New Jersey, drains 14% of the state and is approximately 2,862 km^2 (1,105 mi^2) in area. It is the largest river system wholly contained in New Jersey (Fig. D1). The Raritan rises on the east slope of the Appalachian mountain chain and flows over 100 km eastward into the Atlantic. The major tributary sub-basins are shown on Figure D2, the drainage patterns on Figures D3 and D4, and a comparison of sub-basin characteristics in Table I. The largest sub-basin is the Millstone River (743 km^2), followed by South Branch Raritan River (722 km^2), North Branch Raritan River (492 km^2), South River (344 $km^{2)}$, Green Brook (169 km^2), and Lawrence Brook (116 km^2). The main trunk stream of the Raritan and its tributaries are tidal below the Fieldville Dam located 24 km above the rivers's mouth (Raritan Bay).

The basin is underlain with a variety of rock types (Fig. D5). Headwaters of the North and South Branches are in the Highlands Province composed of resistant metamorphic and igneous crystalline rocks of pre-Cambrian and lower Paleozoic age overlain in the northern portion by Quaternary-age glacial sediments. The branches flow across the western portion of the 50 km-wide Piedmont Province underlain with Jurassic volcanics and (red) sandstones and shales and join near Branchburg to form the main trunk of the Raritan. The strike of the redbeds is NE-SW and they dip to N-NW at 15-20 degrees. The Millstone River and Green Brook-Bound Brook flow mainly on these red beds joining the Raritan at Manville and Bound Brook, respectively. Just downstream from New Brunswick, the Raritan crosses onto the Cretaceous and Tertiary unconsolidated sediments of the Inner Coastal Plain. The South River basin is entirely within the Coastal Plain, whereas Lawrence Brook flows across the boundary on both Piedmont and Coastal Plain rocks. The

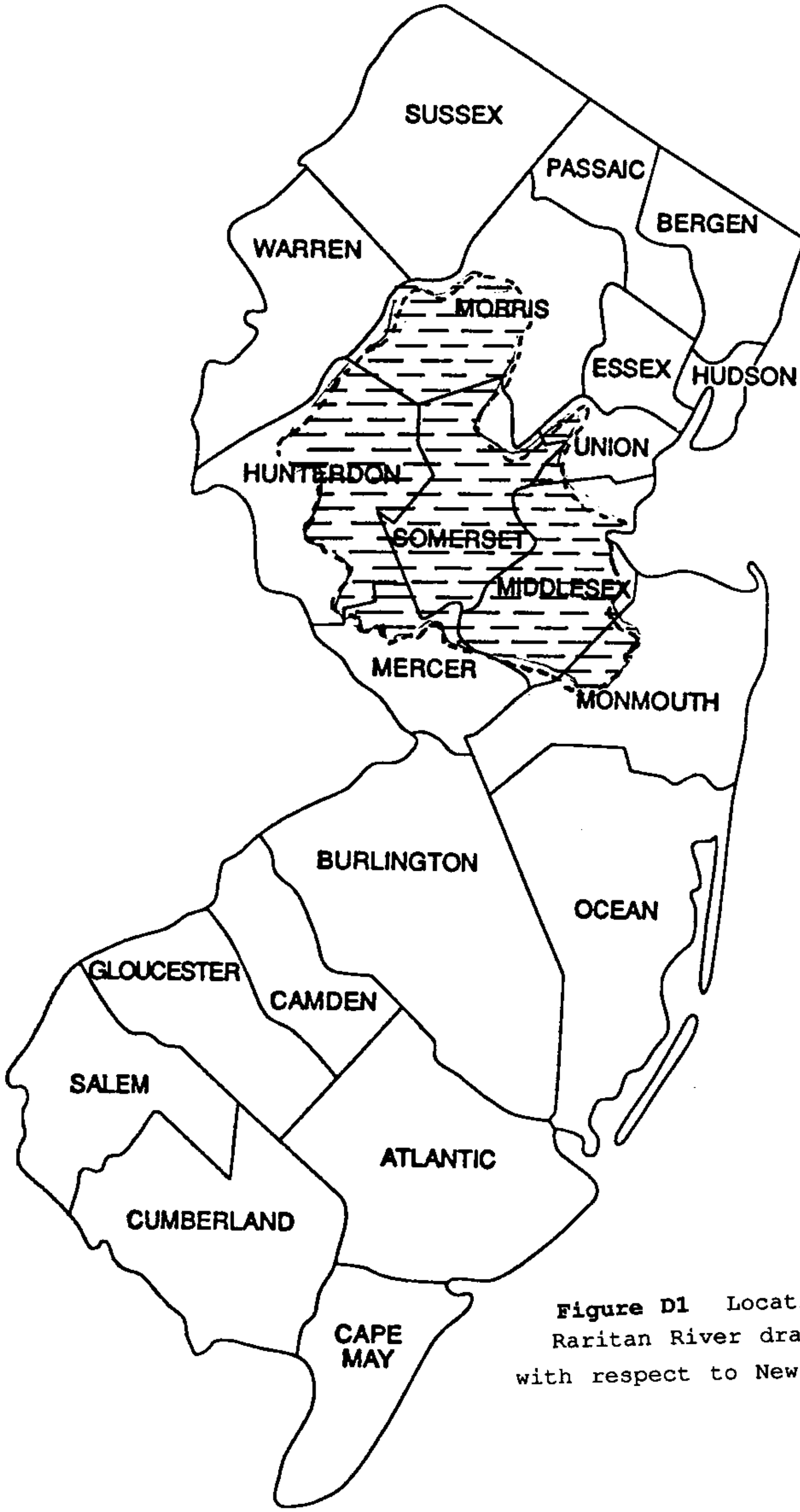


Figure D1 Location of the Raritan River drainage basin with respect to New Jersey counties.

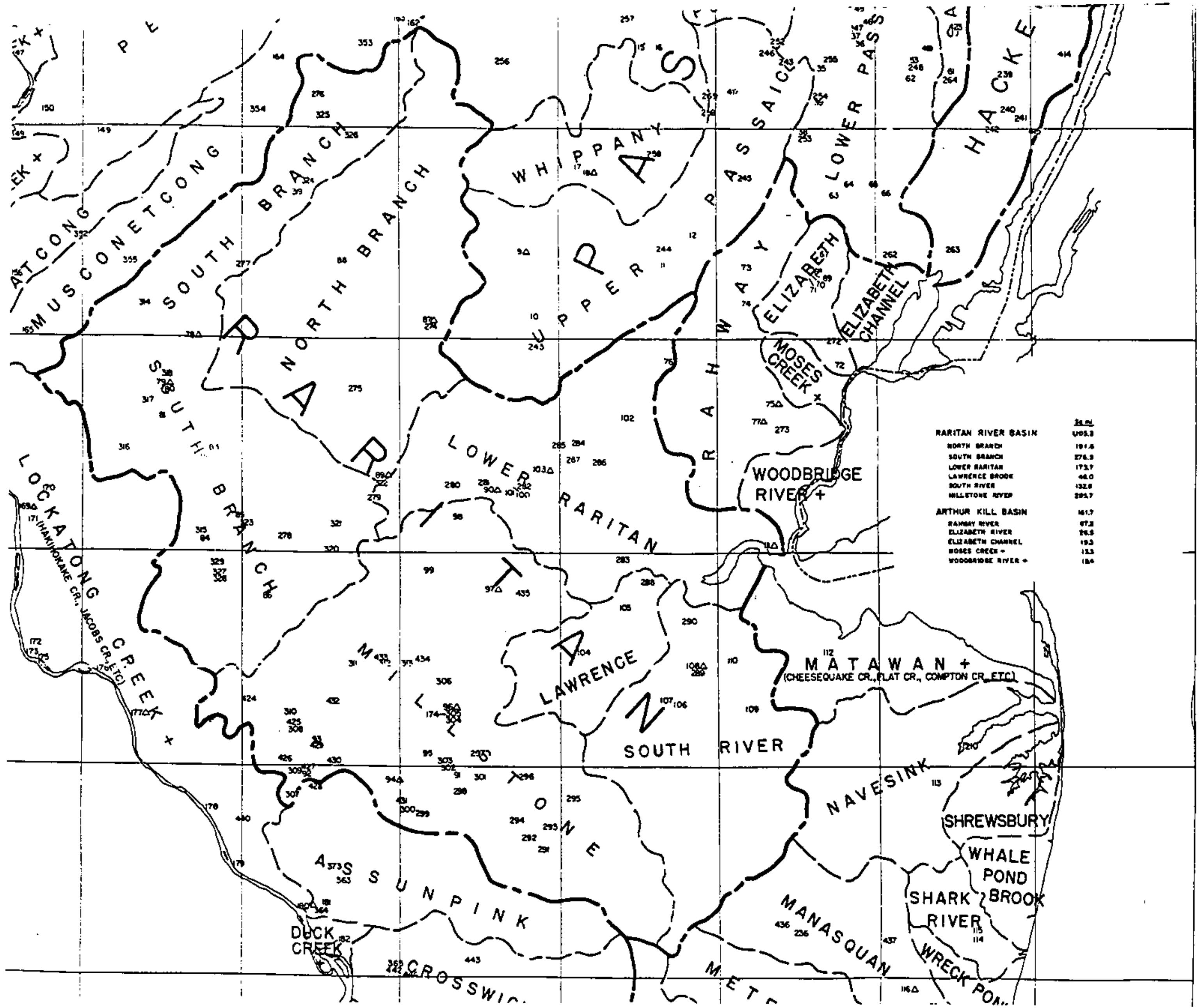


Figure D2 Map shows sub-basins within the Raritan River drainage basin.

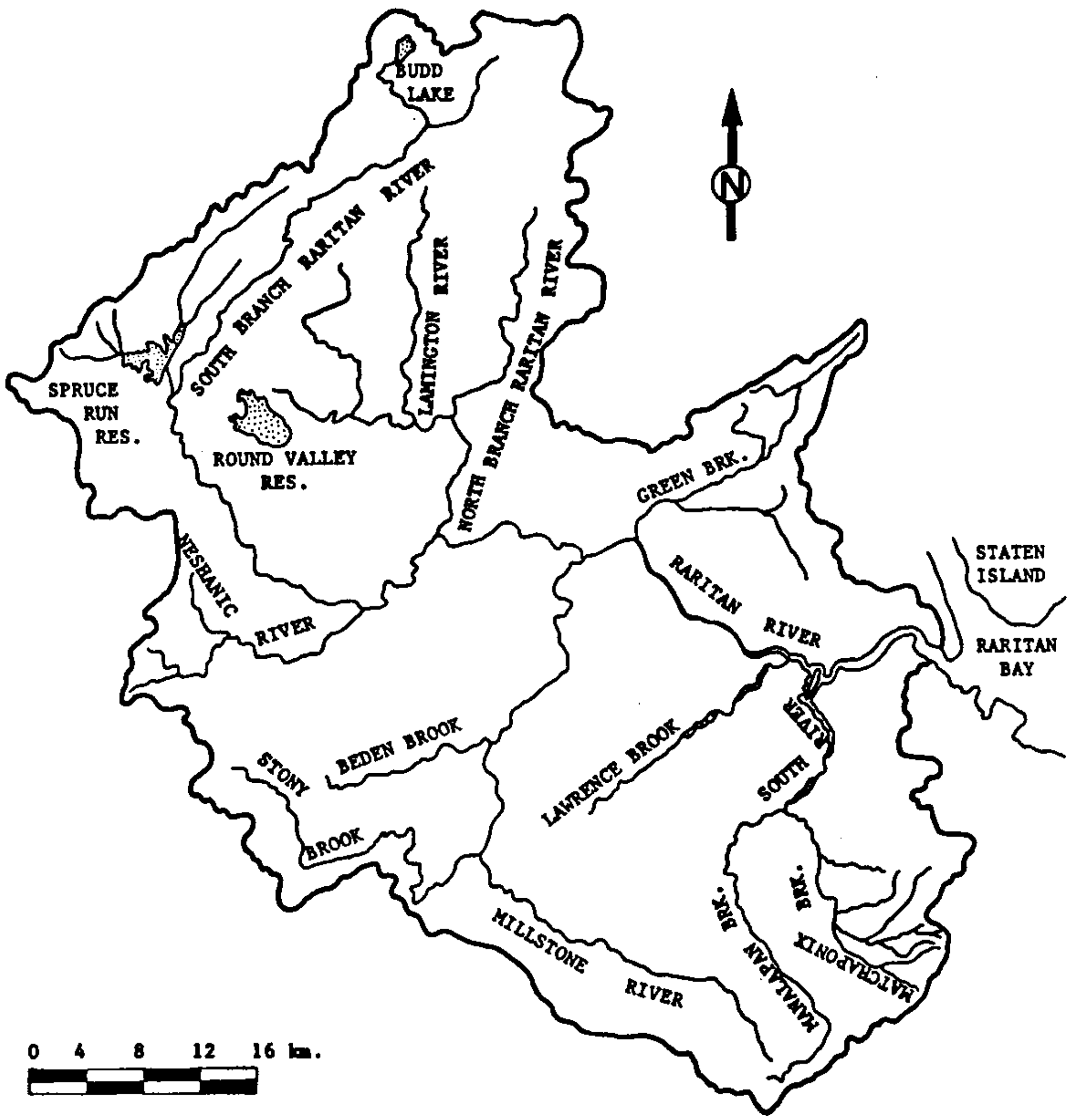


Figure D3 Map of the tributary system of the Raritan River.

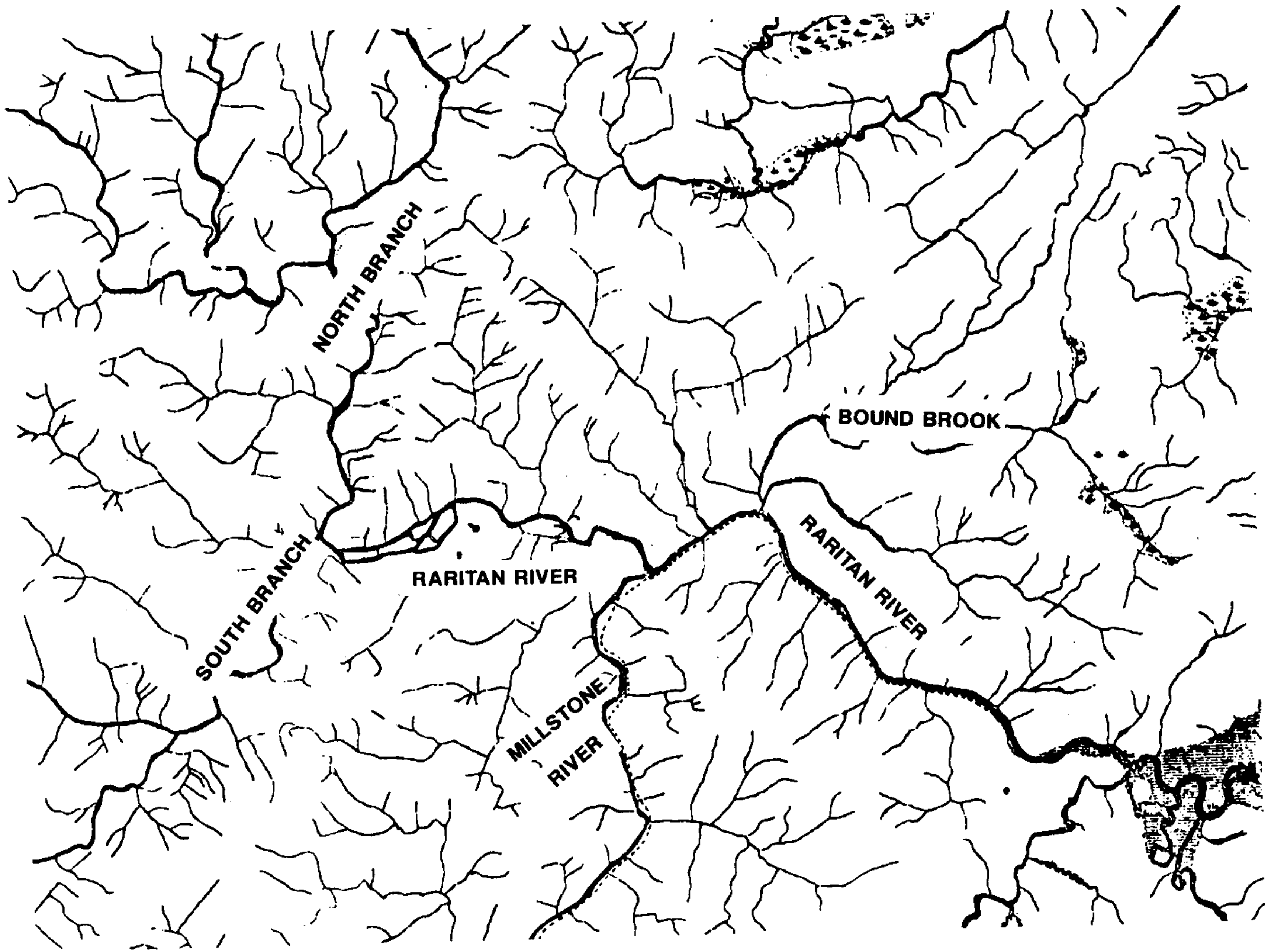


Figure D4 Drainage network of the Raritan River with major tributaries labled.

Table I Physical, cultural, and lithologic characteristics of the Lower Raritan (LR), Upper Raritan (UR), Millstone River (MR), and Bound Brook (BB) basins.

Physical Features	LR	UR	MR	BB
Basin Area (km^2)	2253	1269	702	169
Mean Annual Discharge (cms)	38.1	21.8	11.3	2.9
Mean Study Discharge (cms)	35.0	24.0	11.0	2.8
Mean Monthly High Q (March)	69.0	39.0	21.0	3.5
Mean Monthly Low Q (Oct.)	21.0	12.0	6.0	2.1
Main Channel Slope	0.0031	0.0041	0.0011	0.0027
Basin Surface Storage*	0.146	0.095	0.223	0.242
Hydrologic Behavior**	Normal	Normal	Sluggish	Flashy

Cultural Features	LR	UR	MR	BB
%Forested	33	37	30	20
%Agricultural	48	52	54	4
%Urban#	19	11	16	76
%Impervious Area##	10	7.5	8.5	25
%Wastewater (base Q)###	47.2	14.2	66.6	2.1
%Wastewater (median Q)###	5.0	1.8	7.1	0.2
%Wastewater (high Q)###	1.4	0.5	2.0	0.05
Population####	611	217	142	229
Population Density (/km^2)	271	171	203	1354
Population Density (/mi^2)	702	443	523	3520

Lithologic Features@	LR	UR	MR	BB
%pre-Cambrian gneiss	21	37	-	-
%Jurassic Red Beds	45	44	41	72
%Jurassic Basalt	6	1	-	28
%Jurassic Diabase	3	1	7	-
%K-T Coastal Plain Seds.	12	-	39	-
%C-O Carbonates	2	3	-	-
%other@@	11	13	14	-

* = percent impoundment + lake area
** = relative behavioral changes in discharge in response to precipitation

= industrial + residential (1976 NJDEP Land Use Map)
= from Stankowski (1974), using 1980 population data
= maximum estimated values based on NJPDES discharge permits (from Pavlowsky, personal communication)
= 1980 U.S. Census

@ = by areal coverage
@@ = Paleozoic and Mesozoic Clastic Sedimentary Rocks

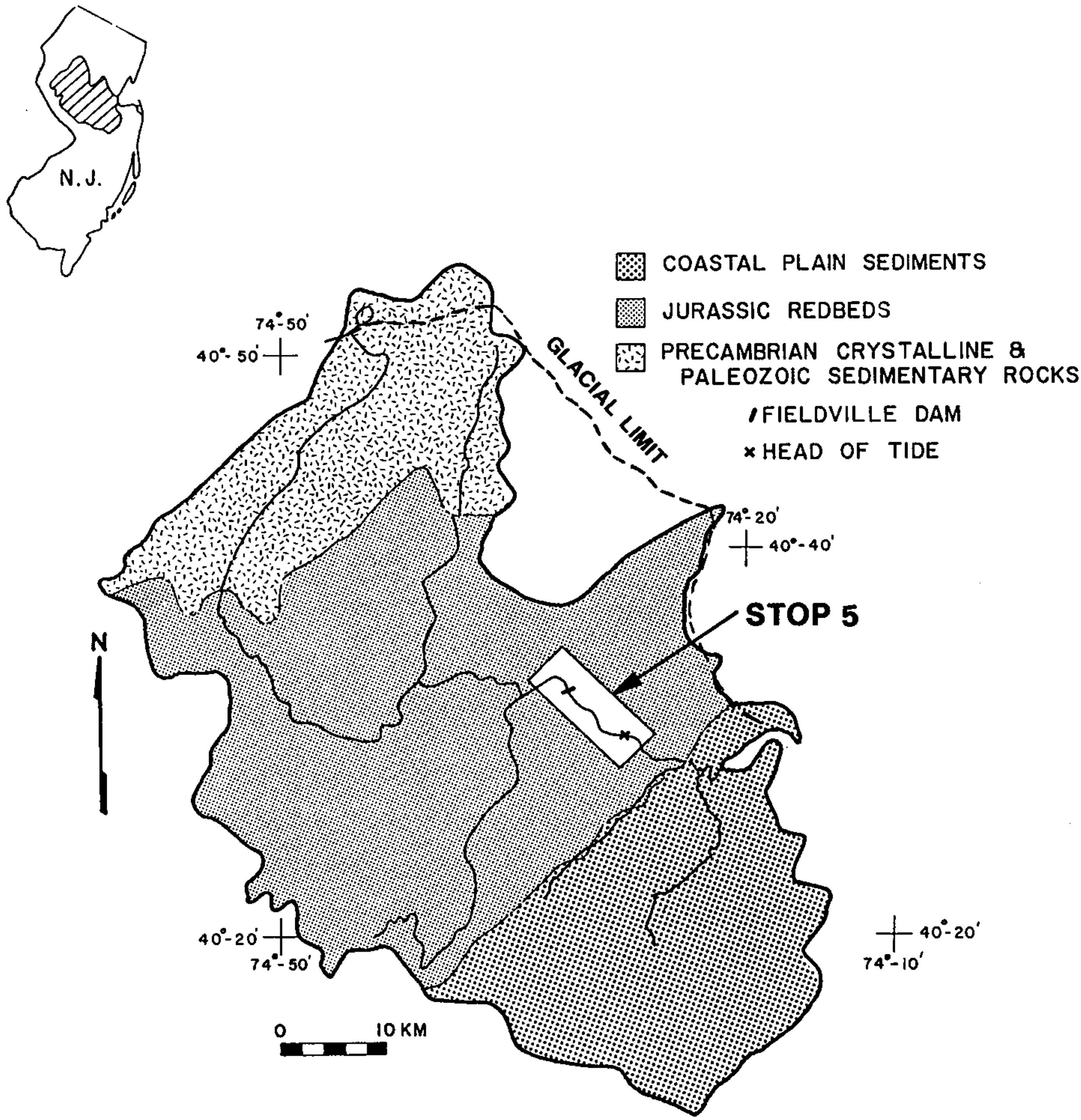


Figure D5 Geologic map of the Raritan River drainage basin depicting the area underlain by crystalline rocks (Highlands Province, Jurassic redbeds (Piedmont Province) and Cretaceous and Tertiary sediments (Inner Coastal Plain). The limit of the last glaciation appears as a dashed line.

longitudinal profiles of the Raritan tributaries reflect the resistance of underlying bedrock; steeper gradients occur in areas of basalt and gneiss, whereas less steep gradients occur in areas of shale, sandstone, and unconsolidated silt and clay (Fig. D6).

Channel geometry and grain size of river bed are highly variable throughout the drainage system (Fig. D7). In the headwaters, flow is in a single channel and the stream bed is gravel but changes downstream (50 km from the river mouth) to a bedrock-floored channel, or gravel patches over bedrock. At 23 km from the mouth the river is a multiple-channel (braided) gravel-bed system. Grain size decreases to sand downstream and the fluvial style changes from braided through high-sinuosity meandering to low-sinuosity meandering channel at the river mouth.

Like all rivers, the channel of the Raritan was (and is being) formed by the water flowing in it (Fig. D8). Fluvial processes in turn are influenced by tectonic activity, underlying bedrock, relatively recent events such as glaciation and modern factors such as land use and river engineering (dams, bridges and dredging). All have affected the Raritan River as we know it today. The field trip will provide an overview of the environmental geology of the Raritan River system by examining the geology and surface hydrology, as well as the effects of humans since european colonization. Although we recognize groundwater hydrology to be an important aspect of the Raritan River Basin it is beyond the scope of this trip.

Climate

The climate of the Raritan River Basin is similar to that of the entire Middle Atlantic seaboard. Marked changes of weather are frequent, particularly during the spring and fall. Average annual temperature varies from 49°F to 53°F with extremes ranging from 24 degrees below measured at Long Valley, NJ to 109 degrees above at Somerville, NJ. The growing season averages 274 days and the mean annual relative humidity varies from 67 to 71%. Prevailing winds are from the northwest with an average annual velocity of about 12 miles per hour.

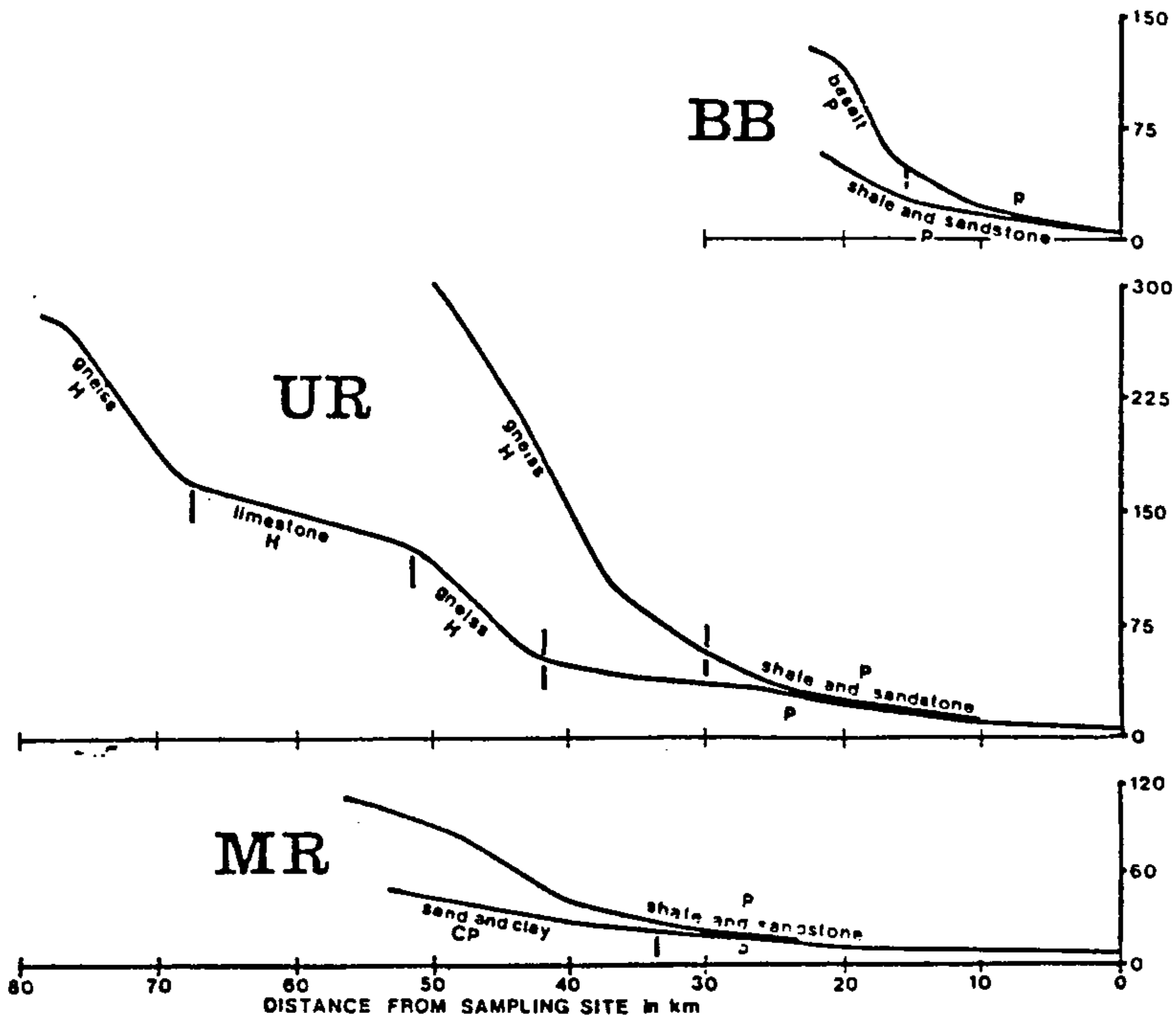


Figure D6 Main channel profiles and underlying types of the major tributaries in the Raritan Basin. BB=Bound Brook; UR=Upper Raritan (North and South Branch); MR=Millstone River. Geologic units are designated H for Highlands, P for Piedmont and CP for Coastal Plain.

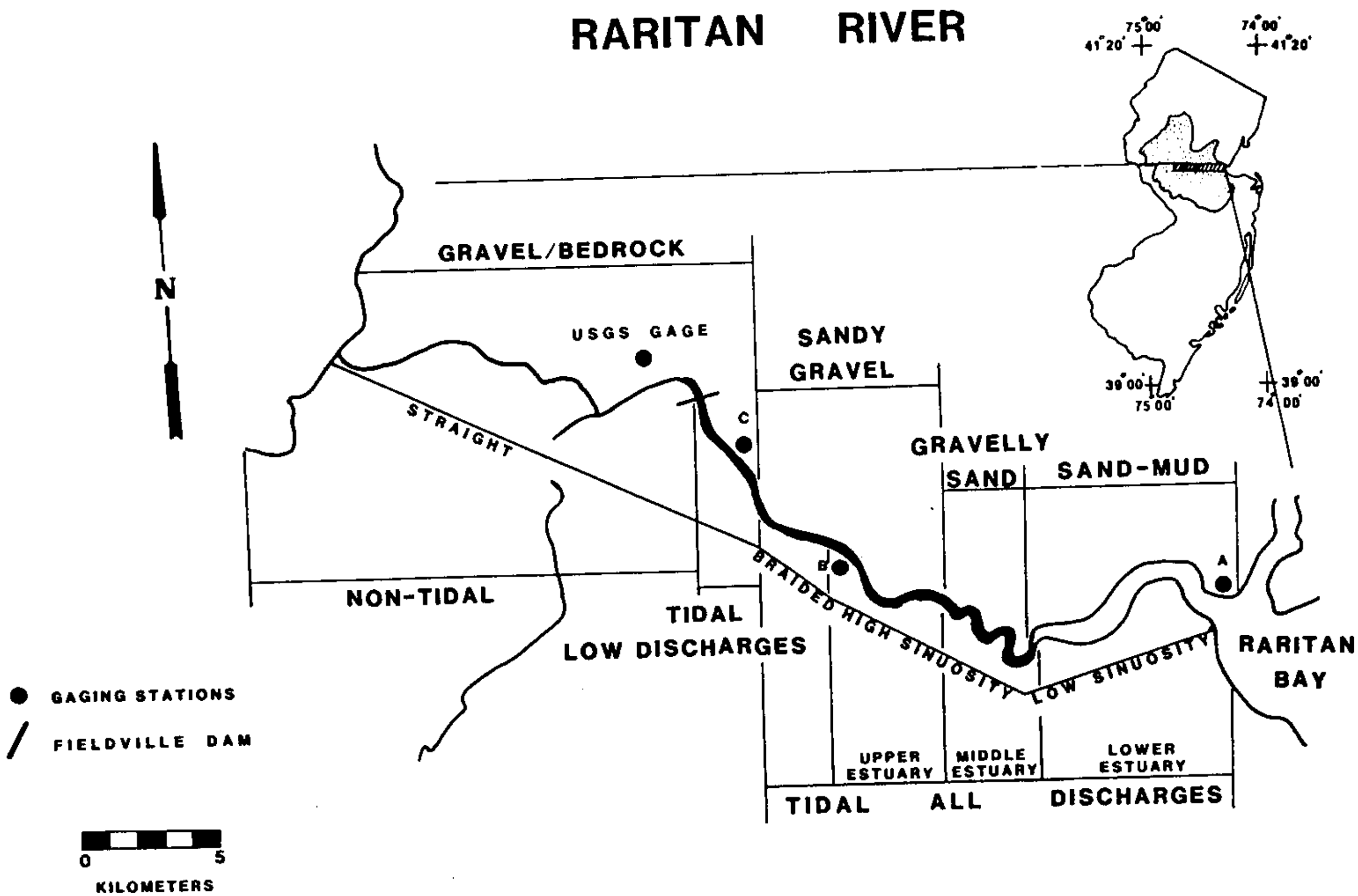


Figure D7 Map of the Raritan from the confluence of the North and South Branches to the mouth at Raritan Bay. The tidal and non-tidal areas are indicated, as well as, the grain size of the channel.

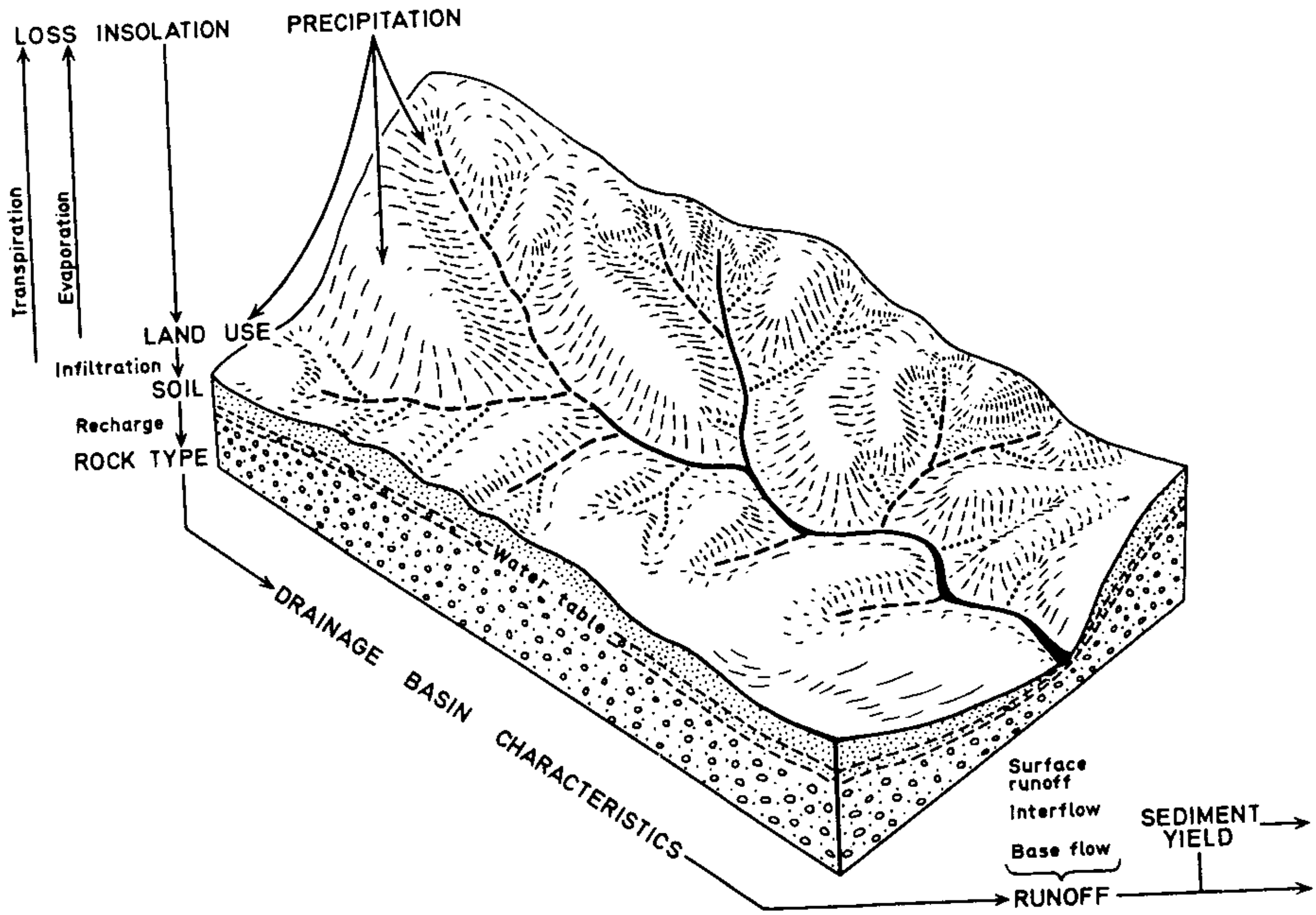


Figure D8 Diagrammatic sketch showing important factors affecting development of drainage basins (climate, bedrock and land use) and some of the products (runoff and sediment yield).

Precipitation

The Raritan River Basin is presently covered by a network of 16 official U.S. Weather Bureau stations. Of these, 3 are equipped with automatic recording rainfall gages and the remainder with standard non-recording gages read one or more times daily. The basin is within the humid temperate climatic zone, and all the tributaries receive similar amounts of annual precipitation (~113 cm). The wet winter season is dominated by continental polar air masses with a seasonal frequency of about 68% (Shulman, 1982). These conditions result in large frontal systems which produce long periods of precipitation with low to moderate intensity. The drier summer season is dominated by marine tropical air masses with a seasonal frequency of about 59% (Shulman, 1982) These conditions produce scattered thunderstorms which in turn produce relatively short periods of moderate to high intensity precipitation. The hurricane season runs from late August to early October and may produce large storm systems with very intense rains and associated flooding.

Pollution

In the recent reports issued by the state on water quality in the Raritan basin (Robinson, 1983; NJDEP 1988), water quality in terms of metal levels present in the Upper Raritan and Millstone is ranked as "excellant", which is defined as "no or minimal pollution". The Lower Raritan is ranked as "good" ("low pollution"). The major pollution sources such as urban runoff, construction, and agricultural runoff in each tributary are summarized in (Table II). In general, the quality of water in the tributaries decreases downstream (Table III). Point sources in the form of wastewater effluents appear to be a problem only in the lower reaches of the basin and in the Millstone River. Wastewater effluent release volumes according to permits issued by NJDEPE amount to 5% of the mean annual discharge of the river.

Water quality monitoring is carried out by the U.S.G.S. including 23 stations in the Raritan Basin with records since 1975. Hay and Campbell (1990) found that in the period 1976-1986 water quality trends were mixed, showing

TABLE II Pollution Sources in the Raritan Basin reported by the NJDEP (after (1) Robinson (1983) and (2) NJDEP (1988).

BASIN	WATER QUALITY	POLLUTION SOURCE
LRB	1. poor to marginal 2. fair to good	(a) municipal and industrial wastewater effluents; (b) urban runoff (c) construction
BB	1. no data 2. fair	(a) urban runoff
UR	1. good to v. good 2. fair to good	(a) construction; (b) agricultural runoff; (c) illegal wastewater inputs; (d) waste dump and septic tank leachates
MR	1. marginal to good 2. fair	(a) construction; (b) agricultural runoff; (c) urban runoff; (d) septic tank leachates; (e) landfills and spills

TABLE III Water Quality at Lower Raritan, Upper Raritan and Millstone Sampling Sites from USGS Monitoring Network Data from 1984 to 1986[a]

Characteristic		LR Queens Br #1403300	UR Manville #1400500	MR Weston #1402540
pH	mean	7.6	8.1	7.4
	range[b]	7.2-8.1	7.2-8.7	7.1-7.9
	sample size	10	16	16
Specific Conductance us/cm		253	230	220
		182-325	181-280	168-319
		10	16	15
Dissolved Oxygen mg/l		10.9	11.2	9.3
		9-13.2	8.5-16	6.4-13.6
		8	16	16
5-Day BOD mg/l		2.8	1.5	2.4
		1.8-5.1	.5-3	1.2-3.7
		10	15	15
Total Nitrogen mg/l		-	1.6	3
			1.1-2.1	2.2-4.4
			15	16
Total Phosphorus mg/l		0.23	0.09	0.3
		0.15-0.34	0.06-0.16	0.16-0.58
		10	16	16
Fecal Coliform		517	611	397
		40-1,300	17-5,400	20-1,700
		7	14	16

[a] USGS (1985; 1986; 1987)
[b] high and low extremes omitted from calculations

increased concentrations of some pollutants, decreased concentrations in others and no significant trends for many. In general, where trends were evident they included increases in specific conductance and dissolved sodium and chloride, and decreases in TOC and many trace metals.

Land Use

The Raritan Basin is densely populated and has been heavily influenced by human activity for two centuries. The area was settled by europeans in the early 17th century, and by the mid- to late-18th century most potentially arable land in the basin was cleared, and by the mid-19th century the basin was almost entirely deforested (Robichaud and Buell, 1973). Forests recovered somewhat in the late-19th and early 20th century, and today they occupy about one third of the basin area (Pavlowsky, 1989).

The earliest use of the Raritan as a resource was as a transportation route between the coast and developing inland agricultural areas. Because of the decrease in river depth in the vicinity of New Brunswick coastal vessels could not navigate further upstream than present day Landing Lane Bridge. There the community of Raritan Landing developed in the 18th century (between 1712 and 1720) as a point where cargos were transferred from boats to wagons and vice versa. Brunswick city was incorporated in 1784. Later, the Delaware and Raritan Canal was built (1830-1840), paralleling the valleys of the Raritan and Millstone Rivers for a total of 65 mi (105 km). Its terminus at New Brunswick spurred the development of that city for nearly 100 years.

Water from the Raritan and its tributaries was also used to provide power for industry, and several diversion dams have been built for this purpose over the years. The first of these was a wing dam built for Suydam's Mill in New Brunswick in the late 18th century, and later diversions for factories at Raritan, Bound Brook, and several other sites were built. In addition, the Raritan has provided potable water to many communities through the years and today the Elizabethtown Water Company plant just above the confluence of the Raritan and the Millstone provides drinking water for about 500,000 people. In addition, the Millstone is used to supplement flow in the

Delaware and Raritan Canal, another important present day potable water supply.

Urbanization is most intense in the lower portions of the basin near and below the head of tide. Major population concentrations occur around Bound Brook, Bridgewater, East Brunswick, Edison, New Brunswick, Perth Amboy, Princeton, Somerville, and South River. Industrial uses are found throughout these urban areas, but the areas bordering the Raritan estuary contain the highest concentration of industrial land use. Major industrial centers include Bound Brook, Edison, New Brunswick, Perth Amboy, and South River.

For much of the past 300 years the Raritan has received, directly or indirectly, all the liquid wastes from the communities along the river. Among the major industries there are several organic chemical processing facilities, metal plating, pigment manufacture, and oil refining. Several major sanitary landfills (all closed but Edgeboro) are adjacent to the channel, including one large toxic waste landfill (Kim-buc), and leachate from these may be a major source of pollution to the estuary. Urban runofff also contributes substantial loads of toxic substances. In combination, these sources contribute a wide range of pollutants, including synthetic organic compounds and toxic metals to the lower Raritan (Whipple and others, 1978; Anderson and Faust, 1974; McLaughlin, 1988; Pavlowsky, 1989).

By the early 20th century sewage pollution had become a major problem and the river was in very poor condition. Today, however, the Middlesex County Sewerage Authority's plant at South Amboy receives nearly all the municipal sewage generated along the valley. As a result the river has recovered substantially. The recovery has been so dramatic that the only remaining major pollution sources are runoff from urban and agricultural lands and licensed discharges from about 80 industrial facilities in the valley.

The land use characteristics within the non-tidal portion (LR i.e. Lower Raritan) and each tributary basin vary significantly (Pavlowsky, 1989)(Table II). The Bound Brook sub-basin has almost 80% of its area urbanized as compared to 11% of the Upper Raritan, UR (North Branch and South Branch combined) and 16% of the Millstone sub-basin (NJDEP 1976). Correspondingly, the highest population density is found in the Bound Brook sub-basin, and, although representing only 7.5% of the area, it contains 37% of the population as shown in the 1980 Census (USDC 1982). The North Branch and South Branch (Upper Raritan) is more rural than the Millstone sub-basin. The North and South Branches are more forested and less urbanized. Since 1960, however, the Upper Raritan population has increased at a greater rate than the other two tributary basins due to high rates of suburban development (Robinson 1983).

Table IV Land use characteristics. LR=Lower Raritan, BB=Bound Brook, UP=Upper Raritan (North and South Branches), MR=Millstone River (Pavlowsky, 1989)

CHARACTERISTIC	LR	BB	UR	MR
Urbanized Area (%)[a]	19	76	11	16
Forested Area (%)[a]	33	20	37	30
Agricultural (%)[a]	48	4	52	54
1980 Population[b]:				
Total Number	624,391	228,816	217,042	155,677
% of LR	100	36.6	34.8	24.9
Population Density:				
per km^2	277	1,354	171	222
per $mile^2$	718	3,520	443	574
Impervious Area (%)[c]	10.2	25.6	7.6	8.9

[a] NJDEP (1976); state land use map
[b] USDC (1982); 1980 Census
[c] Stankowski (1974); regression equation

The marshlands bordering estuarine portion of the river are another important resource neglected in the past, but improving today. In colonial times the wetlands were a source of hay for cattle. Later, the wetlands were regarded as low-value lands and the major use of them was as a site for landfills. Estuarine wetlands serve as breeding grounds for many species important in the marine food chain, and thus directly support important commercial fisheries. The estuary is still unable to support fishing, but there is hope for improvement in the future.

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GEOMORPHIC EVOLUTION OF THE RARITAN RIVER

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INTRODUCTION

The Raritan River Basin (RRB) occupies a unique position in eastern North America. It is adjacent to the Atlantic Ocean, it contains the terminal deposits of three continental glaciers, and it straddles the Fall Line--the landward edge of the Atlantic Coastal Plain. It is eroded into a variety of substrate materials ranging from unconsolidated sand and clay of the Coastal Plain, to shale, carbonate, and poorly-lithified sandstone, to erosion-resistant diabase, mudstone, and gneiss (Fig. E1). The combination of these factors with worldwide glacially-induced sea level fluctuations during the late Tertiary and Quaternary has produced a landscape shaped by multiple fluvial and glacial depositional and erosional events.

The evidence for these events comes from surficial deposits and their associated landforms. The older deposits and landforms are extensively eroded by later events and their record is necessarily fragmentary. Younger deposits and landforms are more complete and their history can be inferred with more certainty. The following discussion is based on 1:24,000-scale surficial geologic mapping conducted as part of a statewide geologic mapping project undertaken jointly by the N. J. Geological Survey and the U. S. Geological Survey. Field mapping was supplemented by examination of records of wells and test borings on file at the N. J. Geological Survey and at the N. J. Department of Environmental Protection and Energy, Bureau of Water Allocation.

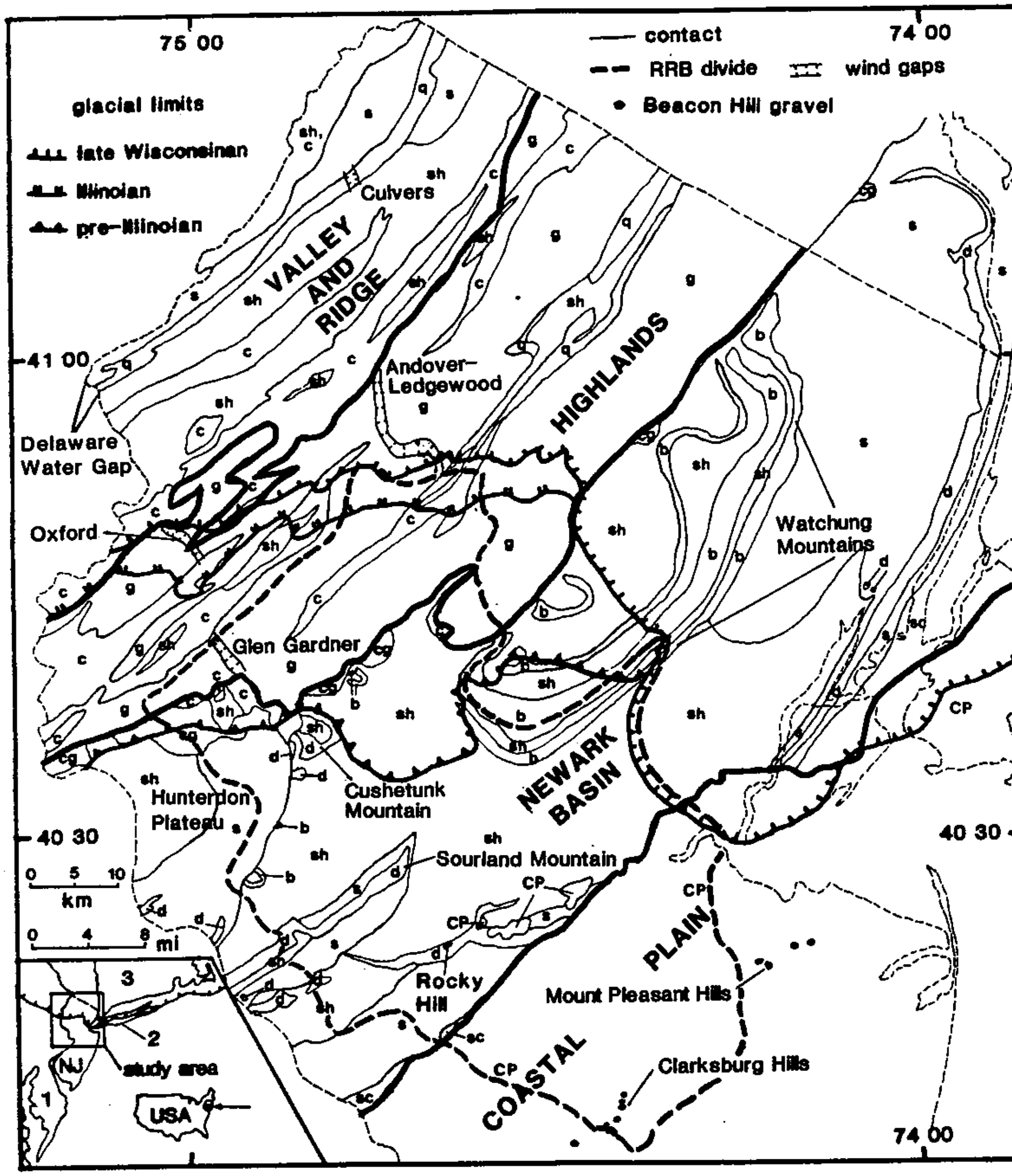

Figure 1: Bedrock map of northern New Jersey, modified from Lewis and Kummel (1912), physiographic provinces, extent of glaciations, and location of wind gaps and remnants of the Beacon Hill gravel. Abbreviations are: sh=shale, s=sandstone and mudstone, g=gneiss, sc=schist, gneiss, serpentinite, d=diabase, b=basalt, q=quartzite, cg=conglomerate, c=carbonate (dolostone, limestone, marble), and CP=sand and clay of Coastal Plain formations. Numbers on inset map indicate: 1=Delmarva Peninsula, 2=Long Island, 3=New England. Hachured line on inset map is the maximum extent of the late Wisconsinan glacier.

CENTRAL NEW JERSEY IN THE LATE MIOCENE

The RRB did not begin to take shape until the latest Miocene and Early Pliocene. Before and throughout most of the Late Miocene the fluvial drainage and landscape of central New Jersey had little or no similarity to that of today. The only depositional record of this landscape is the Beacon Hill gravel (Salisbury, 1898). This is a quartz- and chert-rich fluvial gravel that is preserved as thin, mesa-like caps on the highest hills of the Coastal Plain at elevations ranging from 360 feet in the Mount Pleasant Hills (Stanford, 1992a) to 320 feet in the Clarksburg Hills (Minard, 1964) (Fig. E1). Clasts of Beacon Hill gravel also occur at an elevation of about 320 feet on the flat summit of Rocky Hill, which marks the farthest inland extent of the gravel (Fig. E1). Together, these remnants define a broad fluvial plain with a southerly to southwesterly paleoflow (Owens and Minard, 1979).

Northwest of this plain the Beacon Hill level corresponds to that of the upland erosion surface that bevels the rocks of central and northern New Jersey (the Schooley peneplain of Davis, 1890 and Davis and Wood, 1890, as revised by Johnson, 1931). This surface is best preserved on resistant diabase and mudstone bedrock on Sourland Mountain and on mudstone and sandstone bed-rock of the Hunterdon Plateau (Fig. E1). Further north, it has been modified by glacial erosion. Together, the upland erosion surface and the Beacon Hill define a low-relief landscape with a broad fluvial plain to the southwest. It is not possible to reconstruct drainage in this landscape with certainty because no recognizable fluvial deposits occur inland of Rocky Hill. If the main Beacon Hill river flowed southerly to southwesterly one would expect the inland tributaries to flow southeasterly. Wind gaps in northern New Jersey, presumably eroded as rivers downcut from the Schooley-Beacon Hill level, have been cited as evidence for this southeasterly drainage (Johnson, 1931; Campbell and Bascom, 1933). Two alignments of wind gaps, one from Culvers Gap to the Andover-Ledgewood gap through the Highlands and a second from the Delaware Water Gap through gaps at Oxford and Glen Gardner, may mark the location of the trunk streams that later evolved into the upper Raritan when their upstream reaches were captured by southwesterly-flowing streams (the upper Delaware, Paulins Kill, Pequest, and Musconetcong, Fig. E2) eroding headward along strike belts of weak carbonate rock. The Beacon Hill contains no fossils and cannot be directly dated. Owens and Minard (1979) assign it a Late Miocene age because it rests unconformably on the Cohansey Formation, which is of probable Middle Miocene age.

PLIOCENE LANDSCAPE AND THE BRIDGETON FORMATION

During the latest Miocene and Early Pliocene the Beacon Hill fluvial plain and Schooley surface were dissected by drainage controlled by a major river flowing southwesterly along the inner edge of the Coastal Plain. This dissection may have occurred in response to worldwide lowering of sea level caused by major growth in the Antarctic ice sheet in the Late Miocene (Shackleton and Kennett, 1974a). This river and its tributaries eventually eroded a broad lowland between Perth Amboy and Trenton and northward to the Somerville area on weak shale, poorly-lithified sandstone, and Coastal Plain sediments, and then deposited a fluvial sand and gravel on much of this lowland (Fig. E2). This fluvial deposit was correlated with the Pensauken Formation--the lower yellow-stained quartz gravel of the Delaware valley south of Trenton--by Salisbury and Knapp (1917). Owens and Minard (1979), based on projection of the base of the deposit from its type area in southern New Jersey, correlate it with the Bridgeton Formation of Salisbury and Knapp (1917), which is the upper yellow gravel of the southern Delaware valley. This revised nomenclature is used here.

Paleocurrent measurements indicate that the main Bridgeton river flowed southwestward from the New York City area to Trenton and continued southwestward along the trend of the present Delaware valley before discharging southeastward to the Atlantic across southern New Jersey and the Delmarva Peninsula (Fig. E1) (Owens and Minard, 1979; Martino, 1981).

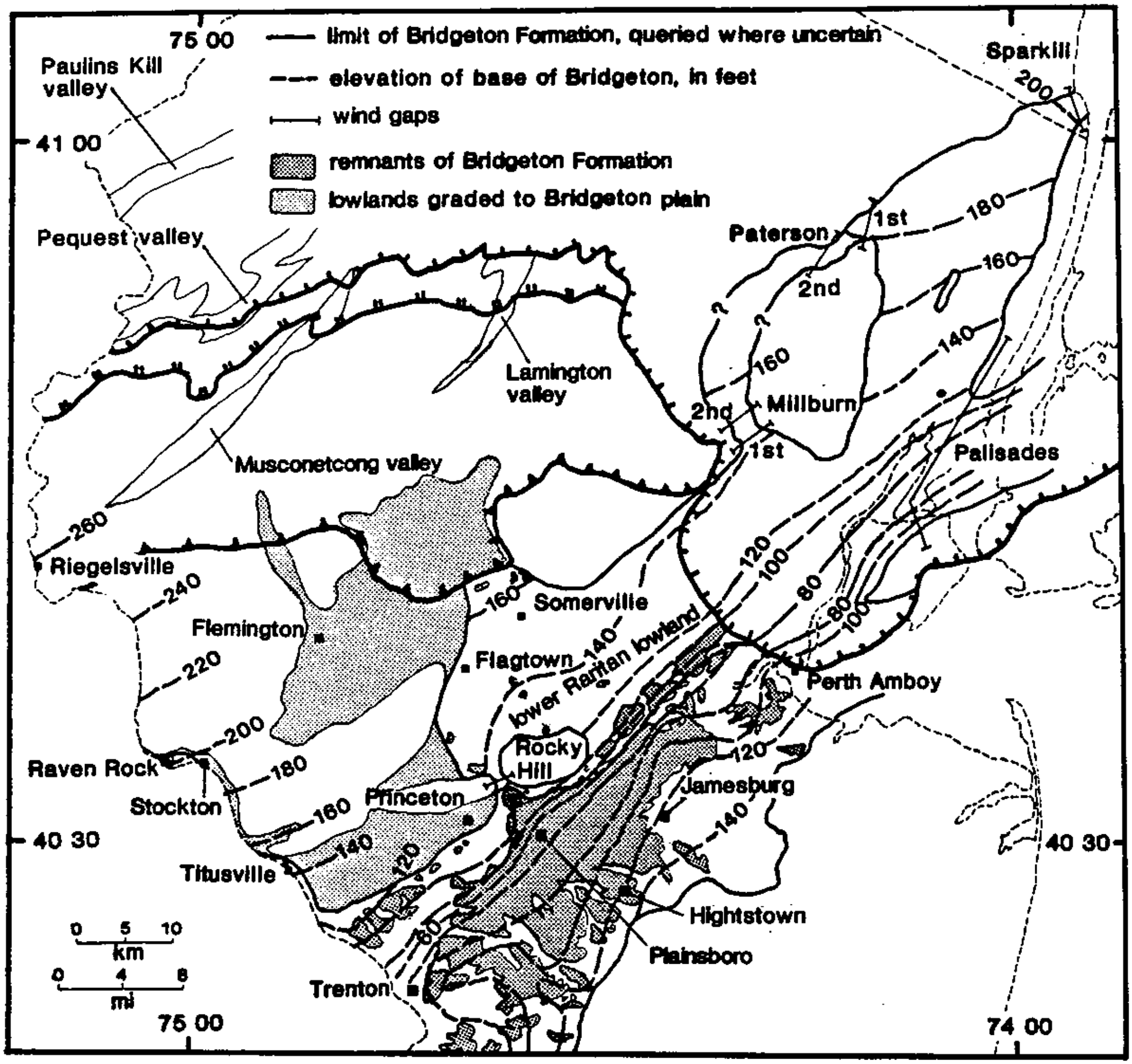

Figure 2: Elevation of the base of the Bridgeton Formation (projected in the area north of the late Wisconsinan margin), extent of the Bridgeton and lowlands graded to the Bridgeton plain, and location of preserved Bridgeton remnants and wind gaps. Glacial limits as in figure 1. Contours on the base of the Bridgeton include data from Lewis and Kummel (1912) and Owens and Minard (1979) in the Perth Amboy-Trenton lowland.

Northward projection of the base elevation of the Bridgeton deposit, and provenance considerations, indicate that the Bridgeton river included both the Hudson and a large river issuing from the Long Island Sound lowland, which likely included drainage from the Housatonic and Connecticut river basins in New England. Contours of the base of the Bridgeton Formation (Fig. E2) show the main axis of the Bridgeton river projecting from the Long Island Sound lowland and crossing the Palisades in the Jersey City area. The contours also show the Hudson branch crossing the Palisades at Sparkill and crossing the two Watchung ridges at Paterson and Millburn. All of these crossings of resistant rock are marked by prominent wind gaps cut during incision of the river from the low-relief Beacon Hill-Schooley surface. The route of the Hudson from Sparkill across the Watchungs was identified by Johnson (1931). He did not associate these gaps with the Bridgeton deposit, but the projected contours of the base of the Bridgeton intersect the floors of the gaps and strongly suggest a correlation. The base-of-Bridgeton contours rise northwesterly near Somerville and southeasterly in the Jamesburg area (Fig. E2); these are the locations of major tributaries to the Bridgeton and are the earliest depositional record of streams within the modern RRB. During this time the upper reaches of the RRB, including the North and South Branch valleys upstream from Somerville and the Millstone valley upstream from the Hightstown area, were eroded by these tributaries. The Bridgeton remnants near Somerville are quartz and chert gravel in arkosic sand, a lithology that suggests provenance from either Paleozoic quartzite and carbonate rock in the upper South Branch valley or from recycled pre-Bridgeton gravels brought in from the Valley and Ridge province to the northwest by the Beacon Hill tributary streams before capture by Delaware tributaries (Fig. E1). The Bridgeton in the Jamesburg area is a quartz gravel in glauconitic sand, indicating provenance from Coastal Plain formations and the Beacon Hill gravel remnants to the southeast. Paleocurrent measurements in the Perth Amboy-Trenton lowland (Owens and Minard, 1979; Martino, 1981) demonstrate southwesterly flow of the main Bridgeton river. Bridgeton remnants in the lower Raritan lowland (Fig. E2) are too weathered and eroded to provide paleocurrent measurements, but a southerly-flowing route for the proto-Raritan tributary from Somerville to Princeton can be inferred from the elevation of the remnants and from the presence of a gap in the Rocky Hill diabase ridge northeast of Princeton. At Rocky Hill the proto-Raritan, flowing south on a covering of Beacon Hill gravel, cut a gap in the diabase as it downcut to the Bridgeton baselevel. Clasts of Beacon Hill gravel occur on the flat summit of Rocky Hill superjacent to the gap, indicating former continuity of the Beacon Hill deposits over the area of the present gap. The continuity of the Bridgeton deposit through the gap is indicated by the presence of Bridgeton gravel clasts on the rock-cut floor of the gap, at an elevation coincident with the base of a Bridgeton remnant half-a-mile to the north (Fig. E2). This gap later provided a route for the north-flowing Millstone River, which cut an inner gorge from a superposed position on the Bridgeton deposit. The age of the Bridgeton is not definitely established. Berry and Hawkins (1935) describe plant fossils from the Bridgeton near New Brunswick that they conclude are of Pleistocene age. Owens and Minard (1979) suggest a Late Miocene age based on correlation to subsurface units in the Delmarva Peninsula, but this correlation cannot be demonstrated because the Bridgeton is discontinuous across Delaware Bay. Pollen from a black clay bed within the Bridgeton, exposed in a gravel pit near Plainsboro (Fig. E2), includes cool- temperate to cold-temperate species and a few exotic pre-Pleistocene species (G. Brenner, written communication), an assemblage suggesting a Pliocene age. A post-Late Miocene age is also suggested by the great extent and depth of dissection of the Beacon Hill before deposition of the Bridgeton. The oldest unit overlying the Bridgeton is the pre-Illinoian till, which overlaps the Bridgeton north of Somerville (Stanford, 1992b). This till has weathering and erosional characteristics much closer to those of the Bridgeton than to the Illinoian and late Wisconsinan glacial deposits. In both the Bridgeton and pre-Illinoian till, gneiss, sandstone, mudstone, and diabase clasts are decomposed to depths of 10 feet or more, and both units are preserved as thin remnants on flat hilltops and divides, with later valleys cut in bedrock 60 to 100 feet below their base. These similarities suggest that they are not widely separated in age. However, the markedly different clast lithology of the quartz- and chert-rich Bridgeton and the pre-Illinoian till, which is a mix of gneiss, mudstone, quartzite, conglomerate, and some basalt and diabase, even where the two units are in contact, indicates distinctly different provenance and suggests that the Bridgeton is of preglacial rather than glaciofluvial origin. If the pre-Illinoian glaciation is Early Pleistocene or Late Pliocene (Braun, 1989), which seems likely based on its much greater degree of weathering and dissection than the Illinoian and late Wisconsinan deposits, then the Bridgeton and its associated landforms would reasonably be assigned a Pliocene age. Thus, the basic form of the RRB was established in the Pliocene.

DIVERSION OF THE BRIDGETON RIVER

The river supplying the Bridgeton sediments was eventually diverted seaward in the vicinity of New York City. The cause of the diversion is uncertain because the deposits and landforms in the New York City area that would date from this time have been erased by late Wisconsinan glacial erosion. If pre-Illinoian glaciation occurred only shortly after the end of Bridgeton deposition, there may have been a direct glacial blockage and rerouting of the Bridgeton river near New York City. Alternatively, headward-extending valleys eroding the Coastal Plain east of the Staten Island bedrock upland may have captured the Bridgeton river. This diversion inaugurated the formation of the lower reaches of the RRB. It left an abandoned layer of fluvial sand and gravel as much as 80 feet thick over most of the present-day lower Raritan and Millstone valleys (Fig. E3). The lower reaches of the Raritan and Millstone established alignments on this surface that are coincident for the most part with their present valleys (Fig. E3). The lower Raritan adopted an easterly course from Somerville to the Hudson, and the lower Millstone adopted a northerly course to the Raritan by way of the Rocky Hill gap.

These new river segments flowed northeastward, against the former depositional slope of the Bridgeton plain. This seeming anomaly may reflect the influence of crustal depression during the pre-Illinoian glaciation. Martino (1981) estimated a valley gradient of 0.00042 for the Bridgeton in the Perth Amboy -Trenton lowland. A delta in a pre-Illinoian ice-dammed lake in the upper Passaic basin (Fig. E3) yields a minimum isostatic depression of 0.00076 to the north, which is sufficient to level or reverse the slope of the Bridgeton plain and induce northeastward drainage.

PLEISTOCENE PERIGLACIAL LANDFORMS AND DEPOSITS

After the new drainage was established, narrow valleys were cut into bedrock as much as 120 feet below the base of the Bridgeton, and the Bridgeton was extensively dissected, particularly in the lower Raritan lowland. At the Rocky Hill gap the Millstone cut a narrow inner gorge (Fig. E3). In the Raritan valley upstream from Somerville, valleys were incised into bedrock below the base of the pre-Illinoian till. Because Late Pleistocene deposits occur in terraces in the bottoms of these valleys, the erosion was accomplished in the Early and Middle Pleistocene. This incision may have occurred in response to a sustained drop in sea level caused by the onset of glaciation in the northern hemisphere in the Late Pliocene (Shackleton and Kennett, 1974b; Shackleton and Hall, 1984). Except where valleys have been filled or blocked by glacial deposits, the landforms and deposits created during Late Pleistocene glacial-interglacial climate cycles occur within, but have not substantially altered, these narrow incised valleys.

Under periglacial conditions vegetative cover was minimal, perma-frost was present (Wolfe, 1953; Walters, 1978), and moderate to steep hillslopes became unstable, particularly when surface soil layers thawed and became water-logged when the underlying perma-frost prevented drainage. Material moved down hillslopes and, at the bases of steep slopes, collected in

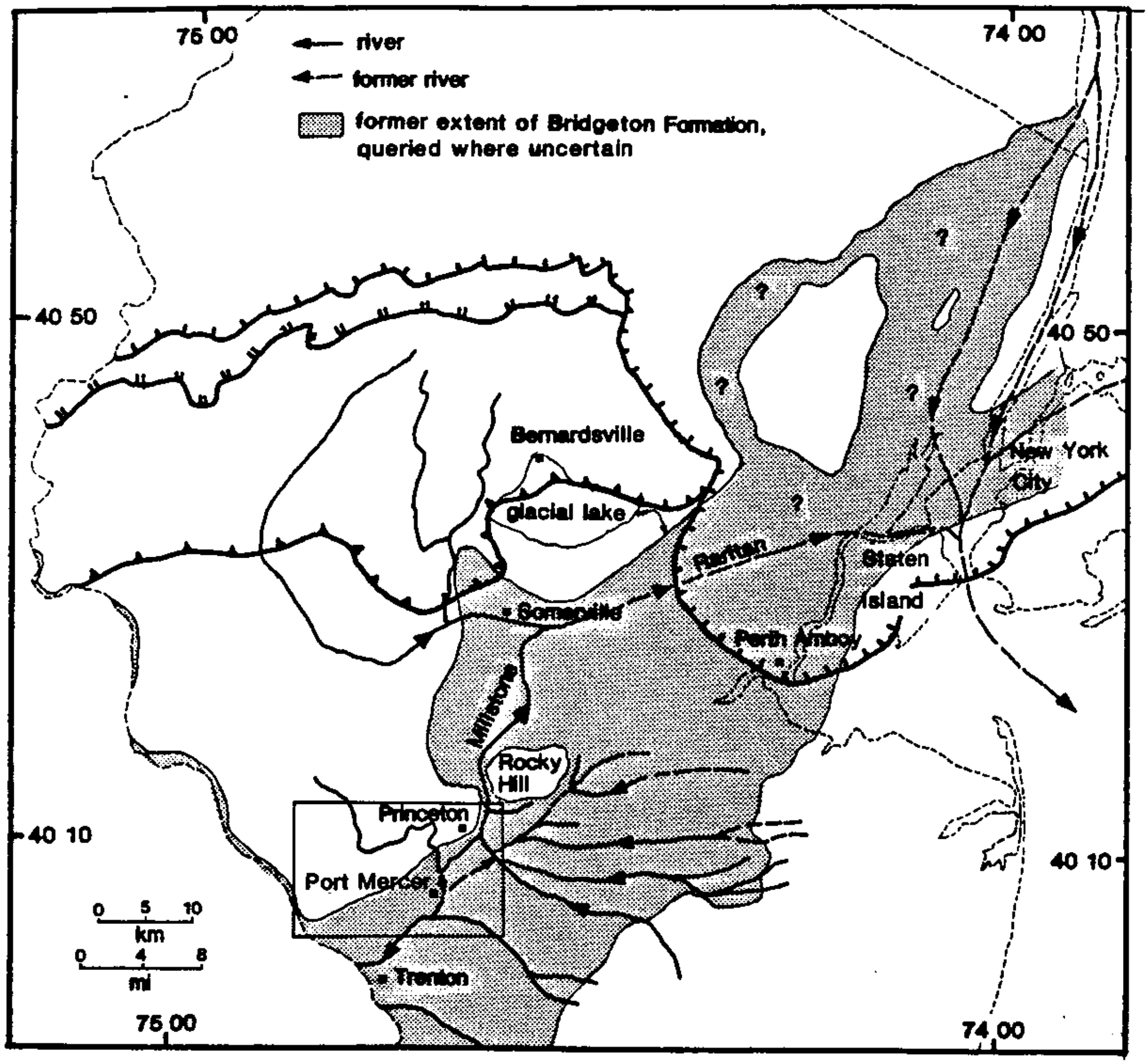

Figure 3: Alignment of the Millstone and Raritan rivers after diversion of the Bridgeton river. Glacial limits as in figure 1.

aprons. This process created a characteristic form consisting of a lower gentle slope on the colluvial apron with a distinct inflection at its upper boundary to a steeper upper slope in weathered bedrock material. These colluvial aprons form nearly-continuous deposits at the bases of major escarpments and ridges in the Newark Basin and Highlands parts of the RRB, particularly at the base of the cuesta slopes of the Watchungs, along the base of Sourland and Cushetunk mountains, along the base of the Hunterdon Plateau, and at the base of escarpments where gneiss of the Highlands borders Newark Basin rocks or carbonate rocks (Fig. E1). In the Coastal Plain, slopes were too gentle to produce colluvial aprons except at the base of a few steep hills and excarpments. Similar colluvium of periglacial origin is also described in areas adjacent to the RRB (Braun, 1989; Newell and others, 1989; Ridge and others, 1992). On gentle to flat slopes colluviation was not widespread and, instead, a variety of permafrost features formed. These include polygonal patterned ground, ice-wedge casts, and frost involution structures on shale uplands and on fluvial terraces in the lower Raritan lowland (Walters, 1978) and abundant pingo scars and frost involution structures on the Bridgeton plain in the Perth Amboy-Trenton lowland (Wolfe, 1953).

The increased sediment supply during periglacial periods also led to widespread alluviation in valleys. Gravelly alluvial fans were deposited in the Highlands and at the base of the Hunterdon Plateau where streams debouched from steep upland ravines into valleys. Broad alluvial terraces aggraded in the widest parts of the main Raritan and Millstone valleys; smaller terraces formed in tributary valleys and the more narrow segments of main valleys. Wind blowing chiefly from the west (as it does today) across the tundra landscape carried very fine sand and silt from these newly-deposited broad terrace surfaces (and,locally, from broad, unvegetated outcrop belts of Cretaceous sand in the Coastal Plain) and deposited the sediment as a thin veneer of eolian loam or, locally, as sand dunes, on the valley slopes downwind from the terraces. These deposits are particularly prominent in the South Branch valley between Flemington and Somerville, in the Millstone valley between Millstone and Bound Brook (Stanford, 1992b), to the southeast of the Plainfield outwash (Fig. E4) and in scattered areas in the Coastal Plain, particularly northeast of Jamesburg, where there are broad outcrops of sand of the Magothy Formation.

GLACIAL DEPOSITS

Both the Illinoian and late Wisconsinan glaciers entered the RRB (Fig. E1). Meltwater and moraine deposits from these glaciers filled several valleys within the RRB and caused two major drainage relocations. In addition, glacially-induced crustal depression during the late Wisconsinan and, possibly, the Illinoian, allowed meltwater descending the Delaware valley to be partially diverted down the lower Millstone. Illinoian ice entered only the northernmost part of the RRB. In the Lamington valley (Fig. E2) the ice front blocked a north-draining valley that, as the topography of the buried bedrock surface shows, was a tributary to the Rockaway River (Cook, 1880; Salisbury, 1902; Stanford, 1989). A glacial lake formed in this valley and rose to the level of the low point on the valley divide near Chester, where it spilled south into the Raritan basin. This lake was partially filled with Illinoian glaciolacustrine and moraine deposits. After retreat of Illinoian ice the lake drained and northward fluvial drainage was again established. During the late Wisconsinan glaciation the valley was again dammed by the ice front and again a glacial lake formed (glacial Lake Succasunna). Glaciolacustrine and moraine sediments were again deposited in the lake and this time completely filled the lake basin (Stanford, 1989). Upon deglaciation, northward drainage was blocked by the valley-fill deposits and the Lamington River now drains southward across the former lake spillway as a tributary to the Raritan rather than the Rockaway. A much larger drainage diversion occurred to the lower Raritan east of Bound Brook. The topography of the bedrock surface beneath the terminal moraine and the Plainfield outwash plain (Fig.

E4) shows a broad valley extending northeast of Bound Brook to the Newark Bay lowland. Glacial erosion of the bedrock has altered the preglacial topography east of the terminal moraine but the fluvial character of the valley is shown by the topography west of the moraine. This valley marks the route of the pre-Illinoian Raritan. During late Wisconsinan glaciation, deposition of the moraine and of the Plainfield outwash filled the valley. Illinoian glacial deposits do not crop out in this area, but they do occur beneath the terminal moraine in the Short Hills area (Fig. E4) (Stanford, 1992c). Thus, it is likely that the valley was also partly filled during Illinoian glaciation. The Raritan River, its proglacial discharge increased by the addition of water draining into the basin from glacial lakes Passaic and Succasunna, and from Delaware meltwater descending the Millstone valley, was diverted eastward across a low shale upland. It cut a narrow gorge in the shale between Bound Brook and New Brunswick. East of New Brunswick it entered and deepened the pre-existing South River valley, cut in Cretaceous sand and clay. Southerly tributaries to there located Raritan, responding to the lowered baselevel created by the newly-carved gorge, eroded headward into the upper Millstone basin (Fig. E4). Lawrence Brook carved a narrow valley in Bridgeton deposits overlying sedimentary rock and diabase and captured low-gradient streams in the Millstone basin. The barbed drainage pattern in the headwaters of Lawrence Brook, and the abandoned valleys on the Millstone-Lawrence divide near Monmouth Junction (Fig. E4) mark these post-glacial captures. The South River deepened and widened its valley. Throughout the Pleistocene, this river, owing to its much shorter route to the ocean, probably had been eroding headward and capturing low-gradient Millstone tributaries flowing on the former Bridgeton plain. The markedly asymmetric divide on the west side of the South River-Manalapan Brook valley indicates that this headward erosion is continuing at present. Another glacial deposit in the RRB is interesting because it documents a meltwater diversion induced by glacio-isostatic depression. The Trenton gravel (Cook, 1880) is the late

Wisconsinan glacio-fluvial gravel of the Delaware valley. In and north of the Trenton area it is composed chiefly of gray and brown mudstone and sandstone clasts, rock types that are common in the Delaware basin but relatively uncommon in the RRB. The Trenton gravel forms a plain at an altitude of about 60 feet in the Trenton area. A branch of this plain crosses the low Millstone-Delaware divide on the former Bridgeton plain at Port Mercer (Fig. E3) and continues as a narrow terrace down the lower Millstone to Manville, where it merges with Raritan alluvial terrace deposits and the Plainfield outwash (Stanford, 1992b). The deposit maintains a nearly level elevation along this stretch and exhibits the same clast lithology as in the Delaware valley. When adjusted for rebound (recorded by tilted glacial lake plains in northern New Jersey), an even gradient down the Delaware, across the divide, and down the Millstone results, demonstrating continuity of the deposit during the late Wisconsinan glaciation. A similar diversion likely occurred in the Illinoian because in the Delaware valley Illinoian outwash forms terraces slightly higher than the late Wisconsinan outwash, defining a surface that would have projected across the divide. Interestingly, this identical route was chosen for the Delaware-Raritan canal, which gravity-feeds from the Delaware valley north of Trenton, across the divide at Port Mercer, and down the Millstone valley to New Brunswick. It is dug into the Trenton gravel terrace for much of this route.

POSTGLACIAL CHANGES

In postglacial time, as in previous Quaternary interglacials, streams in the RRB no longer carried large sediment loads, and hillslopes were stabilized by vegetation. Glaciofluvial and alluvial deposits in valleys have been eroded into terraces 5 to 40 feet above the modern flooplain by postglacial streams, and sizable floodplains have formed in main valleys (particularly in the Somerville-Bound Brook area). Colluvial aprons and alluvial fans have been eroded by gullying and spring-sapping by water emerging on and draining down the landforms, and by bank erosion by the valley streams at the distal edge of the landforms. Typical depths of gullying and bank erosion range from 5 to 20 feet. Postglacial rise of sea level has flooded the lower reaches of the RRB to create Raritan Bay, and has caused tidal marshes to extend inland to New Brunswick and Old Bridge. The tidal marsh deposits cover earlier postglacial alluvial and late Wisconsinan glaciofluvial deposits.

CONCLUSIONS

Landforms and surficial deposits in the RRB indicate that it began to form during dissection of the Beacon Hill-Schooley surface, probably in the latest Miocene. The upstream parts of the basin had established their general form by the time of deposition of the Bridgeton Formation, probably in the Pliocene. Diversion of the Bridgeton river in the late Pliocene led to establishment of the lower reaches of the Raritan and Millstone rivers. A second period of dissection, in the Late Pliocene-Early Pleistocene, carved the basic incised-valley form of the present-day landscape. Glacial deposition in the Illinoian and late Wisconsinan filled these valleys in two places and resulted in a major relocation of the Raritan east of Bound Brook, with attendant effects on tributary streams. Postglacial rise of sea level created the Raritan estuary. The driving force of these landscape changes is the advent and fluctuation of glacial conditions in the late Cenozoic. The continued growth of the Antarctic ice sheet in the Late Miocene and the development of northern hemisphere ice sheets in the Late Pliocene may have initiated the two episodes of dissection that are largely responsible for the present landscape. Fluctuations between glacial and interglacial climates throughout the Pleistocene are responsible for the periglacial, glacial, and interglacial deposits and landforms that occur within the dissected landscape. Future glaciations, vegetation changes, or changes in sea level due to greenhouse warming or return to glacial conditions will continue to shape the evolving landscape of the Raritan River Basin.

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In 1777 the British sent a fleet up the River with supplies for their garrison in New Brunswick. At night the Americans planted a battery of 6 guns where Route 1 now crosses. Next morning they sank 5 boats and forced the remaining boats to return to Perth Amboy.

Figure E5 from the Raritan River Children's Book Vol. 1

RIVER GEOMORPHOLOGY, SEDIMENTOLOGY, AND SURFACE HYDROLOGY

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Gail M. Ashley[3] Gary H. Haag[4]

Flow within the Raritan is both temporally and spatially variable in magnitude and direction due to tidal influence (Ashley and Renwick, 1983). The lowermost long-term USGS gauging station is located just above the head-of-tide, at a drainage area of 1957 km^2. At this point the mean annual discharge is 34 m^3 sec^{-1}, bankfull flow is approximately 160 m^3 sec^{-1} and the mean annual flood is 492 m^3 sec^{-1} (USGS 1964-1980). Discharges greater than mean annual stage occur only about 25% of the time. The proportion of Raritan discharge from each sub-basin is: Millstone (26%), South Branch (25%), North Branch (17%), Lower Raritan, which includes Green Brook (16%), South River (12%) and Lawrence Brook (4%).

Below the head-of-tide discharge varies with each tidal cycle and increases rapidly downstream (Renwick and Ashley, 1984)(see Section J). The mean annual freshwater discharge at the mouth is 52 m^3 sec^{-1}. Semidiurnal tidal volumes range from about 9 to 28 million m3 (Anderson and Lendo, 1969). Channel geometry and grain size of the river bed of the Raritan are summarized in Section D (see Fig. D7).

About 50% of the annual precipitation flows out of the basin with seasonal variations ranging from about 20% in the summer to about 90% in the early spring (USGS 1987). The mean monthly hydrograph of the basin shows the early spring and low flow months are during summer (Fig. F1). March maintains

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the highest monthly average of 70 m^3 sec^{-1}. July and September, and October have the lowest at 21 m^3 sec^{-1}. The most variable flow conditions are found during the drier months due to the effects of episodic thunderstorms. Figure F2 depicts long-term (25 years) flow records of South Branch, North Branch, Lower Raritan, and Millstone River (note discharges are in ft^3 sec^{-1}). Figure F3 shows the average discharge for the Raritan River at the Bound Brook gaging station (Haag, 1982).

The flood of record was August 1971 with a rainfall of 20.4 cm and a peak discharge of 1302 $m^3 sec^{-1}$ (Table I). Flood hydrographs tend to be relatively flashy in urbanized basins such as Bound Brook, and in the upper North and South Branches (Field Trip Stop 1-4), while in the gently-sloping basins of the Inner Coastal Plain discharge is less variable. Because of the summer peak of evapotranspiration, extreme low flows usually occur in the summer. Zero flow is rare above drainage areas of 300 km2, and is less likely in the South River and its tributaries draining the sandy soils of the Inner Coastal Plain than in the North and South Branches, which drain less permeable soils and rocks of the Piedmont.

In the upper and middle parts of the watershed the river channels are narrow (10-50m) and shallow (1-2 m) with sand and gravel beds. Bedrock is sometimes exposed in the channel bottom. The channels are relatively straight with large bends. A detailed site study has shown that flow is meandering within these reaches, as evidenced by the presence of a thalweg (deepest portion in the channel cross section) which meanders between alternate side bars (Haag, 1982). Flow is relatively rapid in these "straight" reaches and sediment is carried through with little deposition except during overbank flooding.

By ~30 km above the river mouth, the channel has gradually widened to 80 m and is laterally confined by bedrock in some localities (Ashley et al., 1988). Bed material ranges from bedrock to patches (or bars) of sand and gravel. Maximum clast size on the bed is 7 cm and silt and clay are minor to non-existant in channel bed sediments (Haag, 1982). The flood plain is narrow, averaging 145 m, although some flood plain sections may be as wide as 400-500 m (Haag, 1982). A series of cores into the flood plain revealed a fining-upward sequence starting with gravel, which is overlain by sand and capped with fine sand and silt (Fig. F4). The lower unit (A) contains 43% gravel, 44% sand and 13% silt and clay. It is similar to the present channel bed sediments and likely represents a former position of the channel. Unit B is 7% gravel and 58% sand and 35 % silt and clay. Unit C is composed of 9% sand, 71% silt and 20% clay. Units B and C are probably flood deposits. All units fine away from the channel.

Analyses for contaminants (D.D.T., P.C.B.s, heavy metals, hydrocarbon bi-products and industrial solvents) in Unit A following an overbank flood event (11/5/79) revealed the presence of pollutants in recently deposited flood plain silts suggesting that pollutants move with the suspended sediment load (Table II).

Flow in these straight channels above the head-of-tide is, of course, unidirectional (not influenced by the tides). The water slope averages 0.0005. At 160 m^3 sec^{-1}, the bankfull discharge, a mean velocity of 1.67 m sec^{-1} was measured. which is capable of entraining clasts up to 5 cm in diameter (Church and Gilbert, 1975). Clasts up to 7 cm can be entrained during higher flows such as the flood (460 m^3 sec^{-1}) in 1980. Suspended sediment is typically composed of approximately equal proportions of silt and clay with minor very fine sand. Concentrations measured near Bound Brook showed a range from 2 to 200 mg l-1 (Fig. F5). This suggests a discharge-weighted average annual suspended sediment load of the order of 10,000 tonnes yr-1. These fines get carried through to the estuary during normal flows or are deposited on the flood plain during overbank events.

Downstream from the straight channel portion, between 23 and 19 km above the mouth, the river is wide (210 m) and shallow (1 m at low tide). The presence of mutiple thalwegs separated by gravel bars produces a distinctive braided fluvial style. Grain size analysis of the bed material shows that the maximum clast size found on the bars is 10 cm, and 6 cm in the channels. The

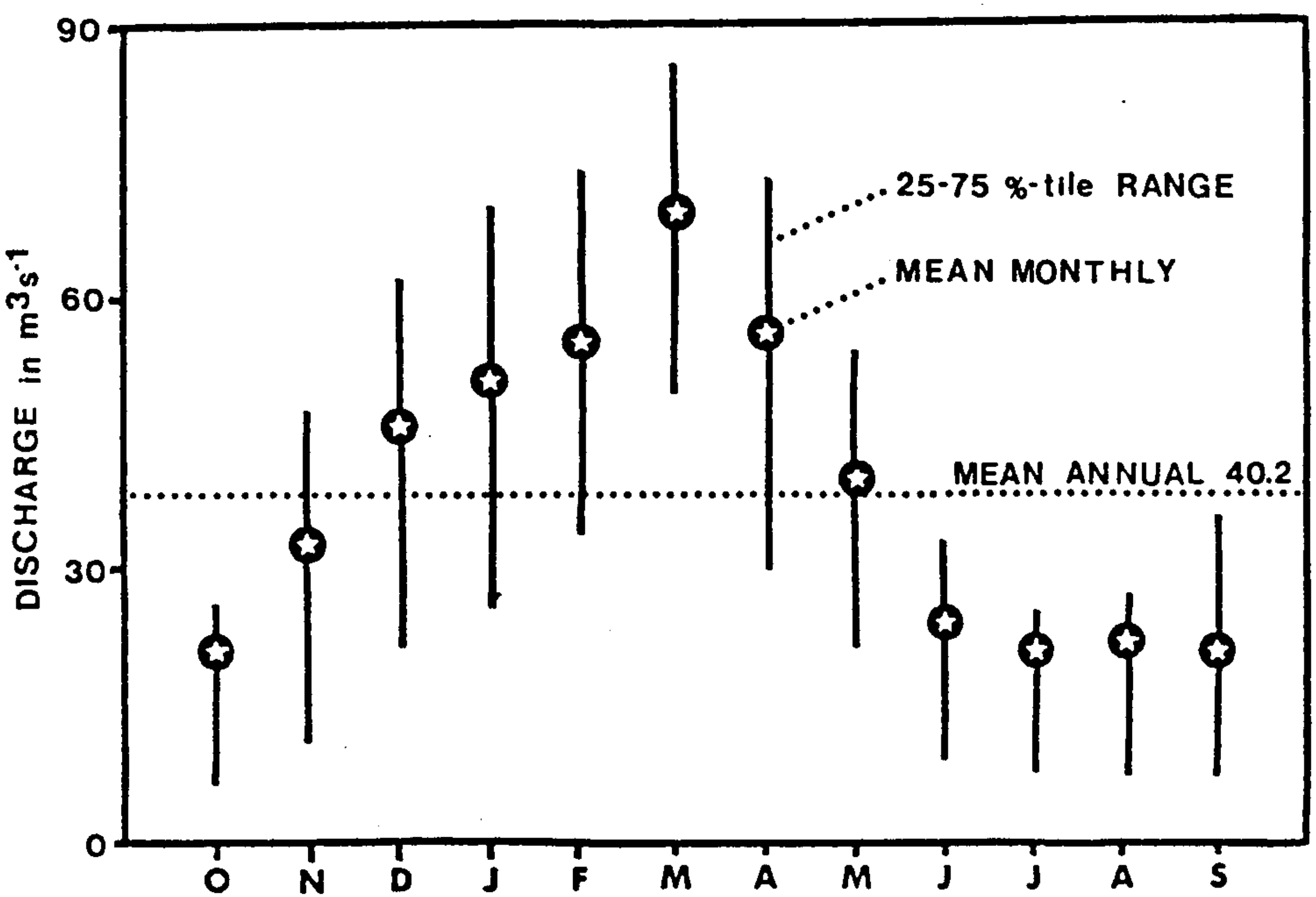

Figure F1 Mean monthly discharge at the basin outlet (LR). Monthly mean values and 25-75 % range are from the USGS gage below Calco Dam (#1403060) and based on a 47 year record. Discharge values from Calco Dam are multiplied by 1.10 to correct for area differences between sites (Pavlowsky, 1989).

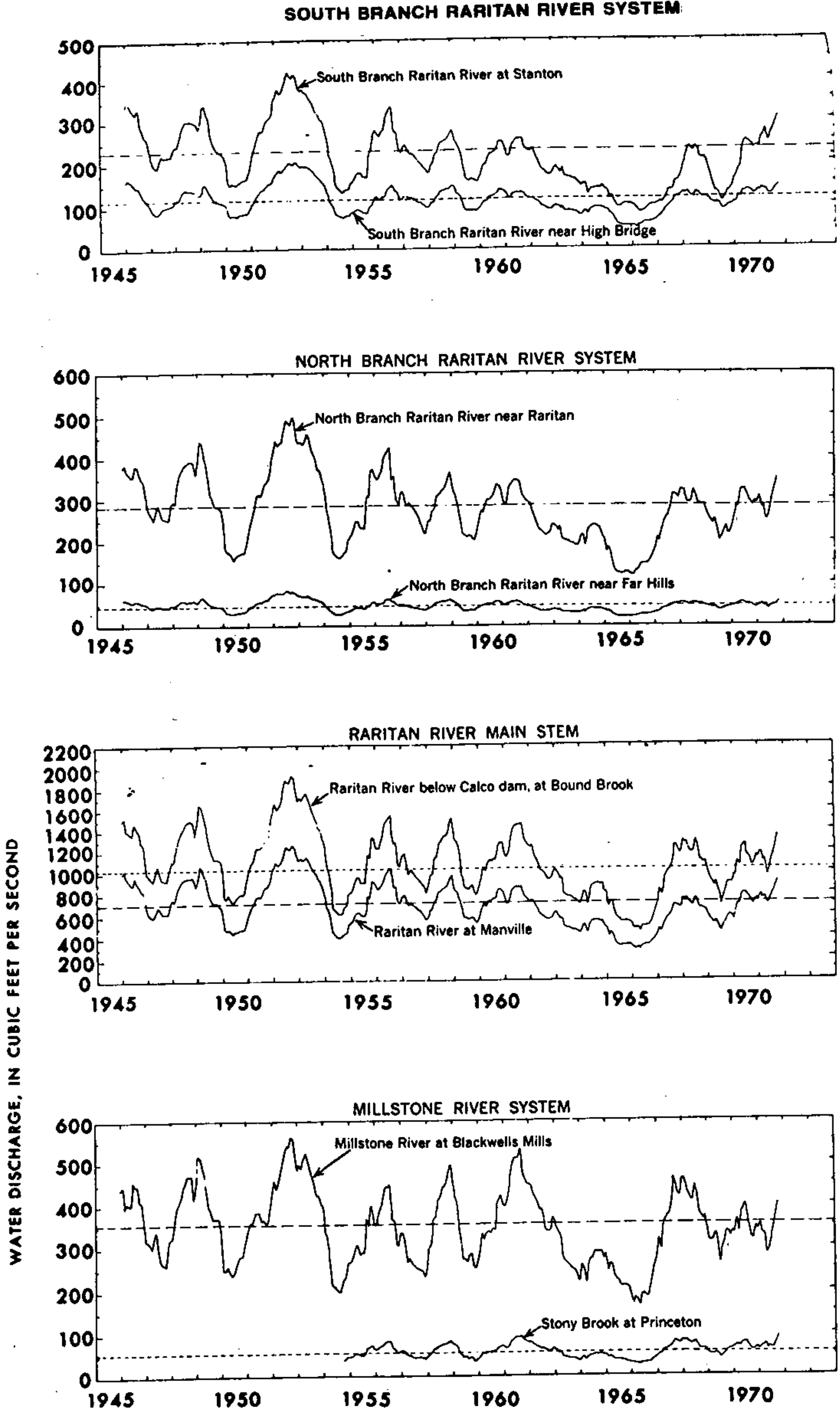

Figure F2 Hydrographs for the main tributaries of the Raritan using trend analysis based on 12 month moving averages of stream flow records at selected gaging stations. Horizontal dashed line represents long term average flow at the gaging station (modified from Anderson and Faust, 1974).

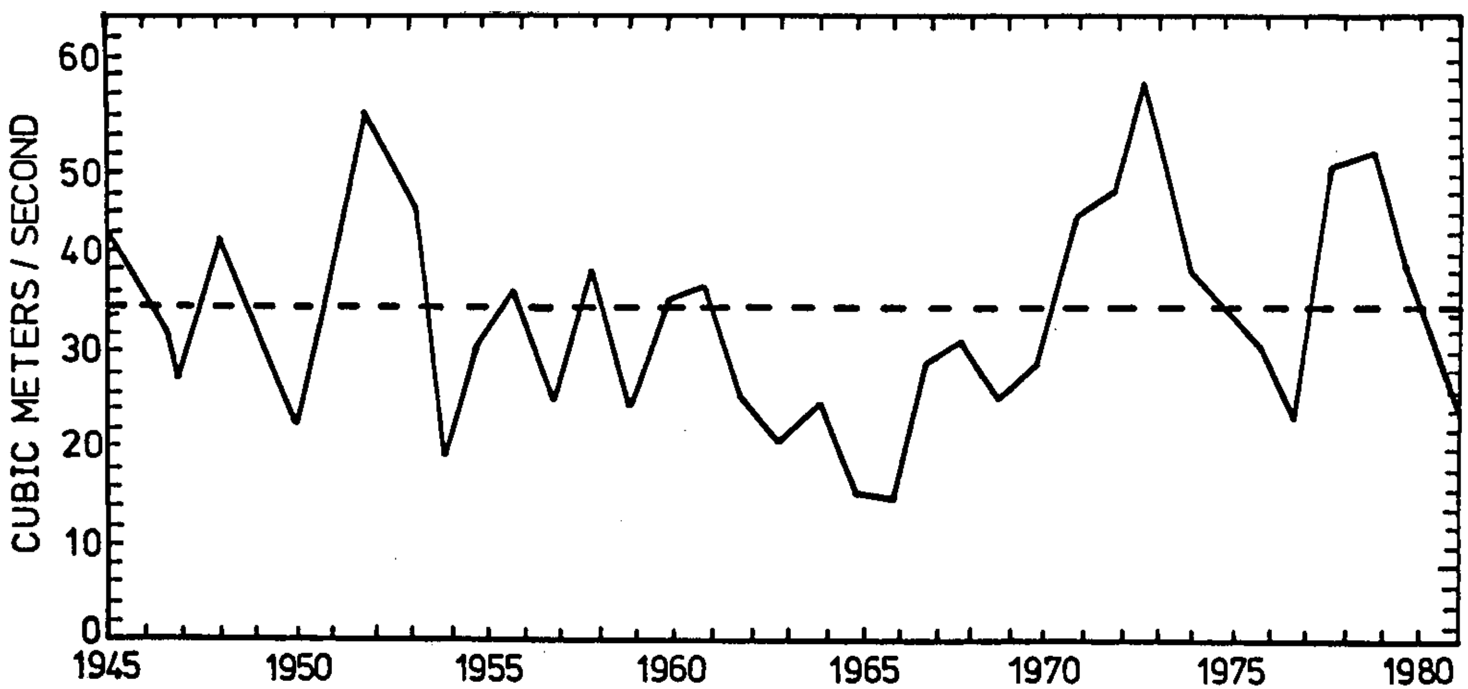

Figure F3 Mean annual moving average discharge (1945-1981) of the Raritan River at the Bound Brook gauge.

Table I Severe Floods on the Raritan River

Date	Peak Discharge (m 3/sec)	Rainfall Volume (cm)	Runoff Volume (cm)
September 1938	906	9.17	4.22
August 1955	872	9.93	5.33
May 1968	821	9.98	5.59
*August 1971	1302	20.37	8.79
August 1973	747	9.86	3.91

*Largest flood of record on the Raritan River

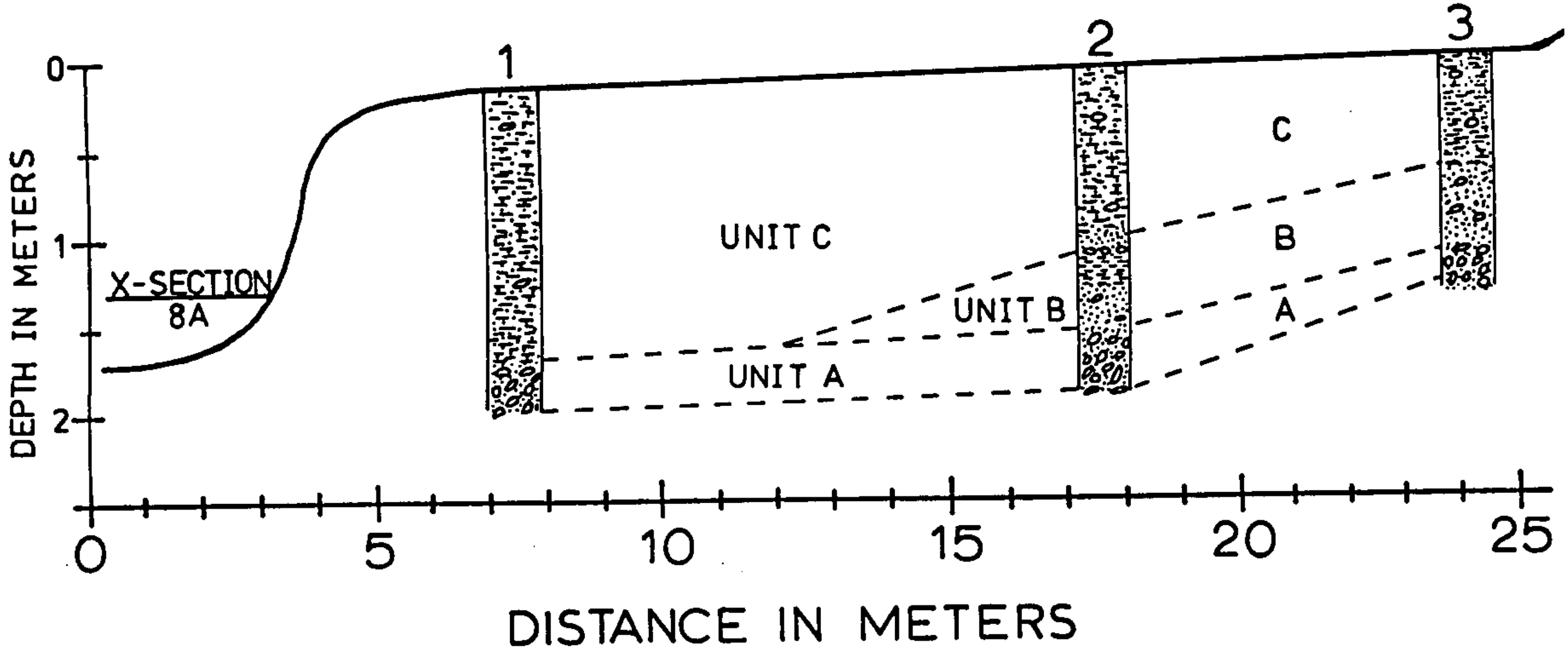

Figure F4 Stratigraphic description of flood plain sediments obtained from a core in the flood plain collected near Bound Brook on the main trunk stream of the Raritan (Haag, 1982).

Table II

List of chemicals analyzed for in the Raritan River sediments by the N.J. D.E.P. and their concentrations

Chemical	Detected	Not-Detected
Organic Compounds (conc. ug/kg)		
Aroclor 1016	x (971.9)	
Aroclor 1242	x (155.6)	
Aroclor 1248		x
Aroclor 1254	x (173.2)	
Alpha BHC	x (4.6)	
Beta BHC	x (1.3)	
BHC (Lindane)		x
Heptachlor	x (1.9)	
Heptachlor Epox.	x (10.2)	
Aldrin		x
Chlordane	x (184.2)	
P,P' DDE	x (20.1)	
O,P' DDT	x (4.9)	
P,P' DDD	x (3.1)	
P,P' DDT	x (4.0)	
Dieldrin	x (4.2)	
Endrin	x (3.0)	
Mirex		x
Methoxychlor	x (56.1)	
Toxaphene		x

Table II
continued

Heavy Metals (conc. ug/g)		
Arsenic	x (88.0)	
Beryllium	x (2.1)	
Cadmium	x (1.3)	
Chromium	x (34.0)	
Copper	x (82.0)	
Lead	x (209.0)	
Nickel	x (38.0)	
Selenium	x (2.0)	
Zinc	x (213.0)	
Complex Hydrocarbons (conc. ug/g)		
Flouranthene	x (3.2)	
Napthalene	x (3.1)	
Chrysene	x (2.0)	
Anthracene	x (3.1)	
Flourene	x (0.5)	
Phenathrene	x (2.4)	
Pyrene	x (2.2)	
Industrial Solvents (conc. ug/g)		
Benzene		x
Toluene		x
P & M Xylene		x
O Xylene		x
Ethylbenzene		x

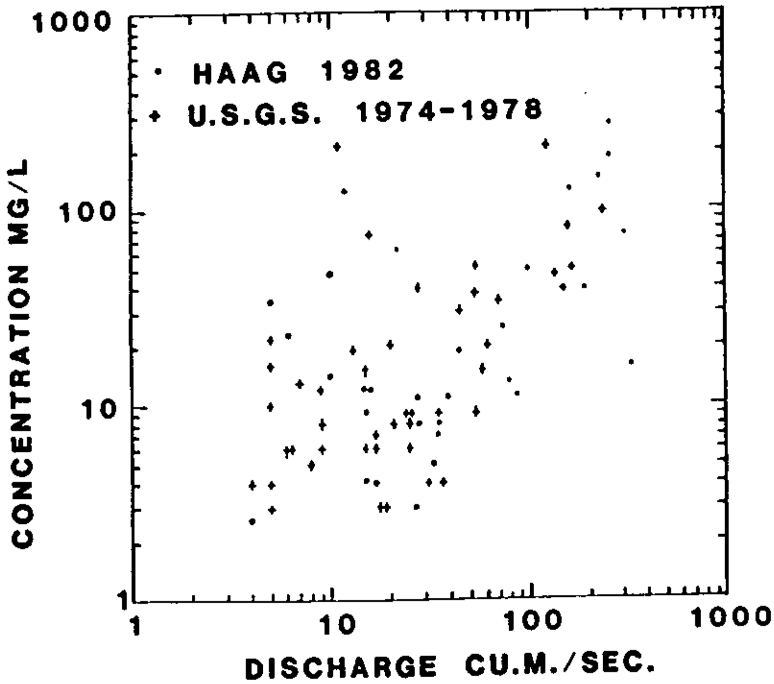

Figure F5 Plot of concentration of suspended sediment mg/l collected from the Raritan River at discharges up to 200 m3 sec-1.

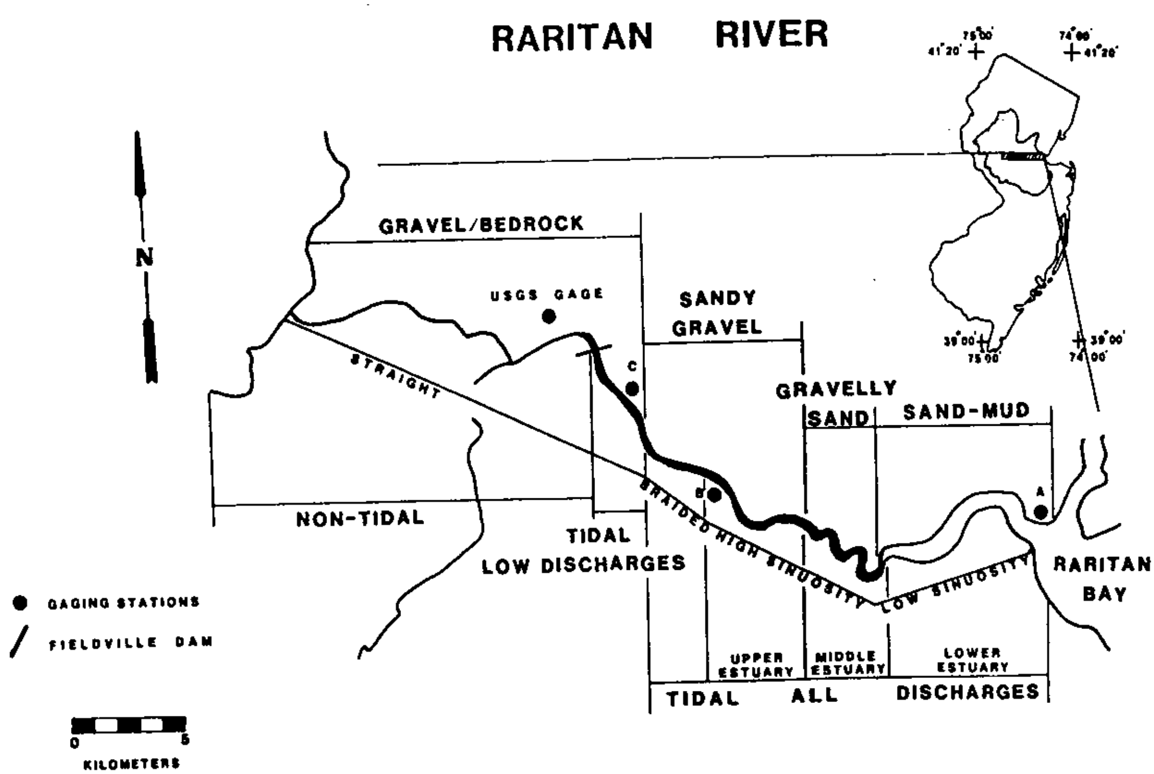

Figure F6 Map delineating the reaches of the river that are tidal and those that are non-tidal. Also indicated are geomorphology of the channel and grain size found on the bed.

flood plain is significantly wider than upstream and extends to a width of 400 m at some points. Trenches in the flood plain at Landing Lane Bridge (Field Trip Stop 5) reveal fine sand and silt deposits overlying gravel lenses; indicating that the channel has migrated in the past.

The reach within the head-of-tide is characterized by diurnal fluct-tuations in stage, current velocity, and current directions. Stage recorders emplaced just above the reach (Recorder A), below the reach (Recorder B) and at the river mouth (Recorder C) revealed a systematic change in water level in response to tidal fluctuations in Raritan Bay (Fig. D7; Fig. F6). During a typical spring tide (1.9 m) the stage at the river mouth fluctuates 1.75 m increasing to 2.3 m just below the braided reach and then decreasing sharply to 0.1 m upstream of the braided reach (Fig. F7). Lag between the flood tide peak at the river mouth and the peak above the braided reach is 2 hr 20 min. During a typical neap tide (1.0 m) range in stage at the river mouth is 1.0 m, which increased to 12.4 m below the braided reach and decreases to 0.0 within the braided reach. Water slopes range from 0 at high water slack to 0.0005 during peak ebb.

During a combination of spring tide and low run-off the head of tide is pushed upstream as far as 26 km and possibly 30 km from the river mouth (Anderson and Faust, 1974). Thus, the braided reach appears to reflect the zone over which the head-of-tide occurs under the complete spectrumm of tidal conditions (neap to spring). Salinity data taken during extremely low river discharge (4 m3 sec-1), and thus probably representing maximum intrusion of salt water, revealed a salinity of 3ppt at the bottom at the lowermost edge of the braided reach and no salt water within the braided reach.

The Raritan Basin includes four major impoundments, and several minor low-head dams that increase low-flow stages but do not inundate significant areas (Table I). Of the impoundments, Round Valley Reservoir (208 million m3) and Spruce Run Reservoir (41.6 million m3) are the largest. Built in the 1960's these serve as water-supply reservoirs for the central New Jersey area, storing water from the South Branch of the Raritan for release to supply

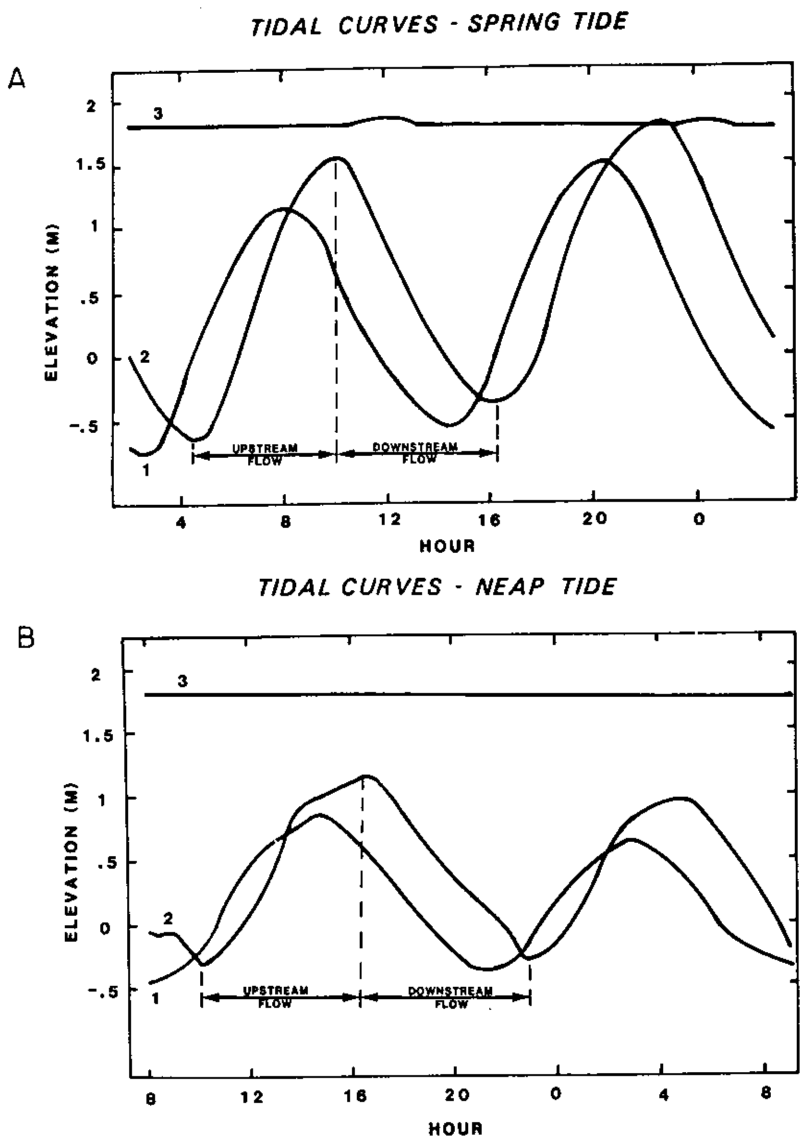

Figure F7 Stage data. A. Water level fluctuations vs. time during a spring tide (T.R. = 1.9 m). B. Water level fluctuations vs. time during neap tide (T.R.=0.9 m). Locations of stage recorders 1, 2, and 3 are A, B, and C in Fig. F6.

communities drawing water from the river further downstream or to maintain water quality during low-flow periods. Carnegie Lake (Field Trip Stop #4) is an impoundment on the Millstone River, built as part of the Delaware and Raritan Canal system. The canal, built in the 1820s, joins the Raritan at New Brunswick with the Delaware above Trenton. It follows the south side of the Raritan and Millstone Rivers, intercepting some minor drainages entering those rivers from the south. The canal delivers drinking water to New Brunswick and nearby communities; an overflow structure returns excess water to the Raritan at New Brunswick.

These hydrologic characteristics are important from a water-quality perspective because the Raritan suffers from a combination of large pollution inputs from both point-source and non-point discharges, and the need for water-supply diversions that reduce the amount available for dilution. These problems were acute during the 1983 drought, when flow in the main stem was reduced in order to maintain maximum storage in upstream reservoirs, resulting in significant water quality problems downstream.

Table III Impoundment characteristics (Pavlowsky, 1989)

CHARACTERISTIC	Spruce Run	Round Valley	Budd Lake	Carnegie Lake
Location	UR	UR	UR	MR
Elevation (m)	83	117	284	15.2
Mean Length (km)	6.4	4	1.5	5.5
Mean Depth (m)	7.9	21.6	-	1.2
Area (km^2)	5.2	9.5	1.4	1
Volume (x 1 million m^3)	41.6	208.2	-	1.2-2.7 dredging
Drainage Area:				
Total (km^2)	106.2	14.8	19.4	445
Percent of Basin Area	8.4	1.2	1.5	63.4

Many cities in this area, such as New Brunswick, were built largely in the 19th and early- to mid-20th century when urban development tended to be relatively dense and there was relatively little concern for flood plain management or open space preservation. As a result there are large areas drained by storm sewers that discharge into streams in which there is little flood storage or riparian vegetation that would reduce flood peaks and trap pollutants. Consequently urban runoff is a major source of pollution in the Raritan basin. Construction since the 1970s has generally avoided flood plains, and provisions for stormwater retention/detention in new developments are now in place.

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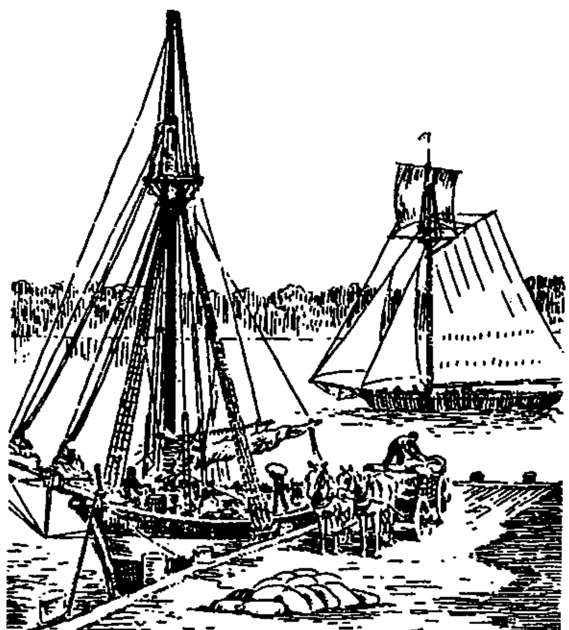

HERE THE GRAIN WAS LOADED ON SLOOPS WHICH BORE IT DOWN THE RIVER. MANY PROMINENT CITIZENS OWNED SLOOPS IN THE FLEET WHICH AT ONE TIME LINED THE RIVER FRONT

SPATIAL DISTRIBUTION OF METAL POLLUTION IN THE RARITAN BASIN

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INTRODUCTION

Sediment and water quality data are often used to identify metal pollution sources and pathways in river basins. Ideally, the data used for these purposes should be collected within the context of the particular spatial and temporal factors that may cause variations of metal concentrations at the scale of interest. Such factors include land use and geologic characteristics, the hydrologic conditions present at the time of sampling, and sediment geochemistry. However, the data available for such assessments are often collected for more general purposes and therefore lack the resolution required for sound scientific analysis. Nevertheless, significant amounts of information on the metal content of streams in the United States have been collected and can be used to evaluate metal pollution patterns given some limitations. This contribution investigates the spatial aspects of bed sediment and river water Fe, Mn, Zn, Pb, Cu, Cr, Ni, and As concentrations in the Raritan Basin using the United States Environmental Protection Agency STORET water quality data base. This report describes metal concentrations in the Raritan Basin in terms of:

1. magnitude and variability;
2. effects of land use and geology; and
3. pollution threshold values for use in water quality assessments.

METHODS

The data base used in this study consists of about 300 bed sediment and 1100 river water samples from 250 sites in the Raritan Basin and does not include estuary samples. Most samples were collected since 1978. The bed sediment samples used for analysis in this report represent metal concentrations described as "recoverable from bottom material" by government monitoring agencies (Bauersfeld et al. 1991). These samples have been subjected to a strong acid digestion. However, complete metal dissolution was not achieved with usual metal recovery at <95% of total content. Only the <2 millimeter fraction was used for analysis. This size fraction contains sand-sized particles that usually contain relatively low concentrations of metals. However, metal pollutants are most commonly associated with the silt and clay fractions (Horowitz 1991).

The river water samples used in this report represent metal concentrations described as "total, recoverable" (Bauersfeld et al. 1991). These samples consist of both the dissolved and suspended phases of metal transport and have been subjected to a dilute acid digestion that releases only the most readily soluble metal fraction. River water samples were collected over a variety of discharges. However, these data generally reflect the base flow conditions of the streams sampled since monthly sampling schemes preferentially sample the most frequent flow conditions. In the Raritan River, as discharge increases the concentration of metals in the water column also increases in response to increased fine-grained sediment concentrations that contain relatively high metal concentrations (Pavlowsky 1989).

Due to the preliminary nature of this report and the frequency of analytical detection limit problems in the data (i.e. "<" values), the results are presented in rank order form. In this report, detection limit exceedance values are ranked in order as one half of their value and higher than equal values of unadjusted data. The most commonly encountered analytical detection limits in bed sediment samples (ppm) are 10 for Pb, Cu, Cr, and Ni and 1 for As. Those for river water samples (ug/l) are 10 for Mn and Zn, 10 and 5 for Pb, 10, 5, and 1 for Cu, 10 and 5 for Cr, 2 for Ni and 1 for As. Additionally, 322 <10 ug/l river water values for As were not used for evaluation here because this limit is far above the range of values commonly found in the basin. Detection limit problems typically do not affect the upper end of the distribution or that portion that is greater than the median value. This is the most important area of analysis in this study.

RESULTS AND DISCUSSION

Metal Concentrations in Bed Sediment and River Water

The metal concentration values reported in the data base reflect five major influences: (1) local and regional background processes; (2) varying sediment particle size and geochemical characteristics; (3) point and non-point pollution inputs; (4) variations in analytical precision and accuracy; and (5) digestion procedure used to extract metals. The magnitude of metal concentrations in bed sediments decrease in the order: Zn>>Pb>Cu>Cr,Ni>As, and in river water in the order: Zn>>Pb,Cu,Cr,Ni>As (Table 1). Metal levels in the estuary are several times larger than those in the rivers of the Raritan Basin, suggesting that the estuary is a major sink of metal pollutants. In most cases, the 75%-tile values of the total sample are 1.3 to 2 times those from only low population density sampling sites, thus indicating that the threshold of anthropogenic influence has been exceeded in the basin. Sites that drain low population density areas are defined as those whose 1980 average township population density is less than 100 persons per square kilometer (USDC 1982). Two exceptions to this trend are found for Cr in both bed sediments and river water and As in river water. In these cases the effect of anthropogenic pollution appears to be limited. However, detection limits are problematic for As. The variability (10%-90% range) of metal concentrations in both bed sediments and river water tends to be from 2-10 times that of the median value. The variability of metal concentrations in both sediments and water decreases among low density sites when compared to the total sample.

TABLE 1: Metal Concentrations in Bed Sediment and River Water Samples

A. Bed Sediments (ppm)

		N	min	10%	25%	50%	75%	90%	max
Zn	all river data	243	<1	10	20	32	60	110	1600
	low density	93	<1	10	20	27	40	50	200
	estuary	51	50	72	170	308	361	448	505
Pb	all river data	239	1.5	<10	<10	10	30	55	560
	low density	93	2.9	<10	<10	6	12	21	80
	estuary	57	4	58	113	162	217	262	1285
Cu	all river data	237	0	2	4.5	<10	19	35	210
	low density	92	0	1.7	3.8	<10	6.7	10	210
	estuary	49	20	28	120	223	319	417	781
Cr	all river data	219	0	0.7	4	<10	10.4	20	260
	low density	84	0	1	4	<10	10	20	170
	estuary	55	7.8	12.5	32.8	49	72	102	306
Ni	all river data	237	0	1	<10	<10	10	20	70
	low density	92	0	1	<10	<10	<10	10	30
	estuary	49	1.4	18.1	27	36	40	55.3	107
As	all river data	228	0	0	0	1	4	9	63
	low density	86	0	0	0.2	1	3	5	14
	estuary	55	0.4	1.1	14	23.9	35	53	131

TABLE 1: Metal Concentrations in Bed Sediment and River Water Samples (con't.)

B. River Water (ug/l)

		N	min	10%	25%	50%	75%	90%	max
Zn	all river data	846	0	<10	10	20	40	70	862
	low density	232	0	<10	10	18	30	50	460
	estuary	83	<10	29	47	110	183	300	1300
Pb	all river data	907	0	2	3	<10	9	20	4800
	low density	254	0	1	<5	5	<10	17	4800
	estuary	107	<2	5	<10	13	24	41	647
Cu	all river data	923	0	2	3	<10	9	14	449
	low density	259	0	2	3	5	6	10	170
	estuary	79	7	13	21	34	50	112	170
Cr	all river data	839	0	2	<5	<10	10	20	2340
	low density	241	0	1	<5	<10	10	20	82
	estuary	59	<1	<5	5	8	20	31	60
Ni	all river data	777	0	1	<2	3	9	21	1460
	low density	224	0	<1	1	2	4	10	1460
	estuary	11	8	22	24	34	38	60	67
As	all river data	574	0	<1	1	1	2	4	42
	low density	179	0	<1	<1	1	2	3	22
	estuary	10	1	6	7	12	21	21	39

Effects of Geology: Fe and Mn Mobility

An examination of the spatial characteristics of Fe and Mn concentrations in fluvial systems may be valuable to studies of metal pollution for two reasons. First, Fe and Mn mobility in rivers is usually determined by background processes (i.e. bedrock weathering, ambient water chemistry, channel sedimentation). Therefore this data can be used to understand the regional differences of metal mobility. Second, Fe and Mn often form coatings on sediment particles in the form of secondary hydroxides or organic complexes which tend to accumulate metals (Horowitz 1991). If these phases preferentially bind metal pollutants, then correlations between metal concentrations and Fe and/or Mn content are required to elucidate pollution patterns. Another advantage here, is that these two elements are not susceptible to detection limit problems. Bed sediments in the Coastal Plain region are Fe-rich and Mn-poor when compared to the Highlands and Piedmont regions (Table 2). River water trends again show that the Coastal Plain exhibits much greater Fe concentrations than the other two regions. However, Mn mobility is much greater than expected from the bottom sediment trends. The poorly buffered, acidic coastal plain river water tends to dissolve and leach Mn most effectively.

Low population density sites exhibit slightly lower Fe and Mn concentrations than the total sample. This pattern may be explained in two ways. First, most of the low density sites are located in relatively high topographic settings that have steeper slopes and coarser sediment sources. Under these conditions both Fe and Mn concentrations would be expected to be lower since the finer sediments that accumulate these metals are relatively scarce or are contained in resistant phases not released during digestion procedures. Second, in higher population areas, the pollution contribution from nutrient inputs and industrial wastes will increase and thus provide an enriched source of Fe and Mn to rivers as either greater loadings from anthropogenic sources or coatings on anthropogenic substrates with high sorptive capacities. In summary, streams draining the Coastal Plain

TABLE 2: Effects of Geology on Iron and Manganese Concentrations

A. Bed Sediment (ppm; except where noted)

			N	10%	25%	50%	75%	90%
CP	Fe	all data	37	2800	4000	9300	2.0%	3.7%
		low density	4			1.4%		
	Mn	all data	36	3	20	57	80	150
		low density	4			53		
H	Fe	all data	88	552	1250	3350	6700	9800
		low density	39	680	1500	4400	5700	9300
	Mn	all data	61	140	180	240	380	650
		low density	29	160	180	200	280	450
P	Fe	all data	114	620	1900	4650	9900	1.7%
		low density	49	500	1500	3300	5400	7700
	Mn	all data	114	110	220	395	670	920
		low density	49	94	210	320	440	520

B. River Water (ug/l)

			N	10%	25%	50%	75%	90%
CP	Fe	all data	106	670	1100	1800	2900	3700
		low density	12	2200		2850		4800
	Mn	all data	125	40	60	100	140	180
		low density	12	50		70		110
H	Fe	all data	270	160	270	410	680	1040
		low density	123	150	260	400	660	1140
	Mn	all data	294	15	22	40	98	211
		low density	133	10	20	32	65	260
P	Fe	all data	222	110	170	310	500	940
		low density	62	110	150	280	340	1000
	Mn	all data	251	20	30	50	90	150
		low density	70	20	30	40	70	180

contain much higher levels of Fe and exhibit greater rates of Mn leaching than either the Highlands or Piedmont regions. These results suggest that the bioavailability and contamination potential of metal pollutants is relatively greater in coastal plain steams than in the rest of the Raritan Basin.

Pollution Threshold Values

A comparison of the low population density 90%-tile values for each metal from each geologic region shows general agreement with a few exceptions (Table 3). Higher bed sediment As and Cu levels are found in the Piedmont. This trend may be produced by the normally higher concentrations of these metals found in the Passaic Shales underlying the region or by the addition of fertilizer and pesticide pollutants from agricultural portions of the region (Pavlowsky 1989). River water Ni and Zn concentrations are higher in Coastal Plain streams and possibly reflect Fe/Mn geochemistry controls. The similarity of metal levels among low density areas should be recognized in terms of the errors introduced by relatively high analytical detection limits.

Pollution threshold values describe concentration levels above which a sample is considered to be enriched by anthropogenic metals. In this report, these pollution threshold values are determined by taking the average of the low population 90%-tile values from each geologic region for each metal and category (Table 4). The absolute range of variation for bed sediments is generally less than 10 ppm. However, Coastal Plain bed sediment data poorly represents low population density drainages. River water variability tends to be less than 10 ug/l, but Zn varies by about 40 ug/l among the three geologic regions. Variations in river water As, Cr, and Ni values fall within the range of error associated with USGS analytical precision (Lucey and Peart 1989). In a recent water quality report (NJDEP 1988), low pollution water quality index values for river water samples in New Jersey were defined a 50 ug/l for Cr, Cu, and Pb. These results demonstrate that more appropriate

TABLE 3: Effects of Geology on Metal Concentrations

A. Bed Sediment (ppm)

		Coastal Plain		Highlands		Piedmont	
		50%	90%	50%	90%	50%	90%
Zn	all data	35	100	30	90	40	120
	low density	27		30	50	23	50
Pb	all data	20	70	10	43	20	55
	low density	10		8	21	<10	20
Cu	all data	7	34	<10	20	7	50
	low density	2		<10	10	<10	20
Cr	all data	7	30	<10	20	<10	27
	low density	20		5	10	<10	20
Ni	all data	<10	23	<10	13	<10	24
	low density	<10		<10	<10	<10	10
As	all data	5	16	<1	4	2	9
	low density	<1		<1	3	2	6

B. River Water (ug/l)

		Coastal Plain		Highlands		Piedmont	
		50%	90%	50%	90%	50%	90%
Zn	all data	30	120	18	50	20	70
	low density	30	90	16	50	20	50
Pb	all data	6	24	<10	15	<10	23
	low density	<5	17	<10	11	4	21
Cu	all data	4	11	<10	13	<10	16
	low density	4	6	<10	10	4	10
Cr	all data	10	30	<5	20	10	24
	low density	<10	30	<5	20	7	23
Ni	all data	7	19	<2	12	4	29
	low density	8	12	<2	10	3	6
As	all data	1	3	1	7	1	3
	low density	1	3	1	3	1	<5

TABLE 4: Metal Pollution Threshold Values (a)

	Bed Sediment (ppm) value	range (b)	River Water (ug/l) value	range	MPSD (c) (ug/l)
Zn	50	(0)	50	(40)	7.5
Pb	20	(1)	20	(10)	3.75
Cu	20	(10)	10	(4)	0.75
Cr	20	(10)	25	(7)	7.5
Ni	10	(5)	10	(6)	7.5
As	5	(3)	3	(1)	0.75

(a) based on the comparison of low density site 90%-tile ranks in Table 3.
(b) absolute variation of 90% values among geologic areas.
(c) minimum "most probable standard deviation"; Lucey and Peart (1989).

levels should be set at less than 25, 10, and 20 ug/l, respectively. Nevertheless, more research is required to determine if the differences between geologic regions are real or just statistical artifacts.

Spatial Distribution of Cu and Pb Pollution

The pollution threshold values for Cu and Pb listed in Table 4 are used to describe metal pollution patterns in the Raritan Basin for 18 sub-basin areas (Table 5). Sub-basin delineations are based on those described in the New Jersey water quality inventory report (NJDEP 1988). The data in Table 5 is normalized by the mean of each category in order to calculate a metal pollution score for each sub-basin (Table 6). The normalized data for Cu and Pb in bed sediment and river water categories have similar means and ranges. The sub-basins exhibiting the lowest metal levels are the Lower Lamington River, Upper South Branch, Stony Brook, and Rockaway Creek and the highest metal levels are South River and Matchaponix Brook, Raritan River, Upper and Lower Millstone River, and Lower South Branch. This ranking is strongly dependent on the samples used for ranking, and although very convenient, this procedure does not take into account actual metal-environment interactions that control the spatial variability of metals in fluvial systems. However, this ranking can be used as a preliminary characterization of metal pollution in the Raritan Basin upon which to develop future studies or management priorities.

CONCLUSIONS

The 90%-tile concentrations in bed sediments in the Raritan Basin are 110 ppm for Zn, 55 ppm for Pb, 35 ppm for Cu, 20 ppm for Cr, 20 ppm for Ni, and 9 ppm for As and for river water are 70 ug/l, 20 ug/l, 14 ug/l, 20 ug/l, 21 ug/l, and 4 ug/l, respectively. Corresponding metal concentrations in the estuary may be an order of magnitude higher than those in the rivers indicating that it is a major sink of metal pollutants. The 90%-tile metal concentrations in low population density subsamples are usually several times

TABLE 5: Lead and Copper Pollution Values

Sub-basin (a)	Bed Sediment Pb	Bed Sediment Cu	River Water Pb	River Water Cu
Upper South Branch	38 (26) (b)	0 (28)	3 (70)	4 (73)
Lower South Branch	32 (28)	21 (28)	12 (90)	18 (100)
Neshanic R.	50 (4)	25 (4)	0 (14)	0 (14)
North Branch	20 (30)	15 (32)	9 (158)	11 (162)
Upper Lamington R.	20 (30)	9 (23)	7 (104)	22 (109)
Lower Lamington R.	6 (16)	0 (16)	0 (12)	0 (13)
Rockaway Ck.	5 (19)	11 (19)	8 (36)	9 (23)
Raritan R.	0 (10)	30 (10)	13 (86)	35 (88)
Middle Brook	no data	no data	11 (87)	15 (87)
Green Bk.	no data	no data	100 (6)	63 (8)
Lawrence Bk.	100 (1)	0 (1)	0 (13)	0 (14)
Upper Millstone R.	50 (16)	31 (16)	10 (48)	9 (53)
Lower Millstone R.	46 (21)	24 (21)	13 (70)	22 (76)
Beden Bk.	50 (10)	10 (10)	0 (13)	14 (14)
Stony Bk.	63 (8)	13 (8)	0 (20)	0 (20)
Manalapan Bk.	30 (10)	9 (11)	7 (29)	11 (28)
Matchaponix Bk.	40 (5)	17 (6)	23 (31)	23 (30)
South R.	75 (4)	50 (4)	16 (19)	0 (11)

(a) basin descriptions are reported in NJDEP (1988)
(b) Units in percentage (%) of samples (n) above the threshold limit listed in Table 4, with sample size in parentheses.

TABLE 6: Metal Pollution Rankings

Class	Score (a)	Sub-basin	Notes
VERY LOW	0.2	Lower Lamington	
LOW	1.8	Upper South Branch	
	2.5	Stony Brook	high bed Pb
	2.5	Rockaway Creek	low bed Pb
	2.8	Neshanic River	small sample size
	n.d.	Lawrence Brook	only one bed sample
MEDIUM	3.2	Beden Brook	low water Pb
	3.2	Manalapan Brook	low bed Cu
	3.4	North Branch	
	3.8	Upper Lamington	high water Cu
	n.d.	Middle Brook	no bed data
HIGH	5.1	Lower South Branch	
	5.2	Upper Millstone River	high bed Cu
	6.1	Lower Millstone River	
	6.2	Raritan River	low b Pb/high w Cu
	n.d.	Green Brook	no bed data
VERY HIGH	6.8	Matchaponix Brook	high water Pb and Cu
	6.9	South River	small sample size

(a) sum of mean normalized pollution values lower than those in the total sample. Chromium appears to be the least affected by anthropogenic inputs in the Raritan Basin. Streams draining the coastal plain contain much higher levels of Fe and exhibit greater rates of Mn leaching than either the Highlands or piedmont regions, suggesting that metal pollutants may be relatively more bioavailable in these streams. The sub-basins exhibiting the lowest Cu and Pb metal levels are the Lower Lamington River and Upper South Branch, and those with the highest levels are the South River and Matchaponix Brook, Raritan River, and Lower Millstone River. Future research on the spatial distribution of metal contamination in the Raritan Basin should focus on bed and floodplain sediment contamination since discharge variations during river water sampling cause interpretive problems that require an unrealistic number of samples to resolve. Sediment investigations should focus on the sedimentological and geochemical fractionation of metals in sediments. Digestion and analytical procedures must be tested, selected, and optimized so that an adequate understanding of the relationships among background, land use, and potential contamination. Above all an appreciation for the spatial variability of metal concentrations in river systems should be maintained.

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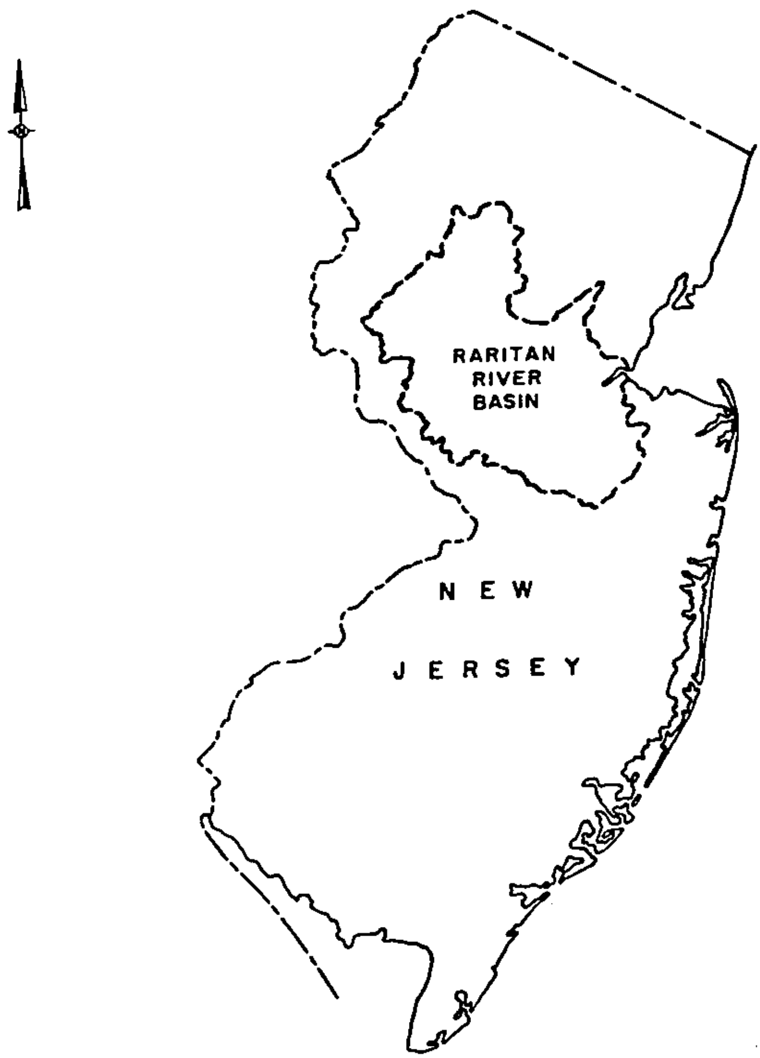
RARITAN
RIVER
BASIN
N E W
J E R S E Y

GEOCHEMICAL FORMS AND TOXICITY OF HEAVY METALS IN THE RARITAN RIVER BASIN, NEW JERSEY

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INTRODUCTION

The source, toxicity, and fate of heavy metals in the environment is of major concern to the general public because of damages to important food, drinking water, and recreational resources. River courses have long been areas where population and industry have concentrated, and this has caused widespread degradation of the environmental health and is a threat to the economic vitality in these regions. Besides being important conveyers of nutrients to estuarine and oceanic systems, river systems also transport heavy metals and other pollutants to these vital resources.

Evaluation of the damage caused by elevated heavy metals in fluvial systems is problematic because the various geochemical forms of each metal have different toxicities to aquatic biota (O'Donnel et al., 1985). Traditional indicators such as total concentration or total soluble concentration of heavy metals in the water column are often inaccurate indicators of the health of aquatic systems (Bernhard et al., 1986). Determination of the chemical speciation of metals in solution and particulate matter can provide an estimate of the toxicity of the metal to aquatic biota and assess the source, potential remobilization, and fate of heavy metals in fluvial environments (Forstner, 1987).

The Raritan River Basin, the southern portion of the larger-Raritan Estuary, drains 2862 square kilometers of heavily populated and industrialized central New Jersey (see Table 1). In addition to its important uses as a source of food, recreation, and drinking water for the residents of central

New Jersey, the Raritan River is also used as a disposal medium for industrial and domestic wastes and non-point source pollution, such as urban runoff. Anderson (1970) reported elevated levels of metals in the main stem of the Raritan River below Manville. Haag (1982) observed metal enrichment in sediments in the floodplain areas in the lower reaches of the Raritan River. Renwick and Ashley (1984) found metal pollution associated with fine-grained sediments in the Raritan Estuary. Greig and McGrath (1977) concluded that metal concentration patterns in Raritan Bay followed both sediment and fauna distribution patterns. The factors thought to control, or influence, the concentration, speciation, and biological availability of trace metals are depicted in Fig. H1.

The purpose of this study was to determine the concentration and geochemical forms of ten heavy metals (Ag, As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn) in the water column of the Raritan River and three tributaries. From this information, the toxicity of these metals to aquatic organisms and humans was assessed. The source, transport, and fate of these heavy metals were also evaluated. The impact of urbanization on the concentration and toxicity of these metals was also investigated.

FIELD AND LABORATORY METHODOLOGY

One hundred and twenty depth-integrated water column samples were taken with a US DH-76 sampler from bridges spanning three tributaries (Upper Raritan (North and South Branches), Millstone River, Bound Brook) and the main trunk of the Raritan River between September 1985 and April 1987. Samples were filtered through a 0.45 micron teflon filter to separate dissolved and particulate metal fractions. To determine the geochemical forms of the heavy metals, the Mahan et al. (1987) microwave digestion technique of the Tessier et al.(1979) extraction method was performed on composite particulate samples from each tributary. A full description of the field regimen and laboratory procedures can be found in McLaughlin (1988).

Table 1: Physical, cultural, and lithologic characteristics of the Raritan River Basin and the four study sections, Lower Raritan (LR), Upper Raritan (UR), Millstone River (MR), and Bound Brook (BB) (from McLaughlin, 1988).

Physical Features	LR	UR	MR	BB
Basin Area (km^2)	2253	1269	702	169
Mean Annual Discharge(cms)	38.1	21.8	11.3	2.9
Mean Study Discharge (cms)	35.0	24.0	11.0	2.8
Mean Monthly High Q(March)	69.0	39.0	21.0	3.5
Mean Monthly Low Q (Oct.)	21.0	12.0	6.0	2.1
Main Channel Slope	0.0031	0.0041	0.0011	0.0027
Basin Surface Storage*	0.146	0.095	0.223	0.242
Hydrologic Behavior**	Normal	Normal	Sluggish	Flashy

Cultural Features	LR	UR	MR	BB
%Forested	33	37	30	20
%Agricultural	48	52	54	4
%Urban#	19	11	16	76
%Impervious Area##	10	7.5	8.5	25
%Wastewater (base Q)###	47.2	14.2	66.6	2.1
%Wastewater (median Q)###	5.0	1.8	7.1	0.2
%Wastewater (high Q)###	1.4	0.5	2.0	0.05
Population####	611	217	142	229
Population Density (/km^2)	271	171	203	1354
Population Density (/mi^2)	702	443	523	3520

Lithologic Features@	LR	UR	MR	BB
%pre-Cambrian gneiss	21	37	-	-
%Jurassic Red Beds	45	44	41	72
%Jurassic Basalt	6	1	-	28
%Jurassic Diabase	3	1	7	-
%K-T Coastal Plain Seds.	12	-	39	-
%C-O Carbonates	2	3	-	-
%other@@	11	13	14	-

* = percent impoundment + lake area
** = relative behavioral changes in discharge in response to precipitation

= industrial + residential (1976 NJDEP Land Use Map)
= from Stankowski (1974), using 1980 population data
= maximum estimated values based on NJPDES discharge permits (from Pavlowsky, personal communication)
= 1980 U.S. Census

@ = by areal coverage
@@ = Paleozoic and Mesozoic Clastic Sedimentary Rocks

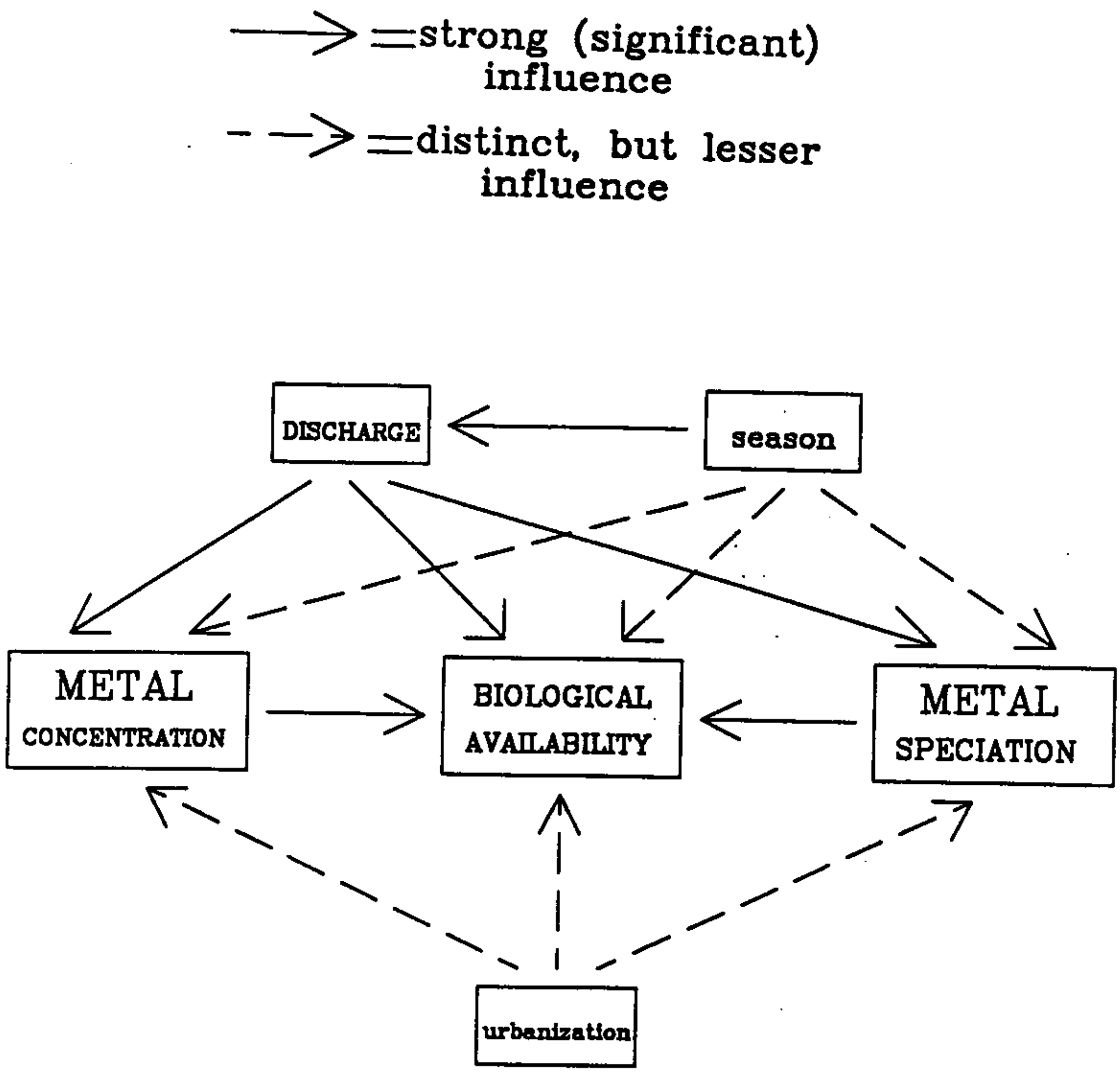

Figure H1 Factors that control or influence the concentration, speciation, and bioavailability of trace metals in the Raritan River.

The concentration of each metal in dissolved and particulate form, within suspended sediments, and in the different geochemical fractions within the particulates were analyzed using a Direct Current Plasma Atomic Emission Spectrometer (DCP-AES) using a specially made cassette which measures ten metals simultaneously. The DCP-AES measures the atomic emission of vaporized elements and compares the emission signal with a calibration curve developed from known stock solutions and from certified National Bureau of Standards River Sediment #1645.

Detection limits of the Direct-Current Plasma Atomic Emissions Spectrometer (DCP-AES) in ug/l (or ppb) are:

Element	Spectrametrics III Detection Limit (ppb)	Experimental Dissolved (ppb)	Experimental Sediment (ppm)
Ag	4	3	7
As	80	20	60
Cd	5	0.5	2
Co	5	0.3	0.8
Cr	2	0.5	2
Cu	2	0.3	0.6
Hg	20	0.1	0.1
Ni	2	0.2	0.4
Pb	10	3	6
Zn	6	2	6

The Mahan et al. (1987) microwave digestion technique of the Tessier et al. (1979) method was used to chemically define five different geochemical species within the particulate fraction: (1) exchangeable; (2) bound to carbonates; (3) bound to Fe and Mn oxides; (4) bound to organics; and, (5) bound to silicates (residual). Heavy metals in dissolved (<0.45um) form are most available for uptake by aquatic biota (O'Donnel et al., 1985). Metals in the exchangeable fraction are weakly held by organic or Fe/Mn oxide films on the surface of particulates and are directly or easily available to aquatic organisms (Morrison, 1987). Metals bound to carbonates, Fe/Mn oxides, and organics are available to aquatic biota only after changes in the fluvial environment (Morrison, 1987), such as pH, redox, or salinity

(Forstner, 1987). Metals bound within the silicate framework of primary or secondary minerals are not available to organisms living within or using river water (Tessier et al., 1980).

DATA REDUCTION

All data generated by DCP-AES were gathered, calibrated, and reduced by a software package (Plasma PC) developed by Mike Carr (1985). This software package was modified by Andrew Rowan (Dept. of Environmental Sciences, Rutgers University) to also calculate regression equations for dissolved, particulate, and total metal concentrations in the water column, as well as the concentrations available, potentially available, and not available to biota. The metal concentrations were determined from least squares regression equations using log-transformed discharge values. Particulate, potentially-available, and not-available fractions were also log-transformed due to their tendency to increase exponentially with the log of discharge and the log-transformed values provided best-fit equations. The least-squares regression lines were tested for statistical significance based on a t-test at a 95% confidence interval using a table produced by Fisher and Yates (1957).

The concentrations of available, potentially available, and not-available metals were calculated for individual samples by dividing the particulate fraction into the different geochemical speciation obtained by analyzing the composite samples. The concentration of heavy metals available to aquatic biota was estimated by adding the dissolved concentration with the exchangeable fraction of the particulate concentration. Potentially available metal concentration was calculated by adding the carbonate, Fe/Mn Oxide, and organic fractions within the particulates. The concentration of metal not available to biota was equal to the residual fraction of the particulates.

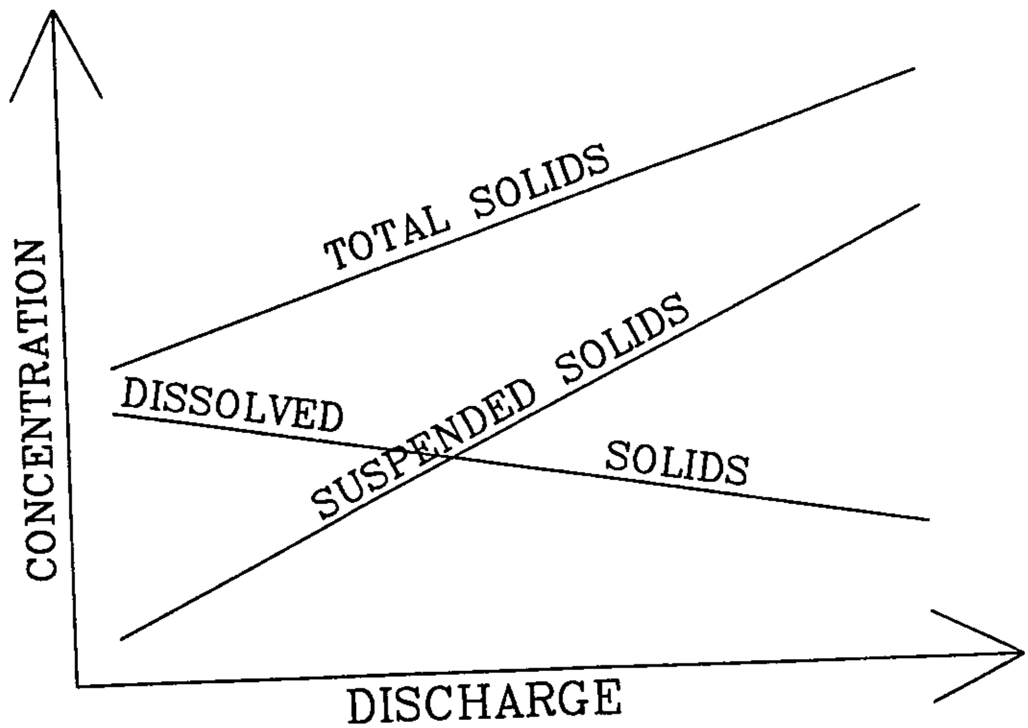

Figure H2 Idealized plot of the concentration of total dissolved solids, total suspended solids, and total solids in response to discharge.

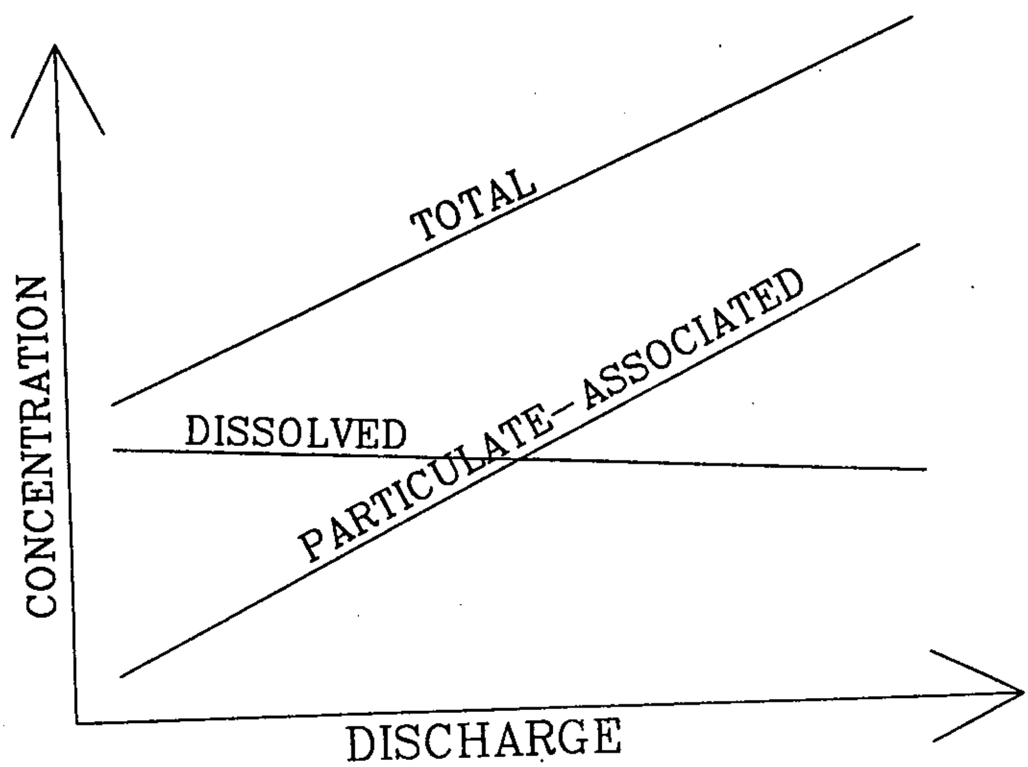

Figure H3 Idealized plot of dissolved, particulate-associated, and total trace metal concentrations in response to discharge.

Table 2: Concentration of metals in dissolved (<0.45um), particulate, total, and bioavailable forms in micrograms per liter (ug/l) or parts per billion (ppb) in the Lower Raritan (LR), Upper Raritan (UR), Millstone River (MR), and Bound Brook (BB) at median flow conditions. Bioavailable concentration is equal to the dissolved concentration plus the concentration in the exchangeable specie of the particulate fraction. The concentration of metals in suspended sediment in micrograms per gram (ug/g) or parts per million (ppm) at median flow conditions is also listed. (from McLaughlin, 1988)

METAL/TRIBUTARY		DISS	PART	TOTAL	AVAILABLE	SUSPENDED (ppm)
Zinc	LR	28	14	42	39	834
	UR	17	5	21	20	584
	MR	38	10	48	43	641
	BB	40	13	53	51	995
Lead	LR	13	7	20	17	321
	UR	10	5	15	13	426
	MR	9	8	17	12	409
	BB	14	10	24	20	533
Copper	LR	16	8	25	19	406
	UR	15	5	20	17	460
	MR	19	8	27	21	429
	BB	27	8	35	29	547
Chromium	LR	4	4	7	4.3	171
	UR	4	2	6	3.6	199
	MR	4	4	8	4.2	185
	BB	5	3	8	5.4	216
Nickel	LR	3	1	4	3.8	64
	UR	2	.8	3	2.1	60
	MR	3	1	5	3.8	70
	BB	3	1	5	3.9	89
Cobalt	LR	.9	.4	1	1.2	19
	UR	1	.3	1	1.1	19
	MR	1	.4	2	1.3	23
	BB	1	.5	2	1.4	22
Arsenic	LR	5	2	7	5.1	19
	UR	3	1	4	3.2	44
	MR	5	1	6	4.9	35
	BB	5	1	6	5.0	89
Cadmium	LR	.3	.5	.8	.4	5.8
	UR	.4	.4	.8	.4	5.9
	MR	.3	.3	.6	.4	6.7
	BB	.3	.3	.6	.4	9.0
Silver	LR	.3	1	1	.3	30
	UR	.7	.7	1	.6	24
	MR	.2	.7	.9	.2	35
	BB	2	.9	3	2.2	55
Mercury	LR	.2	<.1	.3	.2	1.7
	UR	.2	<.1	.3	.2	1.4
	MR	.1	<.1	.2	.1	2.2
	BB	.2	<.1	.3	.2	2.2

RESULTS

Concentration

The concentration of the major parameters were significantly influenced by flow conditions as Total Dissolved Solids (TDS) decreased with increasing discharge and Total Suspended Solids (TSS) increased with increasing discharge (Fig. H2). The concentrations of heavy metals in the four tributaries closely followed the behavior of the major parameters (McLaughlin, 1988). The concentration of dissolved heavy metals tended to decrease with increasing discharge (Fig. H3). Particulate-associated and total metal concentrations strongly increased with increasing discharge. These findings are typical of river systems (Forstner and Wittmann, 1981). The heavy metals zinc, lead, and copper were found in the highest concentrations in dissolved form in all four reaches within the Raritan River Basin at median flow conditions (Table 2). The highly developed Bound Brook watershed exhibited the highest concentration of dissolved metals in the Raritan Basin.

Zinc,lead, and copper were found in the highest concentrations associated with the suspended particulates in all reaches (Table 2). Concentrations of particulate-associated metals were quite similar in all study basins despite the different degrees of development in the four study reaches. Total (dissolved plus particulate) concentrations of per volume of river water were also highest in zinc, lead, and copper in all four rivers within the Raritan River Basin (Table 2). As with the dissolved fraction, the urban Bound Brook basin typically displayed the highest total concentrations of the ten metals investigated in this study.

Concentrations of zinc, lead, copper, and chromium were found in the highest levels in the suspended sediments (Table 2). Again, the developed Bound Brook exhibited the highest concentration of most of the ten study metals. This finding appears to conflict with the earlier observation of similar concentrations of particulate-associated metals found in all basins. It is likely that the lower amount of suspended solids in the Bound Brook

Table 3: Geochemical speciation of particulate metals in the Lower Raritan (LR), Upper Raritan (UR), Millstone River (MR), and Bound Brook (BB) in percent of the concentration in suspended sediment. The speciation of silver and mercury were omitted because results were generally not reproducible within 20% (* = not detected) (from McLaughlin, 1988).

Metal	Trib	%Exch.	%Carb.	%Oxide	%Organ.	%Resid.
Zn	LR	25	24	17	14	20
	UR	36	20	12	11	22
	MR	29	21	18	9	24
	BB	45	23	14	7	11
Pb	LR	29	28	27	9	7
	UR	43	30	15	7	6
	MR	36	22	24	10	9
	BB	32	31	29	5	3
Cu	LR	12	37	21	21	8
	UR	23	32	12	17	16
	MR	13	29	14	24	21
	BB	22	37	14	18	9
Cr	LR	10	4	20	24	42
	UR	2	1	20	18	58
	MR	7	2	13	19	59
	BB	3	6	28	25	38
Ni	LR	33	8	14	11	25
	UR	27	6	15	13	40
	MR	32	11	12	10	36
	BB	33	12	15	10	29
Co	LR	42	2	15	8	33
	UR	37	2	10	7	43
	MR	37	2	18	10	33
	BB	36	3	22	9	31
As	LR	17	51	15	6	11
	UR	13	47	22	9	9
	MR	20	41	20	6	13
	BB	18	48	21	4	10
Cd	LR	36	*	30	8	27
	UR	24	*	34	12	31
	MR	48	*	16	3	33
	BB	51	*	19	12	19
Total	LR	26	28	18	13	15
	UR	31	29	16	10	15
	MR	27	22	21	12	20
	BB	31	32	20	9	9

Table 4: Proposed human and ecological health-based criteria for metals in drinking water, surface water, and surface soil in New Jersey.

METAL	PROPOSED HEALTH-BASED STANDARDS DRINKING WATER	SURFACE WATER	SURFACE SOIL
zinc	5000	59+	1500
lead	5	1.3+	100
copper	1000	6.5+	600
chromium	100	11	500
nickel	100	88+	250
cobalt	-	-	-
arsenic	.02	.02	20
cadmium	4	.66+	1
silver	20	1.2+	40
mercury	2	.01	14

Note: Drinking water (ground water) are based on the proposed revisions to the Ground Water Quality Standards published in the New Jersey register on 21 January 1992. The surface soils criteria are based on the proposed Cleanup Standards for Contaminated Sites published in the New Jersey Register on 3 February 1992. These health-based criteria are calculated using a 1×10^{-6} additional lifetime cancer risk for carcinogens and determined from the reference dose for non-carcinogens. The listed soil standards are the most stringent of the exposure routes including direct contact, accidental ingestion, and inhalation. The surface water criteria are based upon the proposed revisions to the Surface Water Quality Standards. The listed surface water criteria are the most stringent of the acute (48-96 hour short-term bioassay) or chronic toxicity criteria or human health criteria. The values noted with "+" are for the metals whose health-based criteria vary with hardness, with listed criteria based on a hardness of 50 mg/l as $CaCO_3$.

causes the suspended solids to become more highly concentrated with heavy metals in this urban reach as compared to the other rivers (McLaughlin, 1988). Overall, the particulate-associated metals are similar in all basins as higher concentrations of metals in the suspended sediment of the Bound Brook is offset by lower amounts of suspended sediment in the water column.

Speciation

The percentage of each metal within the five chemically-defined fractions with the suspended particulates are listed in Table 3. It is evident that the metals widely associated with anthropogenic activities, zinc, lead, copper,arsenic, and cadmium, have relatively high proportions in the biologically available exchangeable fraction. Except for cadmium, the potentially available carbonate fraction also contains a high proportion of these metals. These two geochemical fractions are known to become enriched in heavy metals in polluted fluvial systems (Forstner, 1987). Chromium, nickel, and cobalt have the greatest proportion within the silicate framework (residual fraction) of the particulates.

Toxicity

The concentration of zinc, lead, and copper were found at the highest levels in forms available to aquatic biota, either dissolved or in the exchangeable fraction of the suspended particulates. Lead and arsenic were consistently found above proposed drinking water standards in all tributaries (Table 4). The highly developed Bound Brook tributary exhibited the greatest exceedances above drinking water standards. The average concentration of dissolved and bioavailable lead (10 and 13ppb) and arsenic (3 and 3.2ppb) in the Upper Raritan River is of particular importance because the intake to the Elizabethtown Water Company is below this sampling station.

Surface water quality standards were typically exceeded for lead, copper, arsenic, and mercury in all tributaries at a hardness concentrations typically found in the waters of the Raritan Basin. The surface water quality

Table 5: Metal concentrations in urban and rural precipitation, wastewater discharge, urban stormwater run-off, and enrichment factors for metals in suspended sediment of all basins at median flow conditions. All values (except enrichment) in micrograms per liter (ug/l) or parts per billion (ppb). Enrichment factors were determined by comparing the average concentration of metals in suspended sediment at median flow in all basins with the concentration of metals in the Jurassic Brunswick Formation.

Metal	Precipitation		Wastewater+	Urban Runoff	Enrichment*
	Rural	Urban			
Zn	7.0@	44.0#	192.0	335.0%	8.6
Pb	5.0@	45.0#	80.0	280.0*	7.4
Cu	6.0@	6.0#	103.0	135.0%	26.5
Cr	0.5*	1.0#	37.0	16.0*	1.8
Ni	0.1*	3.0#	64.0	46.0*	1.6
Co	1.0@	1.0@	1.0	2.0*	0.5
As	1.1@	0.7@	7.0	9.0&	2.9
Cd	0.4*	0.9*	8.0	10.0%	2.1
Ag	0.01*	0.01*	4.0	5.0&	3.9
Hg	0.05@	0.05@	0.4	0.26*	4.7

+ = from Pavlowsky (1990), based on mean values of Feiler (1980) and Mueller et al. (1982)

* = from McLaughlin (1988)

@ = from Peters and Bonelli (1982)

= from Wilbur and Hunter (1980)

% = from Whipple and Hunter (1980)

* = from Mueller et al. (1982)

& = from Field (1985)

standard of silver was normally exceeded in the urban Bound Brook only. These heavy metals may be impairing the environmental health and recreational quality of the four study reaches in the Raritan River Basin. Additional investigation of these river systems, including ecological surveys, bioassays, and biomonitoring, is warranted to quantify the impact of lead, copper, arsenic, mercury and other pollutants on the health of aquatic biota in the Raritan Basin.

Suspended sediment concentrations of lead, arsenic, and cadmium usually exceeded surface soil standards, with silver exceeding standards only in the Bound Brook. Again, the urban Bound Brook reach exhibited the highest levels of heavy metals in the suspended sediments within the basin. Elevated levels of metals in suspended sediments are of concern because these sediments are transported to more sensitive estuaries and also deposited in floodplains during floods.

Sources

The finding of elevated zinc, lead, and copper in the different fractions with the water column of all four basins are consistent with earlier studies in other urban settings in New Jersey, which found these contaminants to be elevated within urban precipitation, wastewater, and urban runoff (Table 5). Comparison of the suspended sediment concentration with the concentration of metals in the Brunswick Formation (Table 2) shows that the suspended sediments are enriched in nine metals investigated in this study, especially zinc, lead, and copper.

Based on the higher enrichment factors (>2X) and the occurrence of these metals in various waste streams, it appears that seven of the study metals (zinc, lead, copper, arsenic, cadmium, silver, mercury) have predominately anthropogenic sources. The speciation patterns of these metals, with a large proportion of metal in bioavailable and potentially available fractions, supports this observation.

The primary source of chromium, nickel, and cobalt appear to be largely from natural weathering processes as the enrichment factors for these metals are considerably lower that the other study metals. The correlation coefficients of the particulate-associated concentration of these metals were also greatest (.87-.98), which also suggests similar and consistent (natural weathering) sources for chromium, nickel, and cobalt (McLaughlin, 1988). Additionally, the speciation pattern of chromium, nickel, and cobalt, with a large portion of these metals within the silicate structure of the suspended particulates, further support this observation.

Elevated levels of heavy metals in all forms are charcteristic of the urban Bound Brook basin, which suggests that increasing development leads to higher concentrations of metals in the water column. The source of the elevated metals in the Bound Brood appears to be the greater percentage of urban runoff that occurs in this basin, as wastewater discharge is least important in this tributary.

Transport and Fate

The transport of heavy metals in all geochemical forms is most significant during high flow conditions (see Pavlowsky, this volume). During flood stage conditions, heavy metals are deposited in the floodplains along the lower reaches of each of the four rivers. Storage of heavy metals within the channels of the rivers appears to be insignificant as bedrock floors much of the study reaches (Renwick and Ashley, 1984). The sediments trapped by impoundments may be temporarily store some metals, especially in the Millstone River and Bound Brook. The ultimate fate of the heavy metals in the Raritan River and tributaries is the downstream estuary and ocean. This fate threatens these downstream resources as they are more sensitive to heavy metal enrichments than freshwater systems.

CONCLUSIONS

Analysis of dissolved, particulate, total, suspended sediment, and speciation of heavy metals in the water column of four reaches within the Raritan River Basin has revealed the following findings:

1) concentrations of lead, copper, arsenic, and mercury exist at levels which may be adversely impacting the health and recreational quality in all four rivers; 2) the urban Bound Brook typically exhibits the greatest concentrations of heavy metals in dissolved, total, suspended sediment, and bioavailable forms. Urban runoff appears to be the most important source of heavy metals in this developed basin; 3) the most important sources of zinc, lead, copper, arsenic, cadmium, silver, and mercury appear to be primarily anthropogenic as these metals exhibit high enrichment factors and are commonly found in precipitation, wastewater, and urban runoff. Chromium, nickel, and cobalt appear to have largely natural sources as these metals have low enrichment factors and have high proportions within the silicate fraction of particulates. 4) the fate heavy metals in the water column of the Raritan River and its tributaries is ultimately the downstream estuary and bay, which are more sensitive to elevated heavy metals. Accumulation of heavy metals in floodplain sediments has also been observed and has the potential to remobilize.

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SEDIMENT ASSOCIATED AND DISSOLVED METAL LOADINGS IN THE RARITAN RIVER

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INTRODUCTION

Trace metal pollutants in aquatic systems may become available to biota and thus enter biogeochemical pathways that ultimately lead to human exposure. High concentrations of metals have been found in water samples of some New Jersey rivers (Anderson 1970; Robinson 1983; NJDEP 1988). In response to the limited knowledge of the loading rates and sediment-metal associations of metal pollutants in New Jersey rivers, a sampling program was undertaken from September 1985 to April 1987 to collect data that could be used to address these issues in the Raritan River. Water and suspended sediment samples were collected during different hydrologic regimes since the importance of discharge variations on metal transport in the Raritan River was not clear (Anderson and Faust 1974; Mueller et al. 1982). This contribution summarizes the results of metal loading investigations in the Raritan River (Pavlowsky 1989). The objectives of this report are to:

1. quantify annual solids and Zn, Pb, Cu, Cr, and Ni loading rates;
2. describe the load duration characteristics for solids and metals; and
3. estimate the importance of anthropogenic sources on metal loads.

The metal-sediment geochemistry aspect of metal transport in the Raritan River is covered in other publications (Maest et al. 1985; McLaughlin et al. 1988; see Chapter G, this volume). METHODS Three sampling sites were selected for study as follows: (1) Raritan River at Manville, USGS station no. 1400500; (2) Millstone River at Weston, USGS station no. 1402540; and (3) Raritan River at the railroad bridge about 1 kilometer downstream of the USGS station at Queens Bridge, Bound Brook, no. 1403300. These site locations are abbreviated in the text as follows: RRU- Raritan River at Manville, MR- Millstone River at Weston, and RRL- Raritan River below the Queens Bridge USGS station (Table 1). The USGS has compiled information on instantaneous discharge, monthly discharge, mean annual discharge, and flow duration probabilities for all three sampling sites (Bauersfeld et al. 1991). Area-unit conversion factors from flow in cubic meters per second as used by the USGS to flow in liters per second per square kilometer drainage area as used in this report are: RRU- x0.02231; MR- x0.04451; and RRL- x0.01408. River water samples were collected from bridges over a wide range of flow conditions with a US DH-76 integrated depth sampler. Temperature and specific conductivity were measured in the field using a portable Yellow Springs Instrument Model 33 meter. All sampling sites were visited during a single sampling run that took about 2 hours to complete. Twenty-nine samples were collected from the RRU and MR sites. However, only 24 were collected at the RRL site, because it was added to the sampling program after the initial study began. Sampling runs were divided equally among base flow, flood rising limb, and flood falling limb hydrologic regimes. Samples were filtered through 0.45 micron teflon filters. The samples were analyzed for metal content on a Direct-Current Plasma Atomic Emissions Spectrometer by Frank McLaughlin at the Rutgers University Department of Geological Sciences (McLaughlin et al. 1988). Acidified filtrate samples were concentrated by 25 times and analyzed directly. Filter residue subsamples (100 mg) were digested with hot HNO_3-HF and then redissolved in 10 ml of 3N HCl for analysis. Sample specific conductance values were used to estimate the dissolved solids concentration by using regression equations of dissolved solids concentration (mg/l) over specific conductance (us/cm), that were calibrated with USGS water quality data (Pavlowsky 1989). Annual solids and metal loadings at each site were estimated for the two-year period from July 1985 to June 1987 by the rating curve-load duration method. This method has been used to calculate metal loadings in other New Jersey rivers (Whipple et al. 1978; Schornick and Fishel 1980) and typically produces loading estimates within 15% of the actual loadings (Walling and Webb 1981; Yaksich and Verhoff 1983; Ferguson 1986). Separate curves were used for base flow, rising limb, and falling limb hydrologic regimes. The regression equations used here take the form of log loading over log discharge. Area-scaled loadings are presented as megagrams per square kilometer per year for solids and as kilograms per square kilometer per year for metals. Load-discharge rating equations are weighted by flow probabilities derived from daily USGS flow gaging station data (Table 1). Twenty-two flood events evenly distributed over the year were sampled at each site to determine total event and rising limb duration values. This sample represents about one-third of all the events and two-thirds of the event runoff occuring during the study (Table 1).

RESULTS AND DISCUSSION

Solid Loadings Suspended sediment (SS) loads among the three sites decrease in the order: RRU>RRL>>MR (Table 2). It appears that relatively low relief and high impoundment frequency reduce the supply and transport rates of SS loads in the Millstone Basin. The SS loads derived here are well within the normal range reported for New Jersey Piedmont streams (Hindall and Jungblut 1980; Table 3). The low dissolved solids (DS) loading found at the MR site may be related to the types of geologic units drained by the Millstone River (Table 1). DS loadings tend to be higher in streams draining the Highlands and lower in streams on the Coastal Plain (Pavlowsky 1989). Metal Loadings Total metal (prefix "t") loadings decrease in magnitude similarly at all three sites in the order: Zn>>Pb>Cu>>Cr>>Ni (Table 2). Metal loads decrease among sites in the order: RRL>RRU>MR, indicating the the drainage area below the RRU and MR sites contributes relatively large amounts of metals to the Raritan River. These differences are most noticeable for tZn, tCr, and tNi. Suspended metals (prefix "s") represent the dominant form of transport in the basin. The percentage of annual total metal loading in the suspended form (%sus) decreases among metals from about 85% to 50% in the order: Cr>>Zn>Ni=Pb>>Cu, with suspended sediments usually comprising less than 50% of the annual TS

TABLE 1: Raritan Basin Hydrologic Data

Sampling Location	RRU Manville	MR Weston	RRL below Queens Bridge
Drainage Area (km^2)	1269	668	2212
Mean Annual Discharge (m^3/s)	21.9	11.3	37.8
Record length (years)	70	77	54
Average Discharge (l/s/km^2)			
95%	2.1	1.9	1.9
50%	9.9	8.9	9
mean	17.3	16.9	17.1
10%	35.5	36.3	36.9
2-year Sample Discharge (l/s/km^2)			
95%	4.6	1.8	1.4
50%	10.3	8.9	7.9
mean	18.6	17.9	16.4
10%	34.8	34.1	34.8
Diversions (% of mean annual discharge; "-" additions/"+" removal)			
Water supply	+0.8	-0.7	+13.1
Wastewater	-1.8	-6.7	-5.2
Flood Hydrograph Duration (n=22; median values)			
Total Event (hours)	34.5	42.5	39
Rising Limb (% of total)	44	36	38
Geology (% of drainage area)			
Piedmont	59	62	64
Highlands	41		24
Coastal Plain		38	12
Data source/USGS Station	Manville	Blackwells Mills	Calco Dam
No.	1400500	1402000	1403060
Drainage Area (km^2)	1269	639	2005

TABLE 2: Solids and Metals Loadings (Mg-solids or kg-metals /km^2/yr)

	RRU load	log s	%sus	MR load	log s	%sus	RRL load	log s	%sus
TS	100.5	0.22	50	72.3	0.18	44	93.2	0.16	47
SS	50.4	0.35		31.6	0.31		43.7	0.28	
tZn	20.4	0.31	63	18.3	0.32	59	28.4	0.32	75
sZn	13.0	0.32		10.8	0.23		21.4	0.29	
tPb	14.8	0.30	63	12.3	0.26	56	15.9	0.26	69
sPb	9.4	0.32		6.9	0.19		10.9	0.24	
tCu	13.5	0.32	53	12.1	0.25	46	13.6	0.19	53
sCu	7.2	0.32		5.6	0.25		7.18	0.19	
tCr	8.9	0.33	82	6.7	0.25	76	10.6	0.24	87
sCr	7.3	0.33		5.1	0.25		9.2	0.24	
tNi	3.2	0.27	73	3.1	0.23	55	4.1	0.21	74
sNi	2.4	0.32		1.7	0.26		3.0	0.24	

TABLE 3: Metal loadings (kg/km^2/yr)

System	Zn	Pb	Cu	Cr	Ni	Source
RIVERS						
Mississippi R.	18.5	4.1	4.3	6.9	5.2	Presley et al. 1980
Susquehanna R.	8.4		1.4	0.7	2.8	Carpenter et al. 1975
Hudson-Raritan R.	112.5	47.1	46.9	13.4		Ayers and Rod 1986
Hudson-Raritan R.	81.3	24.4	24.4	17.6	14.7	Mueller et al. 1982
Hudson R.	17.3	7.0	9.9	8.2	3.8	"
Raritan R.	17.7	12.0	5.2	4.4	0.3	"
Passaic R.	34.9	24.6	15.6	6.6	1.9	"
Mill Ck (NJ)	25.1	31.6				Schornick and Fishel 1980
Saddle R. (NJ)	199.4	369.1	74.6	11.4	24.1	Wilber and Hunter 1979
McDonalds Br. (NJ)		1.7	0.7		1.9	Swanson and Johnson 1980
COMPONENT LOADINGS						
Precipitation	13.9	7.6	4.7	0.6	1.3	ppt of 40.1 l/s/km^2 x Table 5
Annual Leaf fall	68.0	5.6	33.6	0.9	8.4	Pavlowsky 1989
Anthropogenic Releases:						
a. Basinwide 1980	246.9	300.0	34.4	27.5		Ayers and Rod 1986
b. Wastewater	5.2	2.2	2.8	1.0	1.7	Pavlowsky 1989

loading in the basin (Table 2). Copper loadings are equally divided between the suspended and dissolved forms which indicates that it is relatively mobile in the Piedmont surface water systems studied here. Loading estimate errors are described here by the standard deviation of the residuals of the rating regression equation (s) (Table 2). The error values are similar for total and suspended metal loadings. However, total solids errors are lower than those for suspended sediments implying that much less error is associated with dissolved solid loading estimates. This interpretation is difficult to verify since the dissolved solid values were previously smoothed by the specific conductance-to-dissolved solid concentration conversion process. At the lower Raritan site, more metals are transported in association with suspended sediments than at the other sites. The Millstone site transports the least (Table 2). This could mean that suspended sediment loadings in the lower Raritan are more contaminated than those above the other two sites and/or more effective binders of dissolved metals (i.e finer-textured or organic-rich). It is interesting to note that the three metals exhibiting relatively high loadings at the RRL site (Zn, Cr, Ni) tend also to have higher proportions transported in association with suspended sediments. The methods used in this study may tend to underestimate rather than overestimate the relative proportion of suspended sediment-associated metals in loading values. This effect stems from: (1) the tendency of rating curve load estimates to be less biased for dissolved than suspended metals (Walling 1977; Ferguson 1987); and (2) the operationally-defined dissolved form upper limit that may include some particulate metals (Kennedy et al. 1974) (as discussed in Pavlowsky 1989). Therefore, the importance of the suspended phase of metals transport in the Raritan Basin is probably underestimated as reported here. Significance of Metal Loadings. The metal loadings presented in this study compare similarly with those reported by other studies of central New Jersey rivers (Table 3). Drainage basins with proportionally large runoff contributions from industrial, residential, and urban areas exhibit the highest metal yields, such as those found the Saddle River, Mill Creek, and Lower Hudson River. In the McDonalds Branch, metal loads are low due to low sediment loads, low human disturbance, and highly-leached sandy basin soils (Swanson and Johnson 1980).

In order to further understand the significance of the metal loadings in the Raritan Basin and to create an "order-of-magnitude" comparison, metal loading values for other system components were estimated or taken from the literature (Table 3). Annual metal loadings from combined atmospheric and seasonal leaf fall sources usually equal or exceed by several-fold the fluvial loadings presented here. Anthropogenic loading values published by Ayers and Rod (1986) for the Hudson-Raritan Basin are larger by over an order magnitude for Zn and Pb and about 2-3-fold greater than fluvial exports for Cu and Cr. Wastewater metal loadings regulated by NJPDES agencies are about a quarter to half of the metal loadings measured at the three study sites. Two implications result from this evaluation.

First, most of the metals released from anthropogenic sources are not exported by fluvial transport suggesting that large storages of metals exist in basin soils and sediments. Second, these storages can produce temporal lags in metal transport that cause pollutant sources to take on a diffuse nature, making pollution source assessments more difficult in terms of surface water quality monitoring. Load Duration Characteristics of Solids and Metals Load duration assessments are used to examine the temporal relationships Between discharge and substance loadings. In this report, solids and metal load duration relationships are expressed in terms of the percentage of total annual loading transported during a particular time interval as defined by flow duration calculations for the two-year study period (Table 4). The hydrologic definitions of the time intervals chosen for evaluation are as follows (letters refer to column headings in table 4): (A) base flow conditions; (B) flood event discharges less than mean annual discharge; and (C) flood event discharges greater than the mean annual discharge. Generally, base flow conditions (A) occured from 50 to 60 percent of the time with the mean annual discharge being exceeded (C) 26 percent of the time at the three sites. Overall, larger flows with a combined frequency of less than 3 months

TABLE 4: Load Duration Data (% of total loading; see text for column headings)

	RRU			MR			RRL		
	A	B	C	A	B	C	A	B	C
Discharge	18.2	16.6	65.2	18.9	11.5	69.6	16.4	10.7	72.9
SS	0.5	3.5	46.2	2.1	2.5	39.1	0.7	3.8	42.4
DS	11.9	9.5	28.5	16.2	8.5	31.7	12.2	7.2	33.7
sZn	1.1	6.3	56.0	4.5	4.5	50.4	2.2	6.1	67.1
dZn	5.3	5.3	26.0	9.4	3.5	28.0	3.9	2.9	17.7
sPb	2.2	7.5	53.7	5.0	4.1	46.7	1.3	7.7	59.8
dPb	6.2	5.2	25.2	6.5	4.0	33.6	5.4	3.3	22.5
sCu	2.6	6.4	43.4	4.7	4.5	37.1	2.4	6.1	44.5
dCu	7.1	7.9	31.7	13.9	5.9	33.9	9.6	5.4	32.1
sCr	1.3	6.7	74.1	3.8	5.2	67.5	1.1	8.4	77.4
dCr	3.7	3.9	10.2	4.5	3.3	15.8	2.4	2.1	8.5
sNi	0.9	6.4	65.6	3.5	3.8	48.2	1.1	6.8	65.8
dNi	5.4	4.4	17.3	10.8	5.19	28.6	5.6	3.4	17.4

TABLE 5: Average Concentrations of River Metal Loadings

	Suspended (ppm)				Dissolved (ug/l)			
	RRU	MR	RRL	Ref.	RRU	MR	RRL	Ref.
Zn	257	342	490	79	12.7	13.2	13.5	10.0
Pb	186	218	250	45	9.2	9.6	9.6	3.0
Cu	143	178	165	20	10.7	11.6	12.3	2.0
Cr	146	162	211	63	2.7	2.8	2.7	0.5
Ni	47	55	69	33	1.5	2.5	2.1	1.0

accounted for over three-fourths of the annual metal loadings. Low flow conditions are relatively more important for dissolved metal (prefix "d" in Table 4) transport than for suspended transport. Accordingly, the importance of the suspended form of metal transport is inversely related to the flow exceedance probability (Table 4). Lower flows were most important for solids and metals transport at the MR site and least important at the RRU site. Some metals exhibit relatively high suspended proportions during baseflow periods, such as in the case of Zn, Pb, Cr, and Ni at MR and Zn at RRL. This condition may be caused by additional anthropogenic inputs and/or varying sediment properties. The load duration characteristics of solids and metals underscore the importance of diffuse pollution sources in the Raritan Basin that are active during short periods of storm runoff. Future river water sampling programs for metals should focus on flood event discharges greater than mean annual discharge. Anthropogenic Effects on Metal Loadings Mean metal concentrations in suspended sediments and water calculated from loading and discharge data show more "between site" variation in the suspended form han in the dissolved form (Table 5). Given the confidence limits of the regression equation coefficients and analytical detection limits, the mean dissolved metal concentrations may be considered to be similar at all sites for each metal. This observation suggests that metal sorption and solubility equilibria are related to the regional geology of the lower and middle portions of the basin and that sediments are actively scavenging anthropogenic metals. Background reference values are estimated from published bedrock, soil, groundwater, and precipitation data from the central New Jersey area (Table 6). Direct comparisons between the semi-quantitative background reference values reported here and river loads are not possible because of the lack of control for grain size effects and particle geochemistry, high detection limits, and possible contamination problems. However, good agreement between the Passaic Shale, the major bedrock unit underlying the middle and lower Raritan Basin, and Piedmont soils is found for Zn, Pb, Cu, and Ni. It is not clear why Cr concentrations are so low in the soil when

TABLE 6: Background Metal Concentrations in Bedrock, Soil, and Water

		Shale (ppm)		Soil (ppm)		Water (ug/l)	
		NJ (a)	Global (b)	NJ (c)	E. USA (d)	Rain (e)	Groundwater (f)
Zn	value	76	95	81	36	11	10
	sample n	3		10	370	7	63
Pb		46	20	44	14	6	<5
		3		6	370	7	54
Cu		17	45	22	14	3.7	2
		3		11	370	39	54
Cr		103	90	23	36	0.5	<1
		3		7	370	12	54
Ni		38	68	27	13	1	no data
		3		14	370	12	

(a) means: Pavlowsky (1989).
(b) Global average: Turekian and Wedepohl (1961)
(c) Piedmont soils, medians: Pack et al. (1953); Painter et al. (1953); Woltz et al. (1953); Connor et al. (1957); Prince et al. (1957); and Tedrow (1986).
(d) Eastern USA B-horizon means: Connor and Shacklette (1975).
(e) means: Swanson and Johnson (1980); Mueller et al. (1982); and Peters and Bonelli (1982).
(f) Piedmont aquifer means, USGS data from 6/83-9/88: Bauersfeld et al. (1991).

compared to the parent bedrock. The high relative abundance of Cr and Ni in the bedrock and soils indicates a significant geologic source of these metals in the basin. Fairly good agreement is also found between the metal levels found in precipitation and groundwater. Copper in both forms appears to be the most enriched metal at the three river sites when compared to the background reference values thus indicating a relatively high geochemical mobility and/or the presence of active Cu pollution sources above the study sites. Nickel appears to be the least enriched metal in the fluvial loadings. Although limitations on accurate comparisons do exist, in general Zn, Pb, and Cu metal loads in the basin appear to be significantly affected by anthropogenic sources while in the case of Cr and Ni the situation is less clear.

CONCLUSIONS

Metal loadings from the Raritan River to the estuary decrease in the order: Zn>>Pb>Cu>>Cr>>Ni. The loadings are similar in magnitude to those found in other New Jersey piedmont rivers and appear to be enriched to a significant degree by anthropogenic sources, particularly in the cases of Zn, Pb, and Cu. When compared to basinwide atmospheric, anthropogenic, and biologic metal fluxes, fluvial exports are relatively small. This imbalance suggests that large storages of metal pollutants exist in basin soils and sediments. Suspended sediment-associated metal transport in the Raritan River decreases from about 85% to 50% of the total loading in the order: Cr>>Zn>Ni=Pb>>Cu. Mean annual dissolved metal concentrations are similar, while suspended metal concentrations are quite variable. This implies that suspended sediments are actively binding metals and that dissolved concentrations are controlled by regional geologic conditions. Base flow regimes transport less than 15% and discharges greater than the mean annual discharge about 75% of the annual metal loading to the estuary. The importance of suspended sediment-associated metal transport during relatively rare, high discharge events requires that future water quality monitoring efforts utilize event-related sampling strategies to resolve the diffuse nature of metal pollution in the Raritan Basin.

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ESTUARINE HYDRAULICS AND SEDIMENT LOAD

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Based on Pritchard's (1967) definition of an estuary, the upstream limit of the Raritan River Estuary is delineated by the maximum extent of salt water intrusion. During low runoff (fluvial discharge) and flood tide conditions the salt water typically reaches to about 20 km from the mouth (Fig. J1). Therefore, the Raritan River Estuary is defined to extend from the mouth to kilometer 20. Bottom salinities at the mouth reach a maximum of 24.5 ppt and a minimum of 17.5 ppt, whereas those at the surface reach a maximum of 22.5 and a minimum of 12.0 ppt. At 15 km from the mouth maximum and minimum salinities at the bottom were 12.5 ppt and 0 ppt, respectively, whereas maximum and minimum salinities at the surface were 10.5 and 0 ppt, respectively. The intrusion of salt water is at a minimum (about 12 km from the mouth) during high runoff and ebb tide conditions. Even during flood tide, high runoff (fresh water discharge) can significantly reduce the upstream extent of salt water intrusion. Thus, the estuary displays different salinity distributions depending on the fresh water discharge and the stage of tide. Based on the net non-tidal current velocity, the net non-tidal salinity distribution and the relative magnitudes of river and tidal flow, the Raritan River estuary is partially mixed under most tidal flows (Fig. J2). Data collected by Motta (1984) indicate a progressive upstream change towards well mixed conditions presumably resulting from the change in channel geometry (Fig. J3) and associated effects of the river discharge.

The average temperature within the estuary varies during tidal cycles depending on the relative temperatures of the fresh and salt water. Temp.

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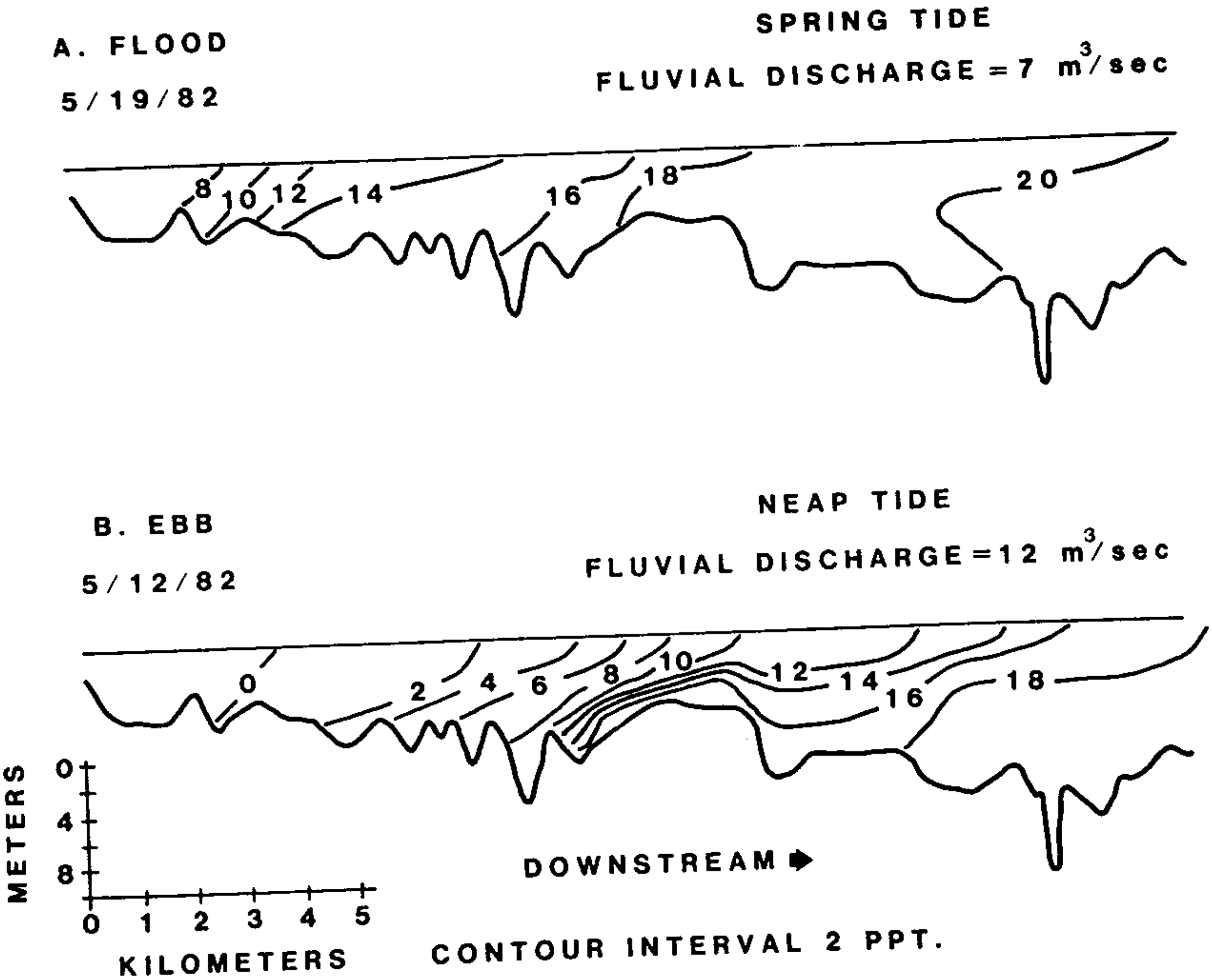

Figure J1 Longitudinal salinity profiles (Motta, 1984).

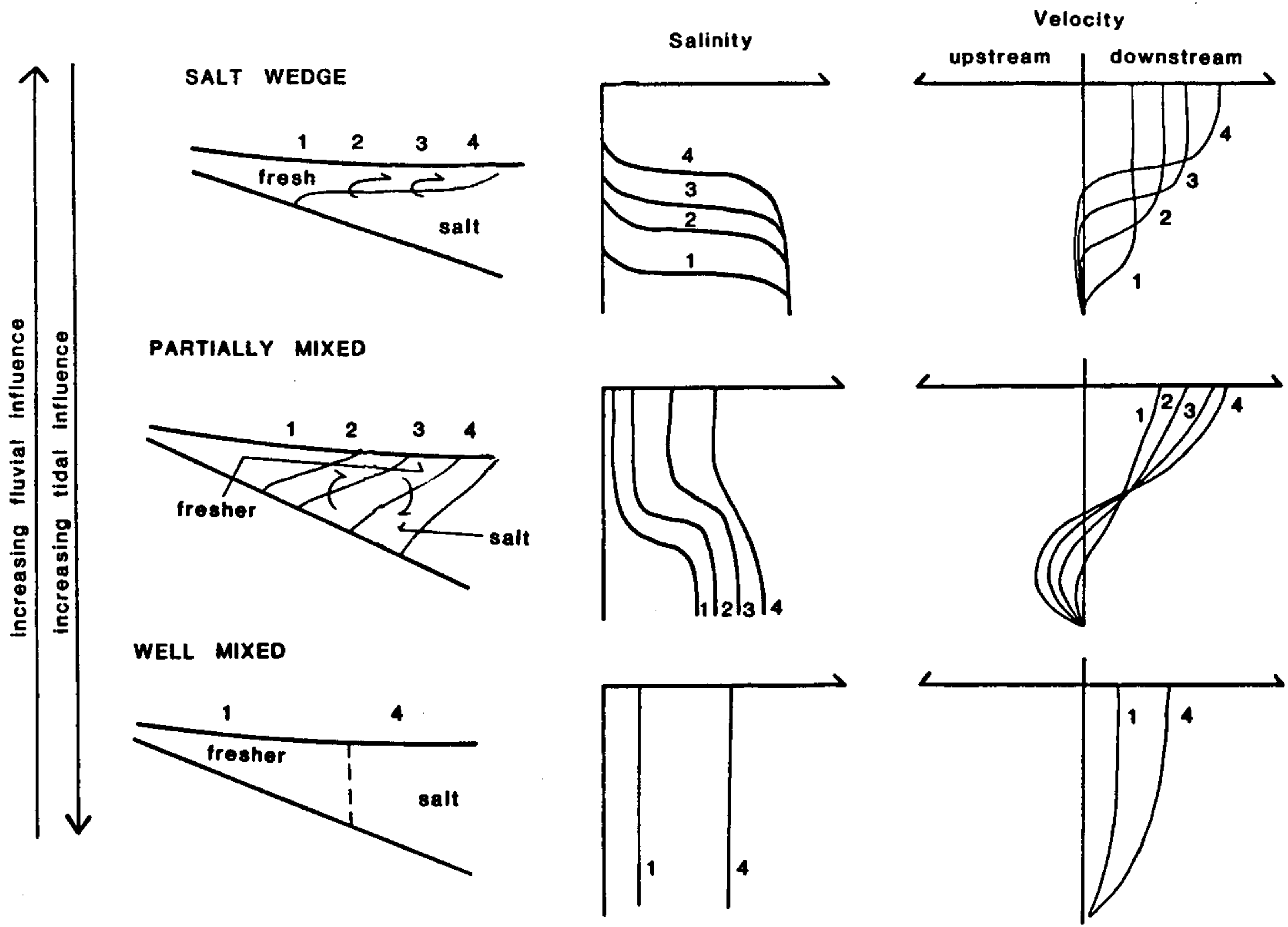

Figure J2 Schematic representations of the 3 main types of estuaries (modified from Dyer, 1973).

RARITAN RIVER CROSS-SECTIONS

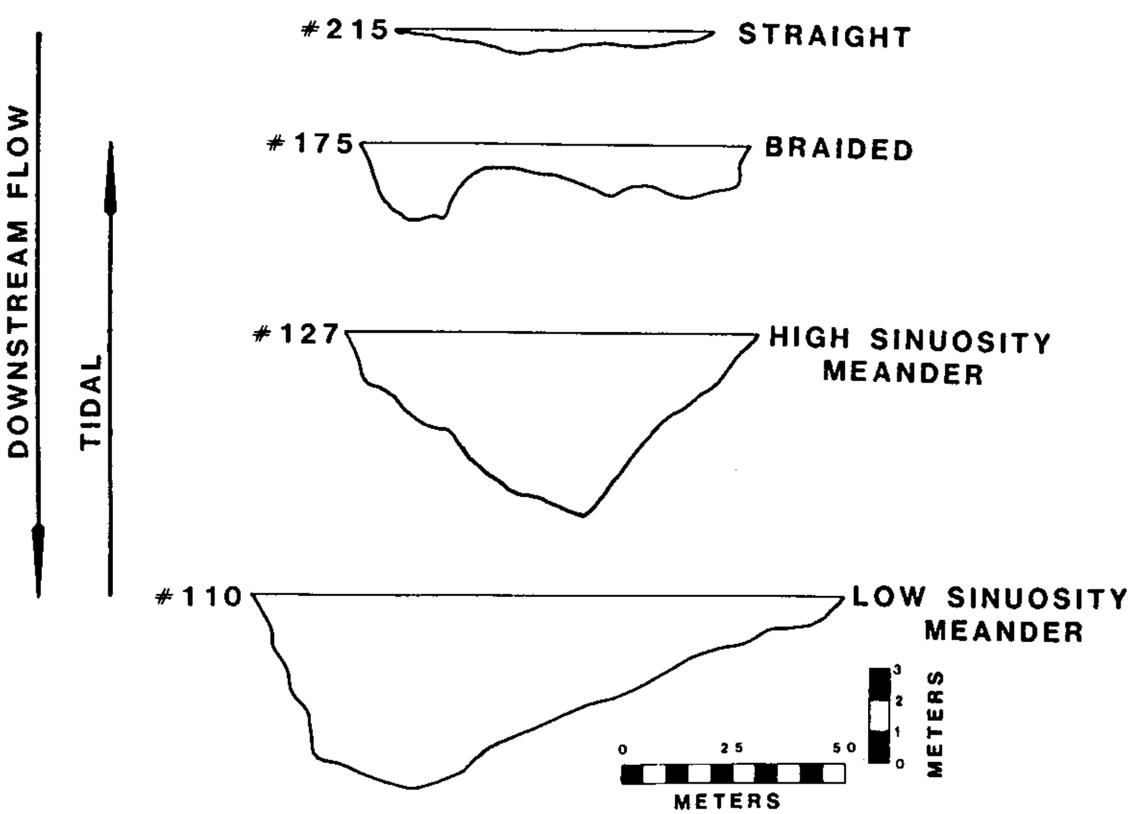

Figure J3 Representative cross-sections of river channel demonstrate the distinctive geometry in each of the four geomorphologically different reaches.

eratures range from 25 C to 5 C. Temperature stratification is usually moderately developed which involves a decrease with depth of less than 3 C. Dissolved oxygen ranges from 5 to 15 ppm and varied inversely as a function of temperature. The dissolved oxygen concentrations do not generally contravene New Jersey's standards for surface water (Motta, 1984).

The average tidal discharges range from 650 to 800 m^3 sec^{-1}. The volume of the tidal prism (total volume exhanged during a complete tidal cycle) is 14,000,000 m^3 at mean tidal range (1.47 m). The tidal prism is generally 3-10 times the fresh water inflow per tidal cycle and about 6 times the mean fresh water inflow per tidal cycle (2,300,000 m^3).

Mean flow velocities at the estuary mouth are greater on flood than on ebb. Progressing upstream, mean flood and mean ebb velocities become equal and further upstream mean flood velocities are less then mean ebb velocities. This spatial trend in flow characteristics reflects the downstream decrease in the effects of the river flow and an accompanying increase in the effects of tidal flow. In terms of vertical velocity structure, flow is stronger near the bottom of the water column on the flood and stronger near the top of the column on the ebb. During low to moderately high fresh water discharges the net non-tidal current velocity distribution is characteristic of a partially mixed estuary (Fig. J2).

Data collected by Motta (1984) on the physical characteristics of the estuary indicate that the flow in the lower 16 km of the estuary has the potential to move its bed load during both ebb and flood flow, but the abundance of cohesive fine material in the bed appears to supress its movement under most flow conditions. Suspended load, on the other hand, moves under all flows. Turbidity maxima develop and migrate with the tidal flow (Figs. J4 and J5). Sediment may enter the mouth from Raritan Bay or from the Arthur Kill on the flood tide. Figure J5 shows the landward migration of suspended sediment during flood-oriented flow. During the subsequent ebb flow, suspended sediment moves back out of the estuary into Raritan Bay.

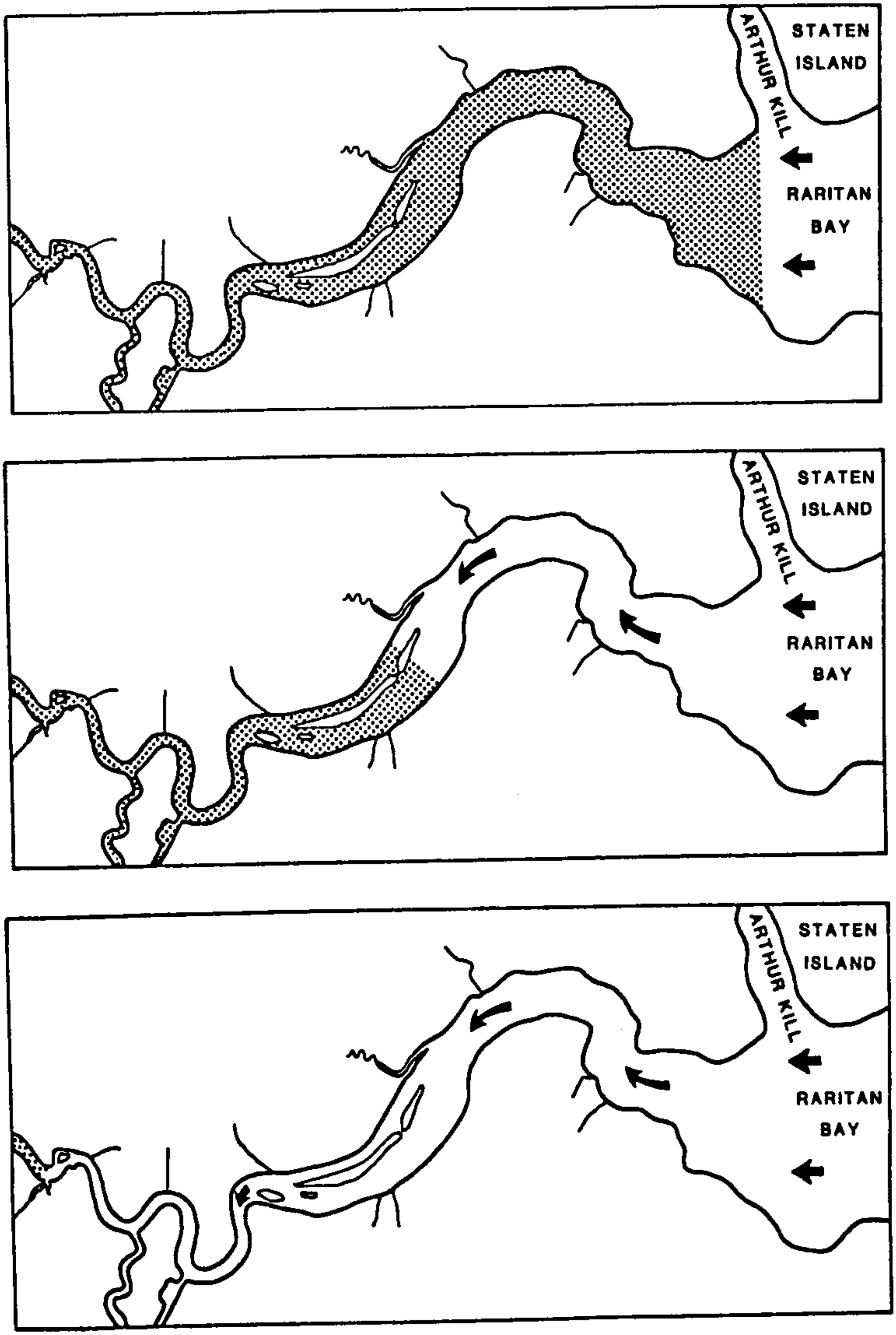

Figure J4 Diagrammatic representation of the landward migration of suspended sediment during flood-oriented flow.

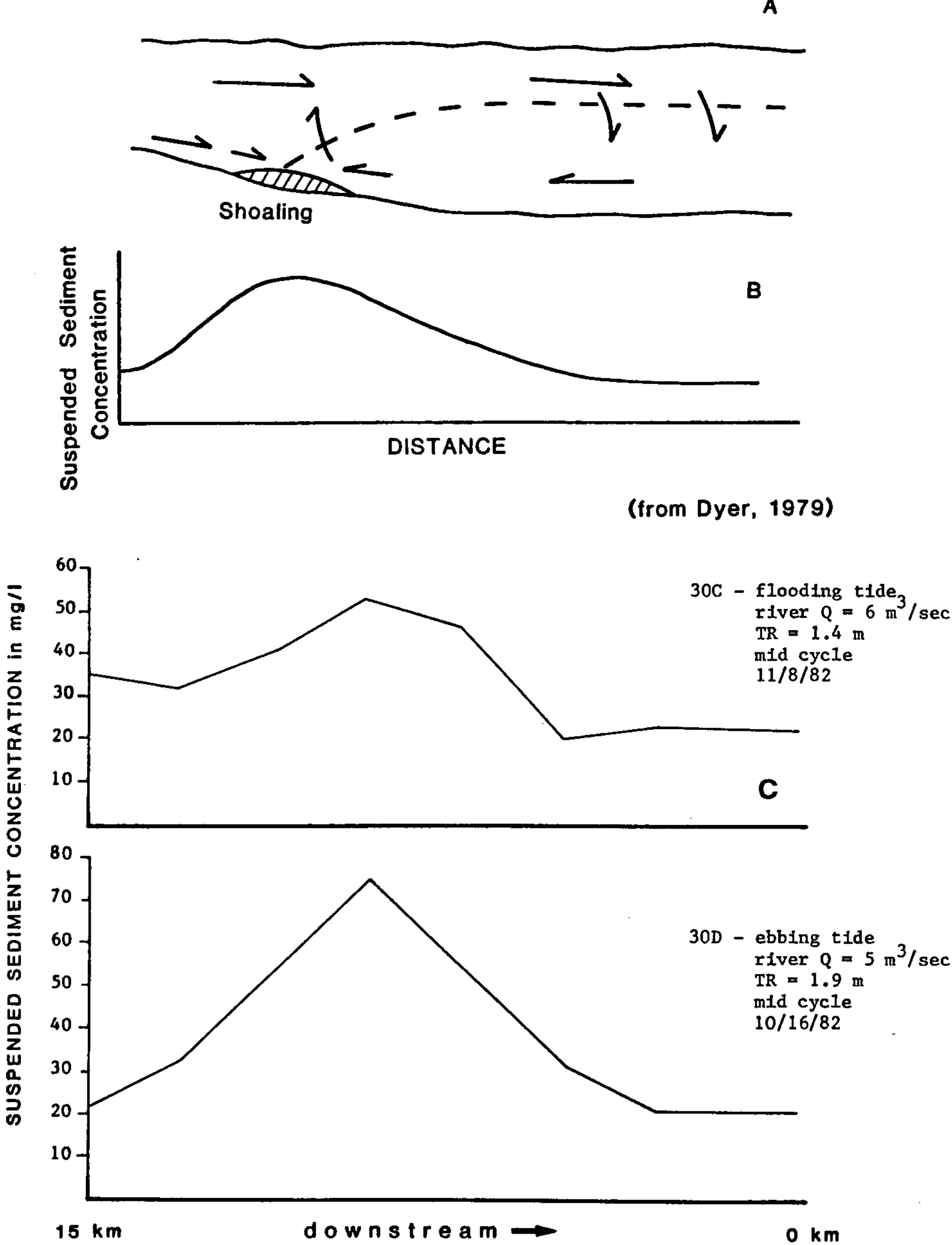

Figure J5 Turbidity maximum. A. Diagrammatic representation of the circulation of suspended sediment. B. Resulting turbidity maximum. C. Examples from the Raritan estuary.

In order to produce a sediment budget for the estuary, velocity profiles and suspended sediment concentrations were measured at the mouth over several tidal cycles. Non-storm suspended sediment concentrations typically range from 10 to 55 mg/l. Storm concentrations may exceed 200 mg/l. Figure J6 shows the result of one complete tidal cycle (9/12/83). More sediment moved into the estuary (391 megagrams) on the flood than left on the following ebb (346 megagrams). This suggests that the estuary may be a sink for sediments originating outside the estuary (Newark Bay, Arthur Kill, Raritan Bay or New York Harbor) (see Section K). Although there may be a net flux of sediment into the estuary, there must be a net export of water from the system because of the addition of riverine discharge. Ebb discharge peak is higher than flood peak, but flood currents flow for a longer period of time. The total volume of water moving out of the estuary mouth is greater than than coming in.

In summary, the Raritan River is a partially mixed estuary although a salt wedge can develop under high river discharge and a neap ebb tide. Suspended sediment enters the estuary from both upstream (the watershed) and downstream (Raritan Bay and the Arthur Kill) and is a sink for sediments and any associated pollutants.

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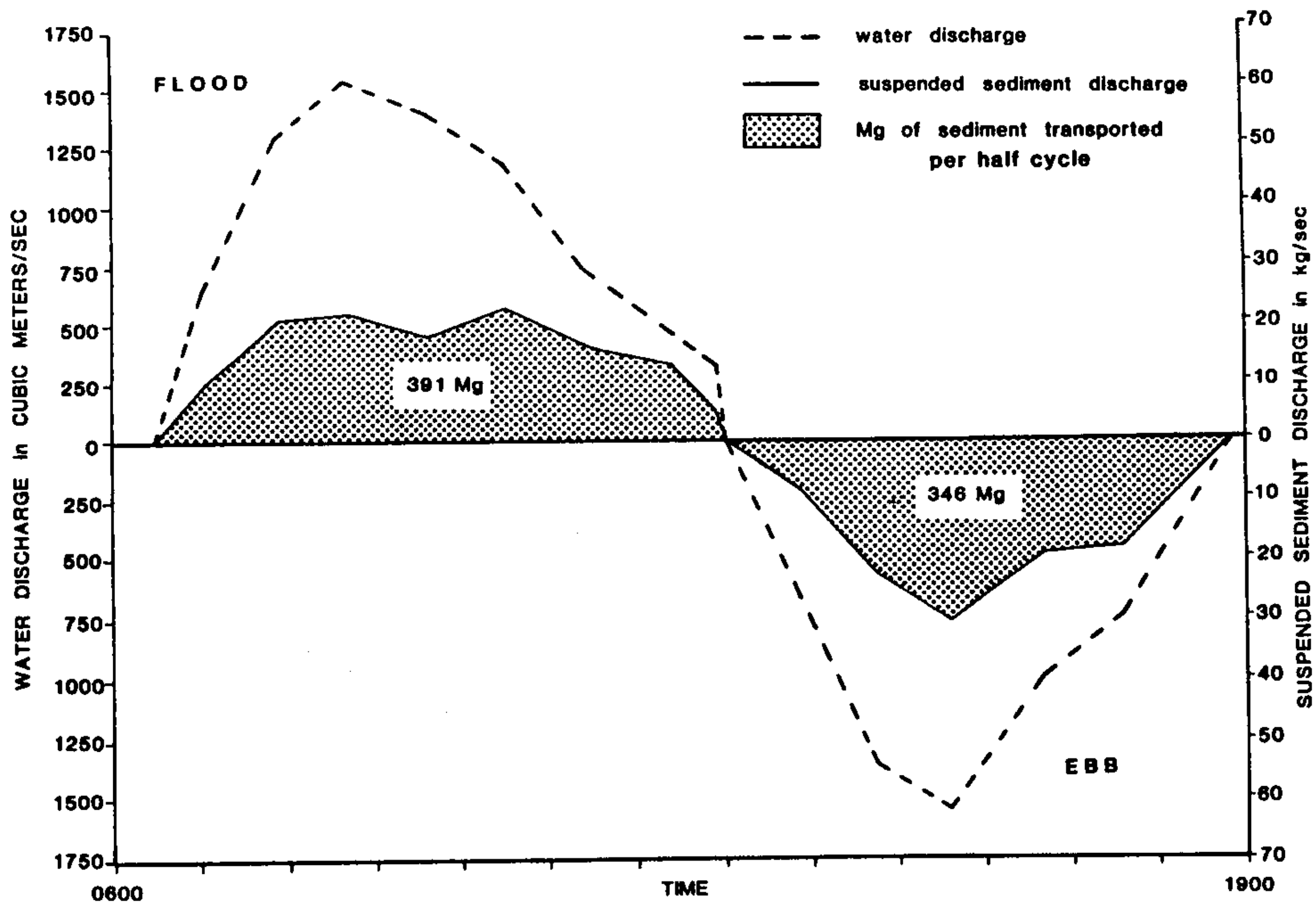

Figure J6 Relation between water, discharge, suspended sediment discharge, and suspended sediment transport (Motta, 1984).

GEOMORPHOLOGY, SEDIMENTATION, AND POLLUTION

William H. Renwick[1] and Christopher J. Motta[2]

INTRODUCTION

Raritan Estuary is a drowned river valley being submerged by rising sea level. The drowned channel is the locus of sedimentation for particles (mineral matter, organic matter and pollutants) transported from upper portions of the watershed. The transition from a fluvial to a marine environment is not an abrupt one; it takes place gradually over the 23 km of river between Landing Lane Bridge in New Brunswick and the mouth of the Raritan at Perth Amboy (Ashley and Renwick, 1983). The changing hydraulic conditions described in the previous section are responsible for a transition of sedimentary environments along the river, from gravel-bed channel in New Brunswick through muddy gravel and sand to the primary areas of fine-grained sedimentation in the last few kilometers of channel inland of Raritan Bay (Renwick and Ashley, 1984). This section describes: 1) the changing channel environments in that fluvial-estuarine transition; and 2) the consequences of this distribution of sedimentary environments for accumulation of sediment-associated pollutants.

In the immediate vicinity of the fluvial-estuarine transition, coarse-grained sediment traveling downstream accumulates as downstream velocity is reduced at high tides (see Section D). Seaward of this braided reach the channel deepens significantly, and becomes increasingly sinuous. The estuary is divided into 3 hydrologic zones: the upper estuary (16-20 km; the middle estuary (9-16 km) and lower estuary (0-9 km) (Fig. K1A) (Motta,

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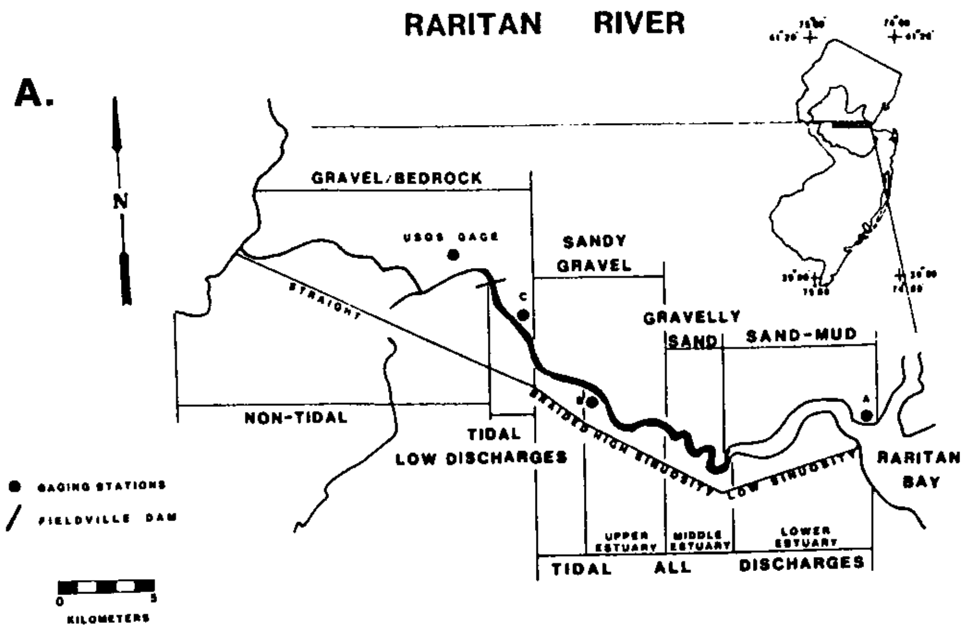
1984). The upper estuary is underlain by Jurassic redbeds of the Piedmont Province. The channel is 100-140 m wide and 1-3 m deep and consists of broad meanders with coarse-grained (gravelly sand) point bars. The middle estuary is characterized by channel that meanders with an average wavelength of 1.6 km through extensive salt marshes and associated tidal channels (Fig. K1B). The channel width is variable but shows a increase downstream from 144 m to 240 m. The depth increases from 5m-7m in a downstream direction. This part of the estuary has not been dredged since 1933 (Fig. K2). The lower estuary is characterized by a moderately sinuous channel with a wavelength of 6 km and a average width of approximately 700 m. The maximum width of the estuary is 1180 m at the mouth. The depth increases downstream from 7 m to 11 m at the mouth. The increase is abrupt, due to dredging (Fig. K2).

Almost all fine sediment originating upstream the Raritan estuary is transported into the estuary. The only opportunity for permanent fine-grained deposition upstream is on the relatively narrow flood plains where materials are laid down during floods as overbank deposits. But, the volume of flood plain deposition is low in comparison to that transported to the estuary (Renwick and Ashley, 1984). In the upper part of the estuary (16-20 km above the mouth) fine sediments may be temporarily stored in the channel, but they are flushed down stream during high discharge events. Minor long term sedimentation occurs in tidal marshes bordering the channel. At about 7 km above the mouth the channel widens abruptly, and flow divides around elongate marsh islands. Many of these islands originated as sidecast dredge spoils. Maps prior to 1920 show only a few islands; maps after 1947 show many. Seaward of this point the entire channel bed is muddy sand, and fine-grained deposition occurs both in the main channel and in the fringing marshes. This is the primary sink for the sediment-associated pollution travelling within the Raritan system.

Most of the fine-grained sedimentation in the Raritan estuary takes place in the area between this gravel- to sand-bed portion of the river and the entrance to Raritan Bay at Perth Amboy. The primary environments of fine-

A.



B.

	NON TIDAL	← TIDAL →		
CHANNEL PATTERN	STRAIGHT	BRAIDED	HIGH SINUOSITY (MEANDERING)	LOW SINUOSITY (MEANDERING)
CHANNEL GEOMETRY	NARROW, SHALLOW	WIDE, SHALLOW	WIDE, DEEP	VERY WIDE, VARIABLE DEPTH
BED MATERIAL	BEDROCK, GRAVEL	GRAVEL	SANDY GRAVEL	SAND
WATER SLOPE	.0005	0 to .0005	-.00004 to .00006	
FLOW DIRECTION	→	⟶ ←	⟶ ←	⟶ ⟵

Figure K1 A. Location map showing river segments. B. Summary of characteristics of the four geomorphologically distinct reaches indentified in the study.

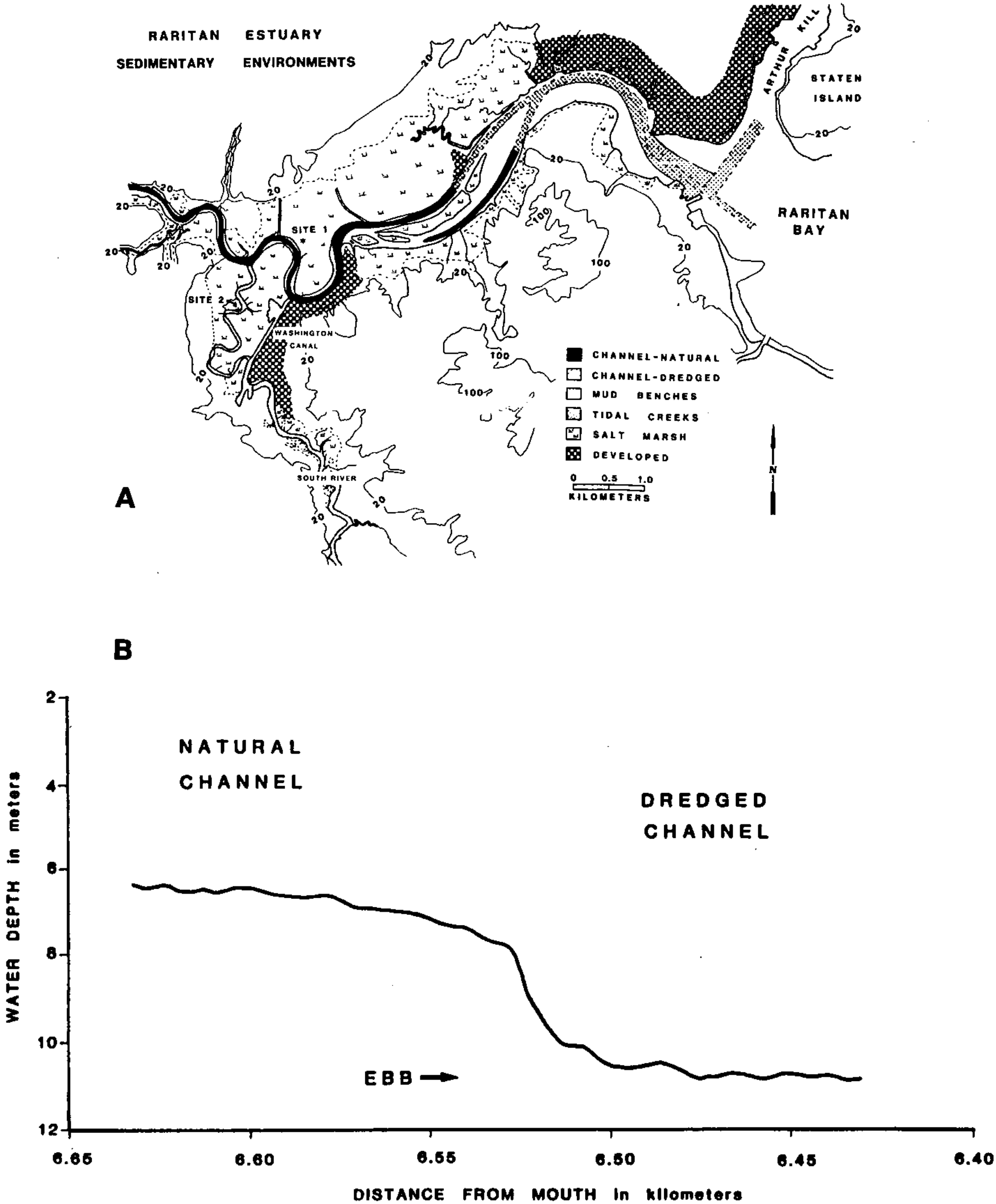


Figure K2 A. Map of sedimentary environments (site 1-carbon 14 site; site 2, pb concnetrations B. Bathymetry in the vicinity of the dredge boundary.

grained sedimentation in this area are: dredged channels; mud benches, tidal creeks, and salt marshes. These environments lie within the lower valley of the Raritan, drowned by post-glacial sea-level rise, which has created about 10 km2 of salt marshes, tidal flats and tidal channels in which sediments accumulate.

The present rate of relative sea level rise in this area is approximately 3 mm yr-1 (Stuiver and Daddario 1963; NOAA, 1983). Elevations in the marshes are variable, including some areas that are inundated only on the highest tides and other areas penetrated by the tides twice daily. Many areas of the marshes have been artificially filled within the past 300 years. Although there are few data on marsh sedimentation rates, sedimentation rates can be expected to vary primarily depending on frequency of inundation. Renwick and Ashley (1984) extracted a core from relatively low-elevation marshes near the junction of the South River (site 1 on Fig. K2). Assuming the large increase in lead concentration at a depth of 12-13 cm represents the post-WWII increase in consumption of leaded gasoline, this suggests a sedimentation rate of 3.4 mm yr-1, roughly the same as recent sea-level rise rates (Fig. K3). A carbon 14 date on sediments from a point bar of the South River (Site 2, Fig. K-2A) indicated a sedimentation rate of 1.7 mm/yr during the last 2,000 years.

Rates of sedimentation in the main channel of the Raritan have probably been increased by dredging. A ship channel was dredged in this portion of the estuary in the early 20th century, and maintenance dredging continues in that channel. This deepening of the channel has increased the depth and cross-sectional area of the estuary with resulting decrease in velocity, further increasing the potential for sediment deposition within the estuary.

Minor channels and tidal creeks in the estuary are also important sedimentation areas. Virtually all these channels have mud bottoms and banks, indicating that fine-grained sedimentation is occurring. One of the more interesting aspects of these features is that although they have very

TABLE 1. SEDIMENT BUDGET FOR THE LOWER RARITAN

		Tonnes yr^{-1}
Inputs		
From drainage basin		235,000
Landward transport past mouth		88,000
	Subtotal	323,000
Outputs		
Removed by maintenance dredging		240,000
Deposition in marsh		36,000
	Subtotal	276,000
	Surplus	47,000

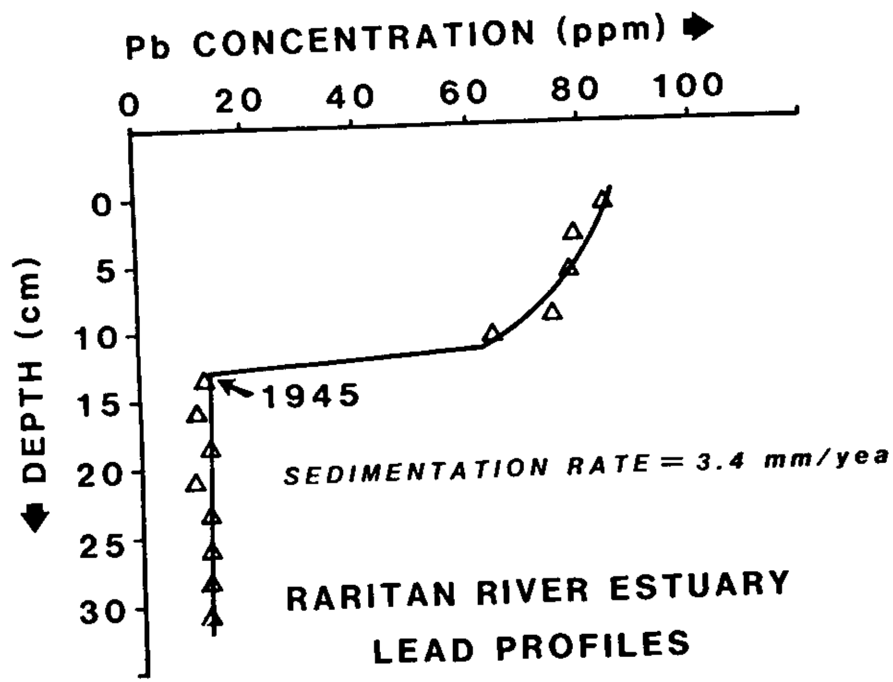


Figure K3 Stable Pb concentrations with depth (site 2) (Renwick and Ashley, 1984).

sinuous meandering channels the channels do not appear to migrate significantly over time. Maps of the Raritan estuary from the early 19th century show very few differences in comparison to the present channel system. This suggests that sedimentation in these areas consists primarily of vertical accretion rather than point-bar deposition.

Renwick and Ashley (1984) compiled an approximate sediment budget for the Raritan estuary indicting the relative importance of these different environments (Table 1). They found that the total sediment inputs are approximately 235,000 tonnes yr-1 from inland sources, and 88,000 tonnes yr-1 from landward transport past the river mouth. Maintenance dredging between 1931 and 1977 removed about 240,000 tonnes yr-1 from the main channel, indicating that most of the sedimentation in that period occurred there. An additional 36,000 tonnes yr-1 are estimated to accumulate in marshes, mud benches, and tidal creeks, based on the assumption that deposition keeps pace with sea level rise of 3 mm per year over the entire 10 km2 area of these environments. Clearly dredging of the channel has had a significant impact on sedimentation; if the channel had not been overdeepened in this way the locus of the fine-grained deposition would almost certainly be shifted seaward.

The long term sedimentation rate for the estuary based on carbon 14 dating of salt marsh is 1.7 mm yr^{-1} during the last 2,000 years. Short term (last 50 years) sedimentation rate is 8 mm yr^{-1} for the entire estuary based on the sediment budget calculations of 67 mm yr^{-1} in the dredged channel. The rate of 8 mm/ yr is higher than the local rate of sea level rise (3 mm^{-1}) determined from tide gauge data and suggests that the estuary is filling (NOAA, 1983). Deposition on the marsh is expected to keep pace with the local rate of sea level rise.

Fate of sediment-associated pollutants in the Raritan estuary.

There is a large transfer of water in and out of the estuary on each tidal cycle (Fig. J6) and consequently there is considerable mixing of fresh and salt water. Because of this mixing, pollutants carried by the water may be distributed widely throughout the estuary, and individual pollutant sources lose their identities. The spatial distribution of pollutant sinks thus does not reflect the geography of sources or inputs; rather it is controlled by the distribution of sedimentary environments within the estuary. The nature of deposition, particularly water velocities and consequently grain-size distribution, is the primary control on pollutant concentration in the sediments.

The homogenization of water by tidal mixing and the importance of sedimentary environments are indicated by a statistical analysis of grain size and pollutant metal concentrations in sediments from the Raritan estuary. In general, metals tend to be adsorbed to fine particles, and to be transported with those particles rather than in sollution (Renwick and Edenborn, 1983). In addition, areas where fine sediments are deposited tend to be areas of relatively low velocity where circulation, dilution, and flushing are reduced. Thus in examining a set of samples taken from a wide range of environments in an estuary one expects to find a positive correlation between percent fine particles and pollutant metal concentrations, and a high intercorrelation between pollutant metal concentrations. Strong positive correlations between grain size and contamination can indicate that either the contaminants are derived from widespread, ubiquitous sources (as is generally the case for metals in urban environments) or the system is well-mixed and pollutants are widely distributed before they are deposited. Clearly both these conditions exist in the Raritan estuary.

A set of 37 sediment samples collected in the main channel, tributary channels, and tidal creeks were analyzed for grain size, silver, arsenic, beryllium, cadmium, copper, chromium, nickel, lead, and zinc. The results of these analyses are shown in parts per million in Table 2. Pearson correlation coefficients were calculated among three grain-size parameters (%sand, %silt, %clay) and 9 metal concentrations; the results are shown in Table 3. The correlation coefficients are somewhat lower than one would expect for this environment. In particular, a positive correlation between percent sand and silver is unusual; one would expect a negative coefficient. Also, there is

Table 2: Data used in analyses. The first column is an assigned sample number; the second is the sample in the initial survey. Samples 1-21 taken May 1983. Samples 22-37 taken May 1982.

		1 SAND	2 SILT	3 CLAY	4 AG	5 AS	6 BE	7 CD	8 CU	9 CR	10 NI	11 PB	12 ZN
1	101	14.7	72.9	12.4	.21	15.7	9.6	.7	78.1	26.2	24.7	61.3	142
2	102	14	61.5	24.5	3.6	38.8	5	2.9	351	141	36	232	505
3	103	31.4	45.8	22.8	1.8	29.2	4.1	2.9	234	59.8	22.3	162	369
4	104	6.8	63	30.2	.8	31.9	2.7	3.3	319	70.7	37	186	428
5	105	12.8	54.4	32.8	3.2	41	11.5	2.95	302	97	31.5	174	233
6	106	2.8	66.4	30.8	1.8	131	14.9	1	376	52.6	107	211	353
7	107	6	57.7	36.3	1.1	23.3	8.1	1.7	781	32.8	23.3	58.4	163
8	108	2.9	58.2	38.9	2.1	47	10.2	2.9	277	61	38.9	199	361
9	109	.6	73.7	25.7	1.4	42.2	3.2	1.4	163	30.1	35.5	110	148
10	110	1.7	60.8	37.5	2.2	23.9	4.5	3.1	210	47.5	37.1	147	313
11	111	.9	65.4	33.7	2.4	25.3	8.9	2.7	177	39.5	22.5	141	268
12	112	4.1	66.2	29.7	1.7	20.5	10.3	2.8	146	34.6	32.1	141	277
13	113	17.8	56	21.2	1.7	20.5	6.4	3.9	165	32.6	33.3	128	308
14	114	.5	62.4	37.1	3.7	28.9	9.7	4.5	232	43.9	36.4	156	309
15	115	4.2	59.9	35.9	3.2	30.2	6.2	3.6	223	46.9	43.2	156	364
16	201	32.2	48	19.8	2.8	62.9	15.1	1.9	111	70.7	18.1	133	142
*17	202	86.8	11.6	1.8	151	4.9	5.6	.14	51.1	9.7	7.6	40.9	60.6
18	203	92.9	4.5	2.6	.2	5.9	0	0	17.6	5.1	1	33.1	28
*19	204	97.9	1.8	.3	42.7	3.2	0	0	27.8	7.8	1.4	15.4	50.5
*20	205	72.8	17.4	9.9	3.5	15.2	3.8	0	61.7	13.7	11.2	85	101
21	206	74.6	17.6	7.8	.13	5.3	3.3	0	22.7	12.5	17.7	38.6	72.3
22	2E	3.8	53.7	42.5	30	43	1.8	10	103	306	36.5	161.5	480
23	5E	9.9	47.4	42.7	70	91	1.65	20	392	132	38	189	310
24	9E	16	52.8	31.2	45	78	1.56	40	340	147	34.5	216.5	430
25	12A	6.1	63.6	30.3	29.5	25	1.84	50	182	54	39	156.5	170
26	12C	3.3	48.6	48.1	24	41	1.95	20	348	108	41	213	190
27	15A	61.3	20.6	18.1	23.5	21	1.43	10	120	51	40	98.5	210
28	15E	72.2	9.4	18.4	43	21	3.5	10	108	47	20.5	70	70
29	18A	1.7	47.3	50	48	40	4	20	315	102	40	172.5	270
30	21	19.4	73.4	7.2	51	17	3.5	10	25	37	33.5	10	70
31	23	6.3	47.2	46.5	11.5	35	2	35	245	80	50	195	310
*32	26	52.3	22.7	25	17	14	4.5	40	20	35	24	1285	130
33	28	1.9	64.4	33.7	42.5	22	3	50	299	95	35	239	330
34	30	7.8	57.9	34.3	23	35	1.5	25	232	72	35	205	250
35	32	8.9	55.7	35.4	27.5	14	4	10	153	54	27	137	390
36	33	55.1	38.1	6.8	30	14	1.5	10	28	29	25	112.5	90
37	34B	1.8	50.3	47.9	35	53	1	15	269	79	36	161	350

* Not included in second correlation matrix.

Table 3: Correlation matrix of sediment properties (N=37)

	Sand	Silt	Clay	Ag	As	Be	Cd	Cu	Cr	Ni	Pb	Zn
Sand	1.0	-.92	-.82	+.29	-.47	-.29	-.24	-.59	-.43	-.62	-.07	-.69
Silt		1.00	+.54	-.33	+.38	+.38	+.11	+.44	+.27	+.56	-.04	+.56
Clay			1.00	-.15	+.48	+.07	+.37	+.64	+.55	+.54	+.21	+.67
Ag				1.00	-.05	-.33	+.25	-.14	+.10	-.19	-.08	-.21
As					1.00	+.34	+.11	+.49	+.44	+.74	+.07	+.48
Be						1.00	-.40	+.20	-.15	+.30	+.02	+.09
Cd							1.00	+.12	+.30	+.19	+.46	+.14
Cu								1.00	+.28	+.43	-.03	+.48
Cr									1.00	+.29	+.10	+.64
Ni										1.00	+.12	+.52
Pb											1.00	+.11
Zn												1.00

Table 4: Correlation matrix of sediment properties (N=33)

	Sand	Silt	Clay	Ag	As	Be	Cd	Cu	Cr	Ni	Pb	Zn
Sand	1.0	-.88	-.76	-.21	-.60	-.38	-.59	-.71	-.58	-.54	-.54	-.75
Silt		1.00	+.35	+.01	+.41	+.30	+.43	+.44	+.33	+.26	+.26	+.54
Clay			1.00	+.40	+.62	+.34	+.57	+.79	+.68	+.54	+.69	+.71
Ag				1.00	+.37	+.53	+.81	+.21	+.64	+.39	+.25	+.23
As					1.00	+.28	+.56	+.71	+.74	+.62	+.64	+.62
Be						1.00	+.61	+.28	+.54	+.77	+.21	+.37
Cd							1.00	+.56	+.75	+.67	+.51	+.56
Cu								1.00	+.63	+.58	+.73	+.76
Cr									1.00	+.64	+.65	+.74
Ni										1.00	+.50	+.68
Pb											1.00	+.79
Zn												

virtually no correlation between lead and texture. This is unexpected given the ubiquitous sources of lead in the area. A close examination of the data suggests some of the reasons for these poor correlations.

Sample numbers 17, 19 and 20 have high proportions of sand and very high concentrations of silver. These samples were all taken from the South River area, an area known to have localized silver sources. Sample 18 is at Duhernal Lake, upstream from the major source, but samples 17, 19 and 20 are all just below that source. Further downstream in the South River area, represented by samples 14 and 15, the silver appears to be relatively diluted. The three heavily contaminated samples are the cause of the anomalous positive correlation between sand and silver.

Sample 32 was taken at the junction of Washington Canal and the Raritan River. This is a moderately high velocity location, and the sample is relatively sandy. This sample has the highest lead concentration of any in the study, 1285 ppm. This is more than five times higher than the next highest concentration found. The reason for the high concentration is unknown. Other samples in the vicinity did not contain particularly high lead concentrations. In any case, the concentration is high enough to significantly distort the relation betwen lead and sediment texture.

A further cause of poor correlation is the large range and right-skewed distribution of pollutant concentrations for many pollutants. Accordingly, the data were log-transformed and the four anomalous samples (17, 19, 20 and 32) were removed. The resulting correlation matrix shows much higher correlations (Table 4). Thus, the distribution of pollutants in the Raritan Estuary conforms to a model in which vigorous tidal mixing and numerous widespread sources cause pollutant distribution to show much closer correlation with sedimentary environments than with location of specific sources. Exceptions to this, such as the localized sources of silver in the South River drainage, are readily identified using simple correlation analysis.

Table 5: Metal loadings and concentrations in estuarine sediment, log-transformed data (N=33).

1 Metal	2 Load kg/km2/yr	3 Load kg/yr	4 Pred conc ppm	5 Obs conc ppm
Cr	10.6	30740	131	63.9
Cu	13.6	39440	168	202.8
Ni	4.1	11890	51	31.7
Pb	15.9	46110	196	168.4
Zn	28.4	82360	350	244.5

Loads in column 1 are for main stem of Raritan above head of tide, from Pavlowski (this volume). Estimated total loadings in column 3 were derived by multiplication of values in column 2 by the drainage area at Perth Amboy (2900 km2). Column 4 is based on dividing column 3 by the mean annual estuarine sedimentation rate from inland sources of 235,000 tonnes/yr. Values in column 5 are average concentrations in 37 samples of sediment collected from estuarine channel environments.

Finally, it is instructive to compare pollutant accumulation rates in the estuary with transport rates measured further upstream. Pavlowski (this volume) estimated total metal loadings from upstream areas based on flow-duration data and measurement of dissolved and sediment-associated metal concentrations in the Raritan above the head of tide. Data for five metals: Cr, Cu, Ni, Pb and Zn are expressed as loadings per unit of drainage area (Table 5). If these loadings are extrapolated to the entire 2862 km2 drainage area above Perth Amboy, and then divided by the estimated annual deposition rate of inland-derived sediment in the estuary (235,000 tonnes/yr) the result should be the average concentrations of these metals in the sediment, assuming all the metal coming from inland sources is deposited in the estuary. The resulting predicted metal concentrations in sediments are in good agreement, within limits of accuracy of the estimates, with average concentrations as determined from the 37 sediment samples listed in Table II.

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THE SHORELINE AND BEACHES OF RARITAN BAY

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Raritan Bay (Figure 1) is a drowned river valley located just south of the terminal lobe of the most recent continental glacier. Mean tidal ranges are between 1.4 and 1.6 m (NOAA 1991). The shoreline backing the beaches consists primarily of low cliffs composed of Pleistocene outwash deposits and Cretaceous sands and clays (Bokuniewicz 1988). The relatively large fetch distances for wave generation and the large amount of sand and gravel in the eroding upland have contributed to the formation of beaches along most of the shoreline. Sediments on the upper foreshores of most beaches range from fine sand to pebbles, with mean values in the medium to coarse sand range. These beaches are found in numerous isolated reaches because the shoreline is separated by headlands (Figure 1), short lengths of bulkhead and salt marsh. Many beaches on Raritan Bay have been artificially widened through beach nourishment. Major engineering projects at Keansburg and Cliffwood Beach have been implemented to provide protection from storm erosion and flooding.

Shore processes

The primary agents of erosion in Raritan Bay are waves generated within the estuaries by local winds, although ocean waves are conspicuous at times at some of the sites. Process controls and shoreline characteristics differ over short distances due to differences in basin shape, and there is considerable local variability between sites due to differences in fetch length, exposure to winds from different quadrants and influence of ocean swell. Summary data on processes gathered during several field investigations are presented in Table 1.

Waves in Raritan Bay are generated across fetch distances as great as 20 km. Ocean waves are dominant at Sites 1 and 2 due to their position relative to the open ocean. The largest locally-generated estuarine waves observed at the 15 sites identified in Table 1 were 0.95 m 4.3 s waves, occurring at Site 12 (Figure 1) during onshore winds of 17.9 m s^{-1} (Nordstrom 1975). Breaking waves associated with light-intensity storms (onshore winds 8 to 15 m s^{-1}) are likely to be considerably smaller (<0.6 m). Higher wave heights and periods occur on beaches facing the outlet to the sea, such as Sites 1 and 2. The average magnitudes of the process variables in Table 1

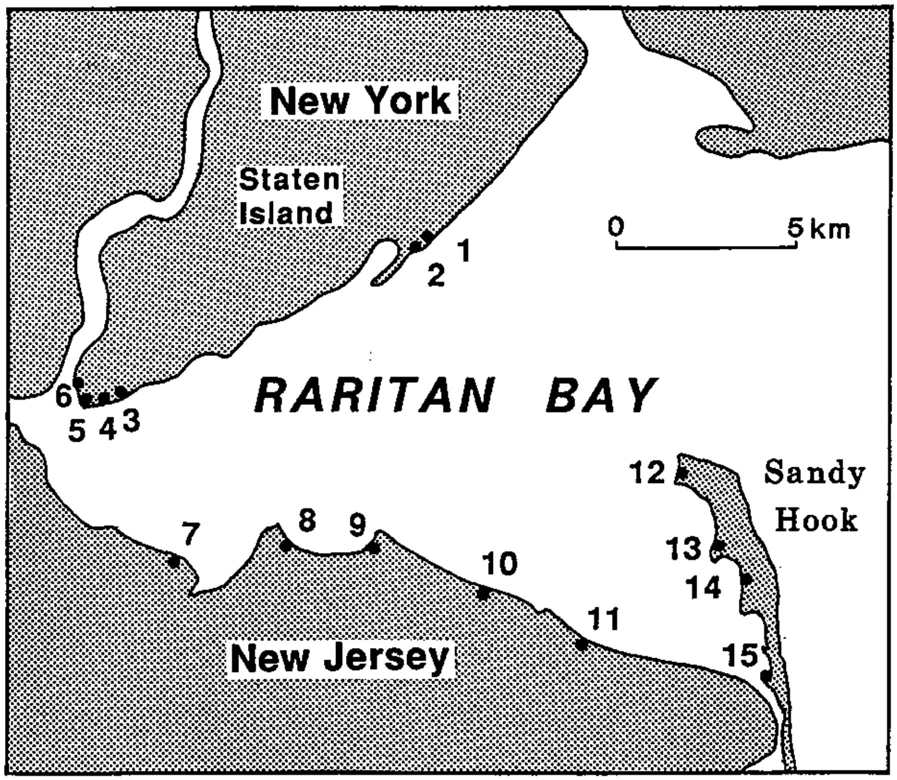

Figure 1. Raritan Bay, New Jersey. Numbers identify study sites for data used in Table 1. Modified from Nordstrom (1992).

are low compared to ocean wave energies. Locally-generated wave heights can be <0.01 m and wave periods <1.0 s during offshore winds of low speed.

Tidal range affects the strength of tidal currents and the vertical distribution of wave energy over the profile, determining the width of the beach and the duration that breaking waves will occur at any elevation. Beaches with high tidal range relative to wave height, such as on Raritan Bay, are characterized by a steep upper foreshore with a broad, flat low tide terrace (Inman and Filloux 1960). A prominent break in slope separates these two components of the beach profile (Figure 2). At low tide, spilling waves break across the gently sloping low tide terrace. The surf zone may be tens to hundreds of meters wide at these times, but the energy in the waves and currents is generally low. During storms (strong onshore winds and wave heights >0.4 m), spilling waves pass over the low tide terrace at both low water and mid-tide levels. Waves break on the upper foreshore at higher water levels as spilling waves or plunging waves depending on

Table 1. Data for field sites identified in Figure 1. Source: Nordstrom (1992)

Site	Experiment dates	Mean breaker height (m)	Mean breaker period (s)	Spring tidal range (m)*	Breaker angle (deg)	Longshore current (m s^{-1})	Citation
1	13/03/84 to 05/04/84	0.67**	7.3**	1.7	5.2	ND	8
2	20/04/78 to 29/04/78	0.17**	6.4**	1.7	4.6	0.06	9
3	07/03/88 to 03/06/89	0.05	2.3	2.0	6.6	0.05	5, 7
4	07/03/88 to 03/06/89	0.06	2.7	2.0	7.1	0.04	5, 7
5	07/03/88 to 03/06/89	0.05	2.2	2.0	10.2	0.04	5, 7
6	07/03/88 to 03/06/89	0.04	1.7	2.0	5.8	0.05	5, 7
7	24/01/89 to 05/05/90	0.20	3.3	1.8	10.2	0.24#	1
8	12/12/87 to 12/12/88	0.10	3.0	1.8	5.3	0.05	4, 5
9	12/12/87 to 12/12/88	0.11	2.4	1.8	13.5	0.14	4, 5
10	12/12/87 to 12/12/88	0.14	2.8	1.8	12.7	0.13	4, 5
11	12/12/87 to 12/12/88	0.09	2.5	1.8	7.7	0.08	4, 5
12	16/02/72 to 18/04/73	0.21	3.9	1.7	11.1	ND	2, 3
13	16/02/72 to 18/04/73	0.18	3.6	1.7	5.7	ND	2, 3
14	01/03/76 to 09/04/76	0.11	2.4	1.7	11.7	0.30	3, 6
15	01/03/76 to 09/04/76	0.06	2.2	1.7	18.0	0.40	3, 6

*Tidal range data are from NOAA (1991). **Ocean swell waves are dominant at these estuarine sites. #Values are high because storms were targeted for data collection times.

Sources: 1 Jackson and Nordstrom (1990); 2 Nordstrom (1975); 3 Nordstrom (1980); 4 Nordstrom and Jackson (1989); 5 Nordstrom and Jackson (1992); 6 Nordstrom et al. (1982); 7 Nordstrom et al. (1989a); 8 Smith et al. (1985); 9 Unpublished field data.

wave height and degree of erosion of the upper beach. Most storm waves are plunging, but removal of sand from the upper beach can create a concave-upward profile and locally gentle slopes that result in spilling waves. Surf zone widths on the upper beach are greatest under these conditions.

Widths of up to 10 m have been observed at Site 7 (Figure 1) at high water under 0.45 m 3.3 s waves. The width of the breaker and surf/swash zones on the upper foreshore is about 2-3 m under typical non-storm conditions (0.10-0.20 m high 2.4-2.8 s waves). Bores loose height rapidly and are nearly indistinguishable from swash (Nordstrom 1992).

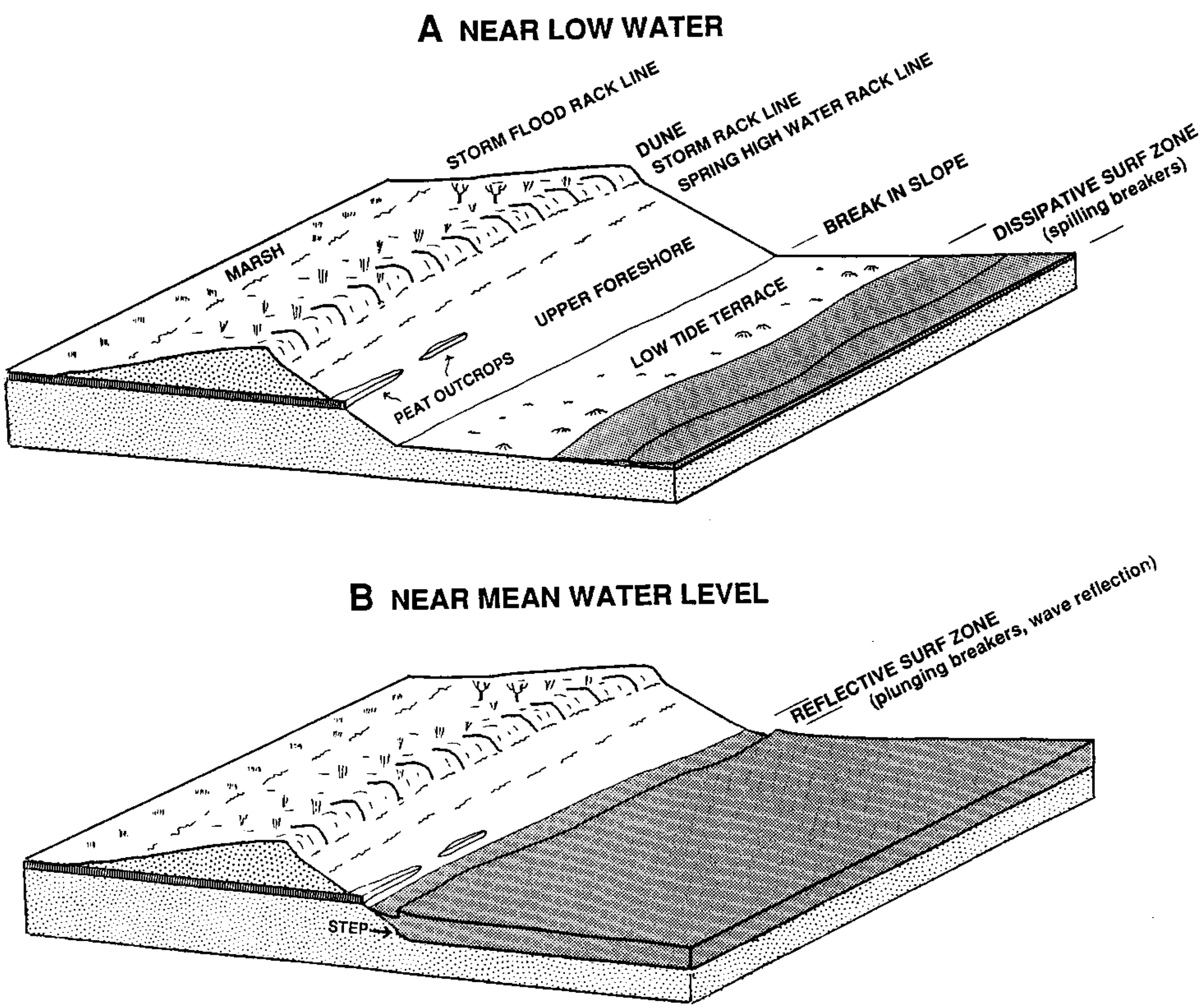

Figure 2. Characteristics of an estuarine beach in a meso-tidal environment at different stages of water level. From Nordstrom (1992).

Local wind waves developed over typical bay fetch lengths at persistent wind speeds over 5 m s^{-1} are likely to have periods of 2 to 5 s. Analysis of wave energy spectra indicates that the largest percentage of energy variance is at the periodicity of incident waves. The peaks are broad-banded because the waves are generated locally in a fetch-limited environment (Nordstrom and Jackson 1992). The size of estuarine waves is determined by wind speed, duration and fetch distance, as on ocean beaches, but estuarine waves are also limited by water depth and alterations to wind flow due to topography and basin shape. Wave refraction, the process whereby incoming wave crests bend to conform to the contours of the shoreline, is less effective on short-period waves, and locally-generated bay waves often break at a sharper angle to the beach than refracted ocean waves. The average height of the refracted ocean swell waves at Site 11, near the outlet to the ocean, is 20% of the average height of the locally generated waves, whereas the height of the ocean waves at Site 13, 3.5 km from the ocean, is 10% of the height of locally-generated waves. The energy in estuarine waves is only a small fraction of the energy of ocean waves; the largest waves likely to occur on the bay side of Sandy Hook have less than 1.5% of the energy of storm waves on the ocean side when average wave-energy statistics are compared (Nordstrom 1992). The ocean waves lose most of their energy when entering the estuary by refraction around the spit platform at Sandy Hook or through breaking on the entrance shoals.

Shoreline orientation may play a greater role in the effectiveness of ocean waves in an estuary than distance from the ocean. Although Site 1 is farther from the ocean than Site 12, Site 1 is characterized by an average wave period comparable to ocean periods and by wave heights that are considerably higher than all other sites in the bay (Table 1). The highest breaking-wave heights observed at Site 1 were 1.5 m, occurring during the northeasterly storm of March 29, 1984 (Smith et al. 1985). These waves were substantially greater than the 0.9 m breaking waves that were the highest monitored at Sites 12 and 13 during a period in which 17 storms occurred (Nordstrom 1992).

Longshore currents include shore-parallel flows generated by local wind-waves and refracted ocean waves as well as tidal flows and wind drift. Currents observed on Sites 3-6 and 8-11, summarized in Table 1, ranged from values near zero to 0.61 m s^{-1} (Nordstrom 1992). The direction of longshore currents usually corresponds to the direction of wind approach in fetch-limited environments, due to the effects of both wind-generated waves and wind shear, although currents generated by refracted ocean waves and tides often obscure this relationship. Ocean waves are often visible approaching from directions opposite the locally-generated wind waves, and the direction of flow of longshore currents inside the breaker zone can be opposite the direction of approach of wind and local waves. Tidal currents may be a more important process on estuarine sites than ocean sites, especially where beaches are located near tidal channels, projecting headlands, or constrictions in the estuary. Tidal flows of 0.28 m s^{-1} have been monitored in only 0.05 m of water at Sandy Hook, where the spring range is 1.7 m; these currents can be the dominant process on days when wave energies are low (Nordstrom 1977a). Tidal currents have the greatest effect on beach change when they operate in conjunction with waves. Velocities as high as 0.76 m s^{-1} have been observed on estuarine beaches at Sandy Hook (Nordstrom 1977a).

Shoreline characteristics

Surface sediments are usually coarser on estuarine beaches than on ocean beaches or ocean-facing beaches within estuaries that have a similar source of sand and pebbles. Sediment samples from estuarine beaches composed of sand and gravel characterized by similar wave energies and source materials often reveal little sediment finer than 0.15 mm on upper foreshores. Part of the difference is attributed to provenance; oceanside beaches have a higher percentage of the fine-sized heavy mineral grains (Yasso 1962). Coarser sediments on estuarine beaches are due partly to the absence of long, flat swell waves that are normally responsible for the delivery of finer sediments from offshore. Estuarine beaches have small volume fluctuations during storm cycles, and the low wave energies restrict both the quantity of sediment moved offshore and onshore in storm cycles and the size of the berm that forms under depositional conditions. Decreased mobility of the upper foreshores of estuarine beaches helps preserve coarse deposits created through preferential elimination of fine particles. The suppression of offshore movement during storms helps retain steep foreshore slopes. Steep slopes are more in equilibrium with coarser sediments, and there is a greater likelihood that random sampling will yield sediment samples with coarser grain sizes (Nordstrom 1989b).

A comparison of sediments from the eroding Pleistocene bluffs at Site 6 (Figure 1) and the beach in front of it provides an example of the relationship between sediments delivered to the upper foreshore and the sediments remaining on the beach. A sample removed from the bluff revealed 508 g of cobble size or larger, 3,921 g of pebbles to very fine sand and 1,146 g of silt and clay. Only a fraction of material in each of these size ranges is found in the mobile layer of sediments on the upper foreshore. Cobbles form an immobile layer under sand and pebbles, although they may be exposed on the upper beach during erosional periods. Comparison of the grain size distribution of the sand fraction from the upper foreshore with the fraction in the cliff sediments (Figure 3) reveals that the fine-sand fraction is winnowed from the beach.

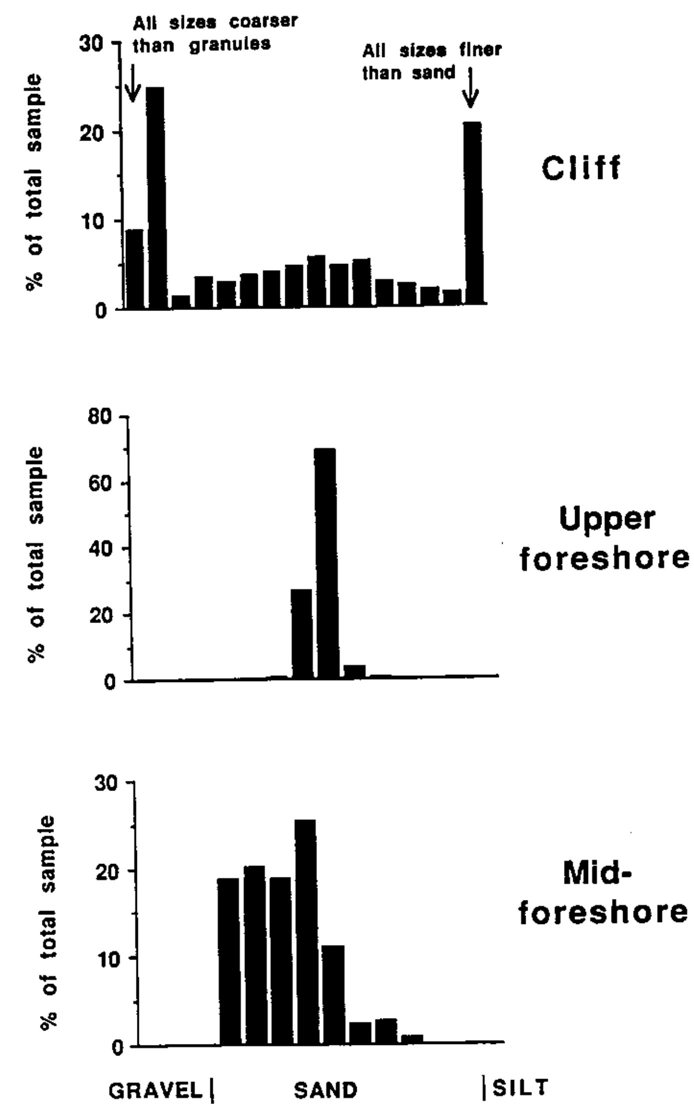

Figure 3. Comparison of grain size distribution of sediment samples from the eroding cliff and upper foreshore at Site 6 (Figure A), showing preferential accumulation of sand on the foreshore. From Nordstrom (1992).

Lag gravel is usually conspicuous on the surface of the beaches in Raritan Bay. Some of the gravel is exhumed by swash from the sand matrix on the upper foreshore by preferential elimination of fine sand by low-energy waves when winds are light (Nordstrom 1977a, 1977b). Gravel is also moved preferentially in the beach step as it migrates up and down the upper foreshore with the rise and fall of the tide. Individual pebble clasts escape the step or are removed from the beach matrix on isolated swash excursions. A series of swash excursions will create a band of gravel at the upper limit of swash. The highest band on the upper beach is formed at the upper limit of wave uprush at high tide. Several bands may be conspicuous, representing successively lower high water marks as the 28-day tidal cycle progresses from spring to neap conditions, and thin bands may form over the foreshore surface between the high water mark and the low tide terrace with daily changes in water levels. The bands formed with daily fall of the tide are often discontinuous and arcuate shaped, reflecting the configuration of swash uprush excursions.

The depth of mobilization of sediments on the upper foreshore due to passage of the surf and breaker zones is small. The thickness of the active beach at mid-foreshore near Site 6 is only 0.15 m. The depth of the active beach at the more exposed Site 4 is 0.35 m at mid-foreshore. The active beach may be underlain by an immobile layer of inactive sediments, resistant gravel, a clay or peat layer, or a wave cut platform composed of material similar to the formation behind the beach and often having a slope similar to that of the beach. The immobile layer below the surface is frequently represented by reddish-brown sediments, stained as a result of oxidation. Black sand from reduced iron is usually found within 10 to 30 mm of the surface just offshore of the break in slope near mean low water, indicating that sediments are even less mobile on the low tide terrace than on the upper foreshore under wave action.

Marsh peat and layers of clay often form distinctive outcrops on the estuarine beaches on Raritan Bay. Resistance of the peat and clay layers to erosion allows these features to remain on the beach longer than the sediment above and bayward of them. Peat and clay usually represent formations that were once landward of the shoreline. Marsh peat is usually a mixture of sand, silt, clay and organic matter. The fine sediments and extensive rhizome systems make this material resistant to erosion by low and moderate energy waves, but it is susceptible to erosion during larger storms; up to 2 m of peat were eroded from the beach at Site 13 in a single storm

(Nordstrom 1975).

Vegetation can be viewed as a process in that it reduces wave energy and reduces beach mobility, but it is also a response to diminished wave competence. Nearshore submerged aquatic vegetation such as sea lettuce (Ulvaa lactuca) is common offshore of the more sheltered beaches, such as Sites 3 and 4. Salt marsh vegetation, primarily Spartina alterniflora, fronts the shoreline in the most sheltered areas, such as just east of Site 8. Fringe marsh, a term used to describe a narrow band of salt marsh that may run parallel to a beach along the intertidal zone (Rosen 1980), occurs in slightly more exposed locations, such as west of site 8 and at site 7. The marsh is most effective where it grows on peat substrate that resists erosion and keeps the plants from being exhumed during periods of high energy. Vegetation is locally important in influencing morphologic change at these relatively sheltered areas in Raritan Bay, but it does not play as great a role as on many backbarrier beaches on the northeast coast of the USA, because of the relatively high wave energies in the bay.

Benthic organisms alter much of the topography and stratigraphic character of lower portions of the low tide terrace of the beaches in Raritan Bay. Scour structures are associated with excavation by burrowing organisms; constructional features include the raised rims around burrow pits and the larger mounds and reefs built by living organisms such as mussels and sand worms. Burrowing by organisms exceeds the depth of reworking by waves on the low tide terrace, and the topographic relief of structures created by organisms may exceed the scale of features created by waves and currents. Mounds formed by the tubes of sand worms have a local relief of 0.15 m at Site 10, and they account for the greatest relief on the inner low tide terrace. They form during warm months, when wave energies are low. Many of these structures are destroyed during the more severe wave climate of the winter storm season, but many survive the winter because they are sufficiently consolidated to resist erosion. Much of the surface roughness of the beaches is caused by lag deposits formed from living organisms such as snails and shells and parts of dead organisms, and biologic material forms much of the substrate beneath the low tide terrace (Nordstrom 1992).

The beaches on Raritan Bay have high variability in morphology and rate of erosion over a relatively small area, resulting from local differences in fetch characteristics and exposure to dominant and prevailing winds, variations in subsurface stratigraphy, irregular topography inherited from drainage systems, diffential erosion of vegetation on the surface of the beach and in clay, peat and marsh outcrops on the foreshore and varying amounts of sediment in eroding formations. The bayside shoreline of Sandy Hook has an irregular orientation resulting from numerous overwash lobes, former flood tidal deltas and spit recurves. The irregular orientation of many bay shorelines isolates beach compartments, reducing or eliminating the exchange of sediments between them and forming isolated longshore drift cells.

The rate of longshore transport on estuarine beaches can be an order of magnitude less than the rate on ocean beaches (Kraft et al. 1979). The rates may be low, but they may cause high rates of erosion because the quantities of sediment in transport represent a sizeable fraction of the total unconsolidated sediment in the active beach prism on the small beaches. An annual loss of only about 7,000 $m^3 yr^{-1}$ from a 1/2 km long estuarine beach at Site 13 results in a net landward displacement of the shoreline of 3.5 m yr^{-1} (Jannik 1980; Nordstrom 1989a).

Narrow estuarine beaches are limited sources of sand for dune building, and dunes are slow to form, even on beaches exposed to the dominant winds. There are wide sediment sources on low tide terraces at low water levels, but this exposure is often of short duration, and water in the interstices causes sediment to resist entrainment. Small dunes are common on Raritan Bay, but they are so small that they may escape notice or be confused with beach ridges. Eolian transport rates on narrow beaches are less than the potential for a given wind velocity because an equilibrium saltation layer cannot develop fully. Substantial source widths only occur over a fraction of each tidal cycle. Incipient dunes may not last because sediment deposited in the wrack line by eolian processes is eroded by storm waves accompanying the storm surge at high tide (Nordstrom 1992).

Significant eolian action and building of large dunes usually only occurs where the upper foreshores of estuarine beaches are unusually wide because they are at locations of artificial beach nourishment. At least 4.2 m^3 of sand per linear meter of shoreline length accumulated at a single sand fence placed behind the 40 m wide nourished beach at Cliffwood Beach (Site 7) in a 14 month period at a location where no dunes existed under natural conditions. At Keansburg (Site 9), where the shoreline is directly exposed to the dominant northwesterly winds, deflation of an artificial beach and dune has created a mobile dune over 4 m high that has migrated into the parking area behind it.

Humans have been modifying the shoreline of Raritan Bay for centuries. Most of the developed shoreline is protected by bulkheads, but beaches still exist in front of many of these structures. Many beaches bear little resemblance to the way beaches appeared under natural conditions. Beach characteristics on natural shorelines are largely a function of tidal range and wave height as affected by fetch distance, offshore bottom configuration and shoreline orientation. These natural constraints rarely change through human development, but the characteristics of a beach may change dramatically as a result of changes in sediment sources. Differences between natural beaches and artificial beaches developed as parks is usually conspicuous when comparison is made with adjacent shorelines. Reclamation, landfill and spoil disposal projects are not designed to provide shore protection, but they often create beaches, and they have pronounced effects on the character of the shoreline and its subsequent development. Landfills designed to cover waste material are not designed to be developed, and they are often left to erode and form beaches. The most conspicuous of these is the large undeveloped fill and beach at South Amboy, just south of the location the Raritan River empties into the bay.

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SETTLEMENT AND LAND USE PATTERNS IN THE RARITAN VALLEY: AN HISTORICAL GEOGRAPHICAL SKETCH

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SETTLEMENT

In 1670, about four years after the first permanent European settlement in the Raritan Valley, Daniel Denton wrote a glowing account of the area.

"Both sides of which River is adorn'd with spacious Medows, enough to maintain thousands of Cattel, the Wood-land is is likewise very good for corn, and stor'd with wilde Beast, as Deer and Elks, and an innumerable multitude of Fowl, as in other parts of the Country [New Jersey]: This River is thought very capable for the erecting of several towns and Villages on each side of it, no place in the North of America having better convenience for the maintaining of all sorts of Cattel for Winter and Summer food."

Denton's narrative emphasized that European cattle would do well in the area due to the natural meadows, which could be used as pasture to support livestock during the growing season and as meadowland to provide hay to bring the stock through the winter. His reference to "corn" was meant in the British sense as a generic term for the small grains, and indeed, early on the Raritan Valley became a major producer of wheat. Of great interest to the earliest settlers was also the abundance of wildlife which could be utilized as food before adequate harvests could be derived from cleared and prepared soil. The reference to "towns and Villages" reveals Denton's New England cultural origins, with "town" referring to the large grant obtained by a group of settlers and "Village" to the relatively close-knit initial settlement on house lot sat a location within the town grant. He was probably referring to the settlement of Piscataway as having been in effect in 1670 as that town grant had been divided from another settlement by New Englanders at Woodbridge in 1666. Although New Englanders established the first permanent European settlement in the Raritan Valley, they did not dominate the area. With the division of New Jersey into two colonies and the Raritan Valley lying mostly in the colony of East New Jersey, the Proprietors of the eastern division built a capitol and port at Perth Amboy and encouraged settlers of other origins to take up land. Perth Amboy was establisbed in 1683, one year after Philadelphia, and planned, with a central square, as was that city.

Many of the East Jersey Proprietors were Scots and they encouraged emigration from Scotland in the 1680's. Some of this settlement was in the form of tenancy on landed estates and this played a major role in land use in the western part of the Valley well into the nineteenth century.

Large numbers of Dutch from Long Island were also encouraged to settle, on their own farms, largely south and west of the river. The Dutch, having accumulated sufficient capital, were able to secure large parcels of land, subseqently to be divided into large farms for their children. They also introduced slavery.

Pennsylvanians, largely, but not entirely of German origin settled, often as tenants, in the very western and northern parts of the Valley. Thus, the Raritan Valley is where several distinct cultural groups came together, beginning in the late seventeenth century.

The initial settlements of these people revealed their cultural origins by virtue of their contrasting built environments. For example, the New Englanders tended to nucleate more than did the others, had smaller farms, one and a half story, two room deep houses for the more affluent and utilized English barns. The Dutch were the most dispersed, on the largest farms. They lived in houses looking very much like those of the New Englanders, except framed in a different manner. They built Dutch barns, with an entrance at the gable end. Pennsylvanians had farms in the middle range, perhaps around 100 acres, lived in two story, one room deep houses, often of stone construction and built barns much like the English type, except that they were of two stories and embanked or with a ramp to the second level.

Well before the Revolution the flow of in-migration to the Valley had ceased. Natural increase swelled the rural population, which began to expand on to more marginal farmland, such as the rocky slopes of the Watchungs. After the Revolution and especially in the first two decades of the nineteenth century, began the new immigration from Europe, then from the rural southeastern United States, and, more recently, from Latin America. Initially at least, this migration went to expanding urban places.

URBAN PLACES

The East Jersey Proprietors had planned for Perth Amboy to be their capitol and chief port. The place was named after Perth in Scotland and the Lenape Amerindian word for a point of land. It had the advantage of deep water immediately adjacent to land and protection from open water by Staten Island. Unfortunately, it also had two tremendous disadvantages. The first was that the port of New York had been established almost sixty years before and the mercantile and political interests in New York did everything in their power to limit Perth Amboy's growth. Second, was the fact that the head of navigation on the Raritan was not at Perth Amboy but rather at New Brunswick, which became incorporated in 1730. In the eighteenth century New Brunswick and Perth Amboy acted as minor ports, shuttling the produce (especially wheat and flour) of the Raritan Valley to the entrepot of New York, from whence they would be exported.

Other small agglomerations of dwellings, hardly to be called "urban" also existed early on. There was, for example, the village of Piscataway, with its typical church, village green and burying ground (now in Edison). Princeton began as a pleasant stopover for travellers on the main road between New York and Philadelphia. But, for most places, real growth was to be in the nineteenth and twentieth centuries and related to enormous changes in transportation and industry.

TRANSPORTATION AND INDUSTRY

Initially, transportation was tied to a network of existing Amerindian trails (such as route 27) and to the Raritan and its tributaries. Local residents of the townships were responsible for maintaining the roads and constructing new alignments. This was a very unsatisfactory system and the heavy clay soils of the region provided deeply rutted and almost impassable roads, especially in early spring. Early in the nineteenth century townships began to raise tax revenue to maintain roads and companies were authorized to construct new routes and take over existing roads and improve them. These turnpikes and improved local roads allowed a much more rapid movement of goods and travellers within the region. With the 1820's came the construction of canals. For the Raritan Valley it was the Delaware and Raritan Canal, which was built to allow inexpensive transport of coal from the Lehigh Valley of Pennsylvania.

Coal fueled the growth of industry in the nineteenth century. Before the use of coal, industries requiring a power source located at water power sites, which were predominantly rural. Steam power allowed such industries to locate where coal could be delivered cheaply. New Brunswick clearly benefited from the D&R Canal, which also delivered other raw materials, such as the cotton required by the now giant Johnson and Johnson corporation.

Following the canals came the railroads, increasing the amount of coal which could be delivered and also, not needing a dug waterway, allowing for greater flexibility in the location of industry. The corridor followed by the railroads was the eastern portion of the Raritan watershed and it is here that most of the industry and population clustered - an effect clearly seen today. The railroads also allowed greater flexibility in the location of the more affluent, and commuter exurbs such as Plainfield arose, especially after the

Civil War. These remain today, with an architectural heritage mirroring their past purpose.

At about the end of the nineteenth century, the increasing use of electricity further affected transportation, industry, and the location of population. Trolleys ran on electricity and allowed a decentralization of population from the larger urban places to nearby suburbs. Highland Park is a good example. Industrial plants gained even greater flexibility in location and newer technology, which stressed plants built in a horizontal rather than a vertical plane encouraged a move out of central cities such as New Brunswick. World War I had an enormous effect on the building of such industrial plants, as any casual look at the founding dates of industries in places such as Bound Brook can attest. Unfortunately, the war also brought an expansion in the pollutants entering the air, soil and water of the region, which has continued and has led to the creation of several infamous superfund sites, such as the Kinbuc landfill.

World War I also brought the increasing use of the internal combustion engine. This allowed even greater flexibility in the location of both industry and population. Industries continued to flee built-up urban places for the countryside, which became served by hard-surfaced, well-maintained roads. The affluence of the 1920's allowed many to own automobiles and their settlement beyongd the farthest reaches of the trolley lines. This suburban spread was halted by the depression and then by World War II.

The end of the war witnessed a tremendous demand for new housing stock and for consumer items, such as automobiles. This was combined with an ambitious road building and improvement program lasting more than four decades (New Jersey Turnpike, Garden State Parkway, Interstate 78, 287, etc.). Suburban growth for commuters, industry and shopping malls expanded tremendously during the period. Indeed, new "Edge Cities," divorced from the old central cities have emerged. Bridgewater Township in Somerset County is a good example. On the other hand, a lack of regulation of access has allowed the choking of some of the older routeways. Route 1 between New Brunswick and Princeton is a classic example.

RURAL LAND USE

The earliest store records for the region reveal that some settlers specialized in hunting and trapping and did very well by it. Clearance of the woods was encouraged by the fact that oaks often dominated the native vegetation and the white oak, especially, was valued for construction and for cooperage. As mentioned above, wheat became the main staple of the Raritan Valley by mid-eighteenth century, much of it bound for export, although the raising of beef cattle and dairying were also important, especially in the Dutch areas. Scots and Scots-Irish were responsible for a large production of flaxseed.

After the American Revolution wheat was much less important in the agricultural economy due to an introduced disease, the Hessian fly, declining soil fertility and competition from other regions. Corn became more important and much was fed to burgeoning numbers of cattle bound for the New York market, as were dairy products and eggs.

The revolutions in transportation during the nineteenth century discouraged traditional mixed agriculture in the region as the land in the eastern part of the Raritan watershed filled with industry and population. Even so, many carried on some agricultural activities such as dairying, on a part time basis, as did immigrant Bavarian rubber mill workers in Milltown in the 1880's.

The decline in traditional agriculture was also due to competition from outside the region, made possible by ever more rapid and inexpensive transportation. Wealth generated by industry allowed an affluent elite to purchase farmland in order to erect substantial estates, often devoted to raising fine horses. These are still in existence, especially in northern Somerset County. In general, suburban dwellings, located on large lots, account for most of the rest of the former farms, especially in the northern part of the watershed.

GEOLOGY AND LAND USE

In closing, a few words are in order in regard to geology and land use. The Brunswick Shale and Stockton Sandstone underlying much of the area have developed, under a humid climate, quite good soils which have encourageed agriculture. This has also been encouraged by generally gentle slopes in most of the region, although there is enough slope to encourage the development of waterpower, such as for gristmills. The stream network also encouraged transportation early on.

Jurassic vulcanism provided abundant basalt, which has been extensively quarried and locally important copper ores. The Stockton sandstone has been widely used for building and local clay deposits for a large brick-making industry. Magnetite is found in many locations in the Highlands (Reading Prong) and provided ore for an extensive iron industry in the eighteenth century. Finally, the varied terrain and stream network of the area have provided a very pleasant backdrop, through time, for human activities.

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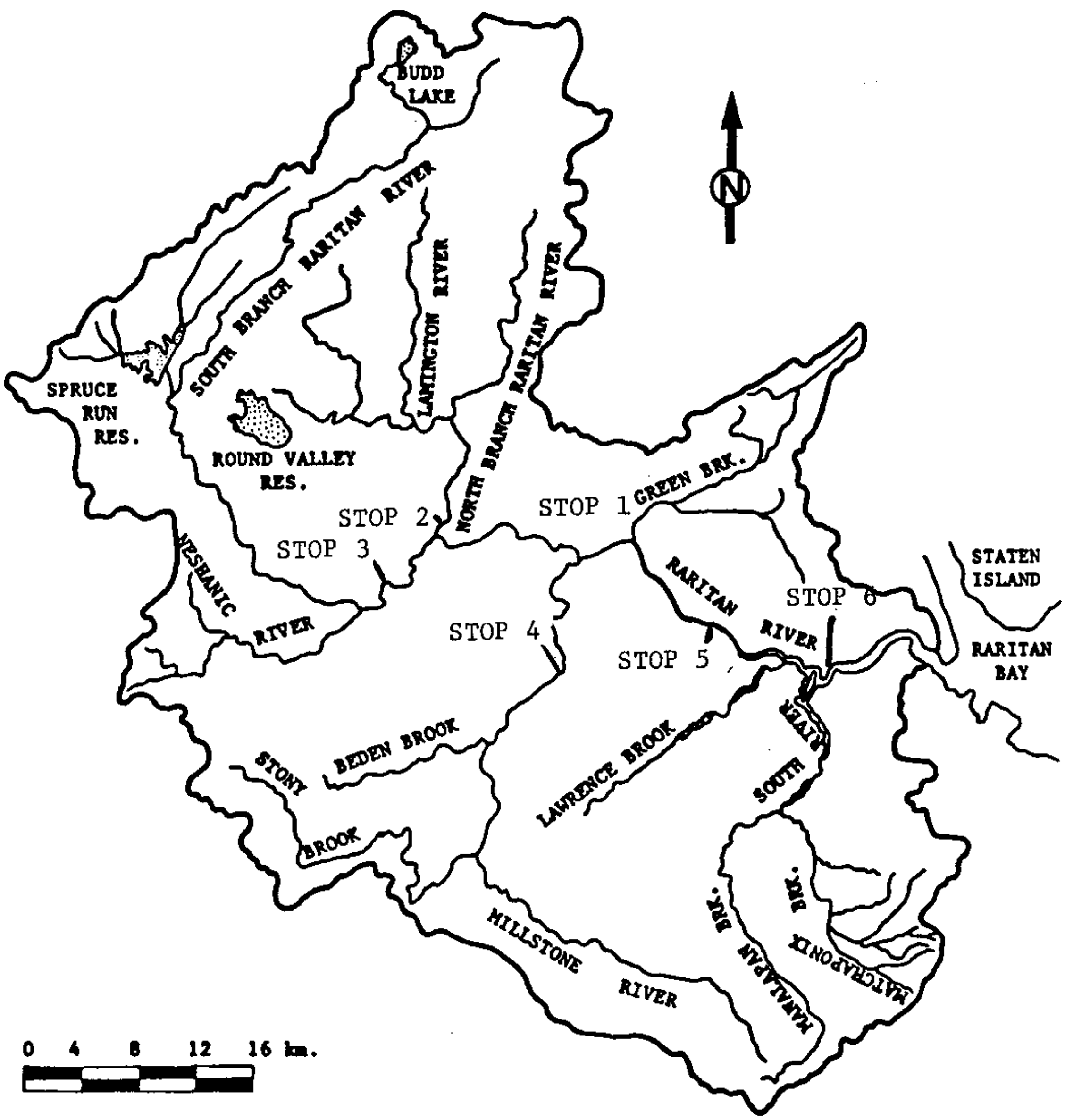
FIELD TRIP

The field trip will examine the surface hydrology and geomorphology, as well as the sediment transport characteristics and sedimentation of both the non-tidal and tidal reaches of the Raritan River. There will be an emphasis on the pollution (as measured by heavy metal contamination) of the Raritan, in particular the effects of agriculture and residential pressures, industrial development, and urbanization on the natural environment. The ground water aspect of the drainage basin is beyond the scope of the field trip.

The stops have been chosen to illustrate the spectrum of modern environments in the Raritan River watershed which are controlled by variations in bedrock structure and lithology, topography, discharge (tidal and non-tidal) and land use.



Road Log

Mileage		Community
00.0	Quality Inn parking lot	Somerset
00.1	T-intersection, left onto Worlds Fair Drive	
00.15	Traffic light, left onto Easton Ave. (Rt. **527North**)	
01.9	Cross D&R canal and Raritan River	
02.0	Traffic light, T-intersection, right onto E. Main Street	Bound Brook
02.1	Y-intersection, left	
02.4	Y-intersection, right onto East Street	
02.5	T-intersection, right onto Union Ave.	
02.6	Turn, right (Nat West Bank parking lot)	

STOP #1 GREEN BROOK

02.6	Turn, left onto Union Ave (Rt. **28**)	
04.0	Turn, right onto Rt. **287North**	
04.9	Exit, left onto Rt. **22West**	
07.9	Exit, right onto Rt. **202South**	Somerville
08.6	Somerville Circle, follow Rt. **202South**	
11.0	Traffic light, right onto Milltown Road	
11.4	Turn, left into North Branch County Park	

STOP #2 NORTH BRANCH RARITAN RIVER

11.6	Turn, right onto Milltown Road	Branchburg
12.0	Traffic light, cross Rt **202**, stay on Milltown Road	
13.1	T-intersection, right onto Old York Road (Rt. **567**)	
13.9	Bridge at confluence; S. Branch (left) and N. Branch (right)	
14.4	Turn, left onto South Branch Road (Rt. **567**)	
15.2	Turn, left onto Studdiford Road (Rt. **606East**)	
15.35	Bridge, South Branch Raritan River	
15.4	T-intersection, right onto River Road (eventually turns into Opie Rd)	
16.9	Bridge, South Branch Raritan River	
18.0	Bridge, South Branch Raritan River	
18.4	T-intersection, right (Rt. **567South**)	
18.7	Turn, right across bridge (South Branch)	Neshanic Station

STOP #3 SOUTH BRANCH RARITAN RIVER

18.75	Re-cross bridge	
18.8	Turn, right onto River Road	
19.8	3-way Stop, left onto Amwell Rd. (Rt. **514East**)	
24.8	Traffic light, right onto Rt. **206South**	
31.9	Traffic light, left onto Rt. **518East**	Rocky Hill
32.4	Turn (Y), right onto Rt. **605South**	
34.7	Traffic light right onto Rt **27South**	
35.0	Turn, left Carnegie Lake parking lot	Kingston

STOP #4 CARNEGIE LAKE, MILLSTONE RIVER

35.1	Turn, right onto Rt. **27North**	
35.6	Bridge, Millstone River	
35.6	Bridge, D&R Canal	
46.0	Railroad tracks	North Brunswick
46.3	Traffic light, left onto Franklin Blvd.	
46.7	Traffic light, cross Rt **514**	
48.1	Traffic light, cross Easton Ave.(Rt. **527**)	
48.5	Bridge, Raritan River at Landing Lane	
48.9	Turn, right into Johnson Park	

STOP #5 RARITAN RIVER, HEAD-OF-TIDE

50.3	Traffic light, right onto River Road	
50.9	T-intersection (traffic light), right onto Rt. **27South**	
51.0	Bridge, Raritan River	
51.1	Turn, right jug-handle onto Rt. **18South**	New Brunswick
52.9	Exit, right jug-handle onto Rt. **1North**	
53.7	Bridge, Raritan Estuary	
54.6	Exit, right onto Woodbridge Ave (Rt. **514East**)	Edison
55.4	Traffic light, right onto Meadow Road	
56.5	Edison Municipal Boat Basin parking lot	

STOP #6 RARITAN ESTUARY

56.5	Leave Boat Basin parking lot	
57.6	Traffic light, left onto Woodbridge Ave.	
57.9	Traffic light, right onto Plainfield Ave. (Rt. **529**)	
58.1	Traffic light, right onto Rt. **1North**	
61.0	Exit, right jug-handle onto Rt. **287North**	
70.3	Bridges, Raritan River and D&R Canal	
70.6	Exit (Easton Ave.), right	
70.7	Y-intersection, bear left to New Brunswick	
70.7	Y-intersection, bear right to New Brunswick	
70.9	Turn, right into Quality Inn parking lot	Somerset

Stop Descriptions

STOP #1 Green Brook Tributary, Bound Brook, NJ

The Green Brook drainage system (169 km2) includes Bound Brook and Ambrose Brook (Fig.1-1). The Green Brook system and the Middle Brook system head in the Watchungs (Jurassic-age basalts) and drain southward into the Raritan at Bound Brook, NJ. The mean annual discharge is 2.9 m3 sec-1 and the watershed is 76% urbanized, 20% forested and 4% agriculture. The sub-basin is an archetypal urban watershed in that the channel banks are commonly lined with non-erodible rock or concrete and storm sewers discharge directly into the streams. The area of impervious cover is estimated to be 25% of the sub-basin. Consequently, it has rapid runoff and the highest concentration of pollutants of any of the tributaries. **Stop #1** is on Green Brook and the location is shown on Figure 1-1 and on the Bound Brook borough map (Fig. 1-2)

The location of the gauging satations are shown on Figure 1-3A and an illustration of the effects of urbanization on runoff in Fig. 1-3B. The Bound Brook basin hydrograph shows the effects of a relatively small urbanized drainage area with a steep channel slope (Fig. 1-4). Floods peak quickly with short lag times and steep rising limbs. As runoff is quick with little chance for channel and bank storage, falling hydrograph limbs are also steep and relaxation periods are short. When bankfull discharges are normalized (corrected) by the drainage area, the Bound Brook bankfull discharge is 30% greater than any other portion of the Raritan. This is due to the fact that the sub-basin has the greatest impervious surface coverage (buildings, roads, and parking lots) in proportion to its size in the entire Raritan system. This sub-basin exhibited the highest concentration of heavy metals in river water within the entire Raritan Basin. The elevated levels of heavy metals are mainly dissolved and thus primarily occur in a geochemical form most available to aquatic organisms. Urban stormwater runoff and other non-point source pollution appear to be the greatest contributors of heavy metals in the Bound Brook-Green Brook system.

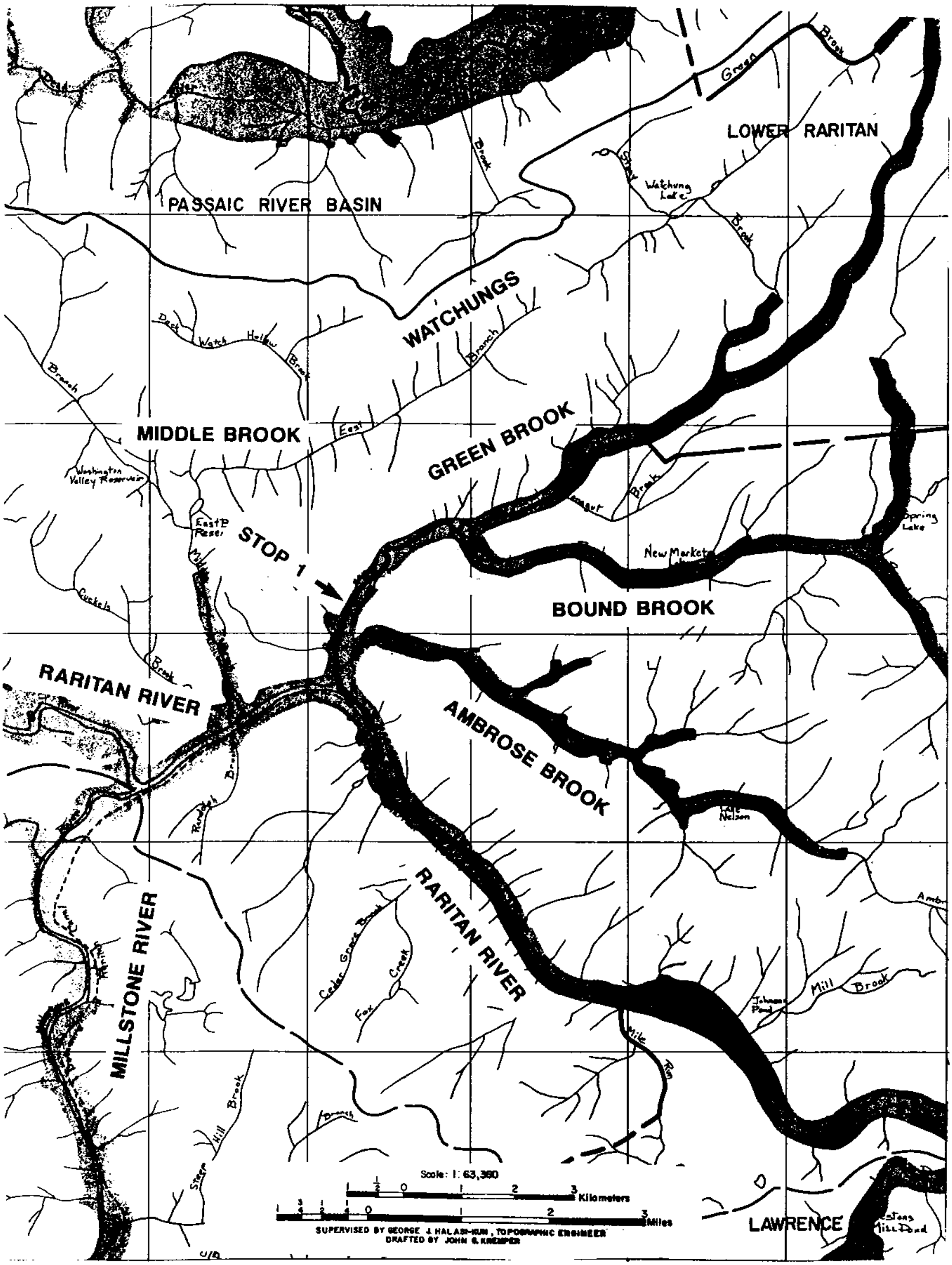


Figure 1-1 Drainage pattern of the Bound Brook system which lies within the Lower Raritan sub-basin (Fig. D2).

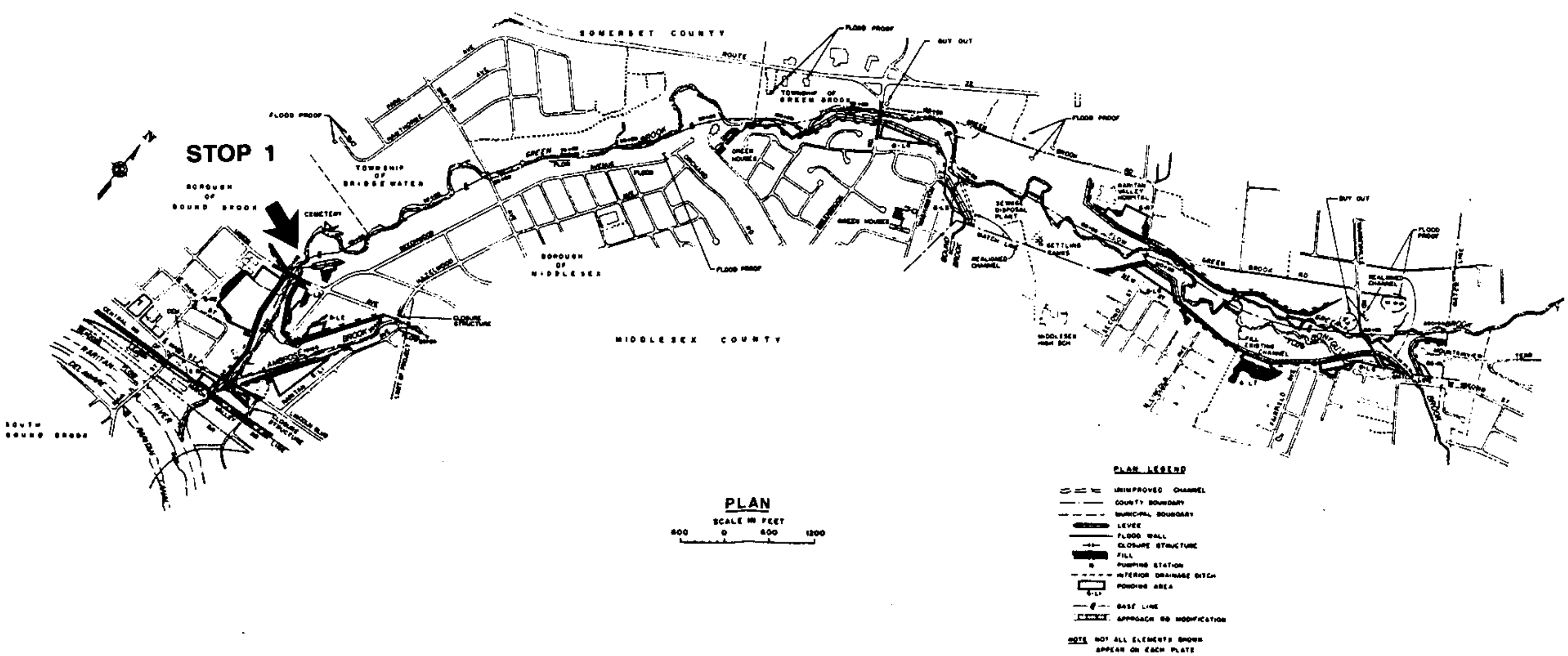


Figure 1-2 City map of Bound Brook showing location of **Stop #1**. The Bound Brook drainage is an archetypal urban water shed. Major alterations have been made to channel and storm sewers empty directly into the river.

A.

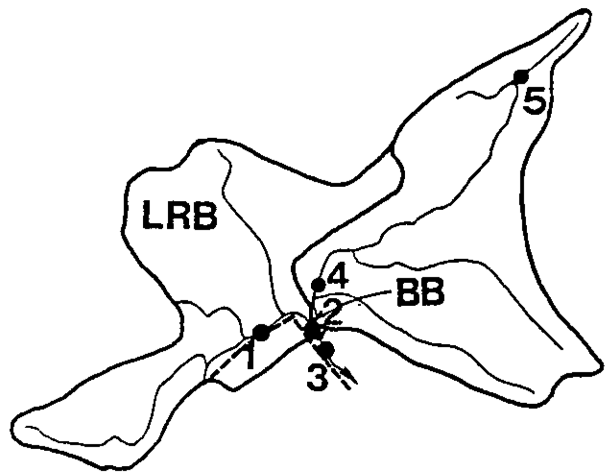
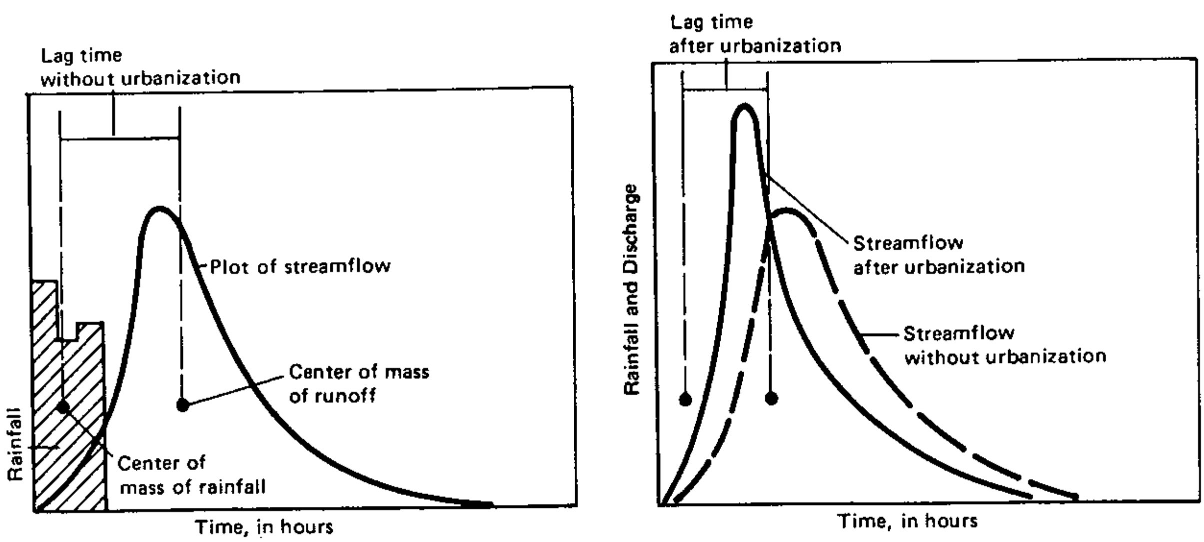
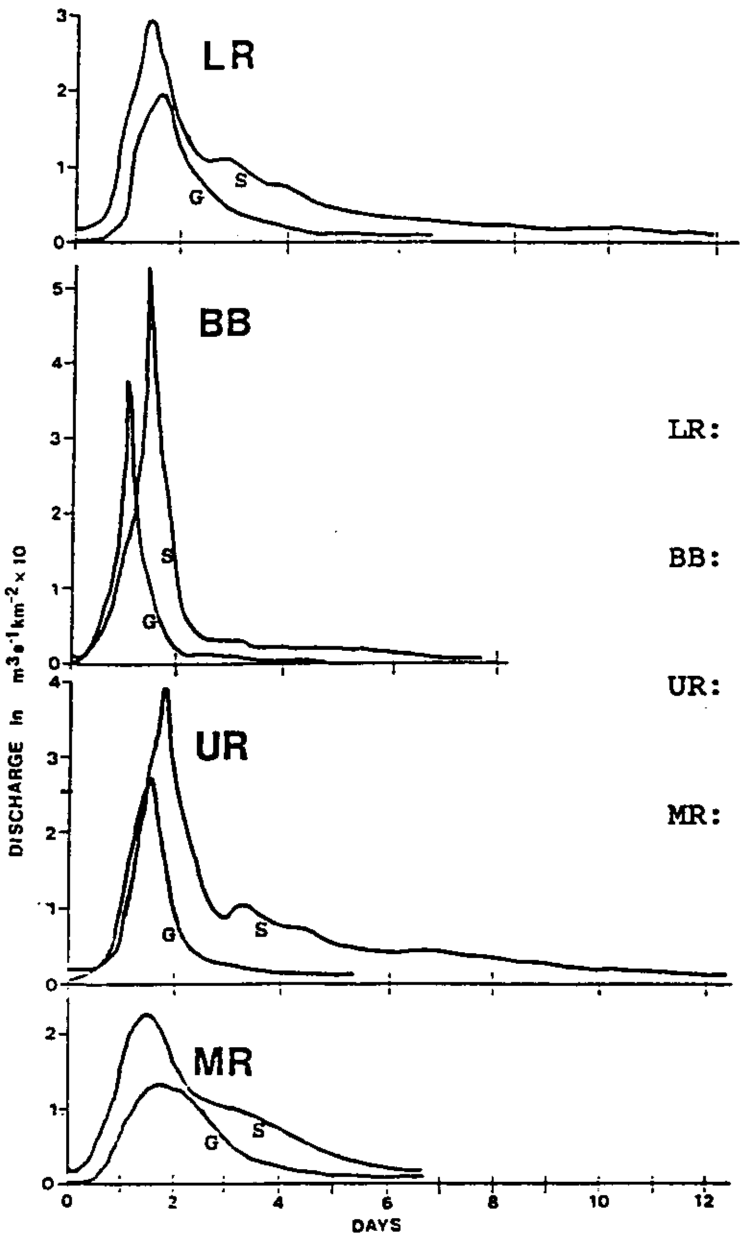


Figure 1-3 A. Location of U.S. gaging stations in Bound Brook sub-basin. B. Graph showing relationship between rainfall and runoff and the effects of urbanization in decreasing the lag time between rainfall and runoff.

B.





		G	S
LR:	T	14.5	8.1
	R	0.74	0.51
	Q	437	654
BB:	T	13.2	6.4
	R	0.64	0.43
	Q	100	148
UR:	T	19.3	11.4
	R	1.02	0.76
	Q	328	498
MR:	T	10.7	6.6
	R	0.58	0.36
	Q	94	164

Figure 1-4 Stream hydrographs for the major tributaries in the Raritan River Basin. G=Hurricane Gloria during Sept. and Oct. 1985 (dry antecedent period; high rainfall rate, high total rainfall); S=early spring freshet, March 1987 (wet antecedent period; moderate rainfall rate, moderate total rainfall). T=total rainfall for storm (cm), R=average rainfall rate (cm.hr-1), Q= peak channel runoff (m3 sec-1)(Pavlowsky, 1989).

STOP #2 North Branch Tributary, North Branch (Somerset) County Park

The North Branch drains 492 km^2 of which 52% is agricultural land, 37% is forested and 11% is urbanized. The North Branch has a mean annual discharge of approximately 7.9 m3 sec-1 which is 17% of the total flow of the Raritan basin. **Stop #2** is located just upstream of the confluence with the South Branch (Fig.2-1). The bed is composed of sandy gravel which is entrained and transported only during high discharge events. In between flood events gravel is stored in bars; one prominant bar is exposed at Stop #2. A cut bank in the flood plain reveals crudely bedded, silty fine sand. These deposits are a record of the suspended sediment load transported by the North Branch during floods.

The channel cross section at Stop #2 is asymmetric. The tributary is flowing against bedrock on the west bank and a 900 m wide sloping flood plain occurs on the east. Overbank flow occurs in many areas with recurrence intervals of less than 10 years (Fig.2-3). There is ample evidence in the the floodplain for recent flood activity. Sandy levee deposits line the river banks and behind the levees are poorly-drained swales floored with silts and clays in which river water ponds after floods. The fine-grained deposits are a potential sink for sediment-associated pollution. Although, the North Branch is relatively clean with only 10% of the water samples showing Pb or Cu over the threshold limits (Section G; Table 4). The North Branch flows south from Stop #2 and is abruptly deflected to the SW by a topographic high. This right angle bend is likely controlled by the inactive Flemington Fault which runs approximately NE/SW beneath the North Branch valley just south of Rt. 202. The North Branch and South Branch display the lowest concentration of heavy metals in the entire Raritan Basin. The levels of bioavailable metals are also lowest leading to a healthy population of aquatic organisms including sport-fishing species. The heavy metals found in these tributaries appear to have been generated naturally by weathering of bedrock with minor contribution from agricultural and urban runoff.

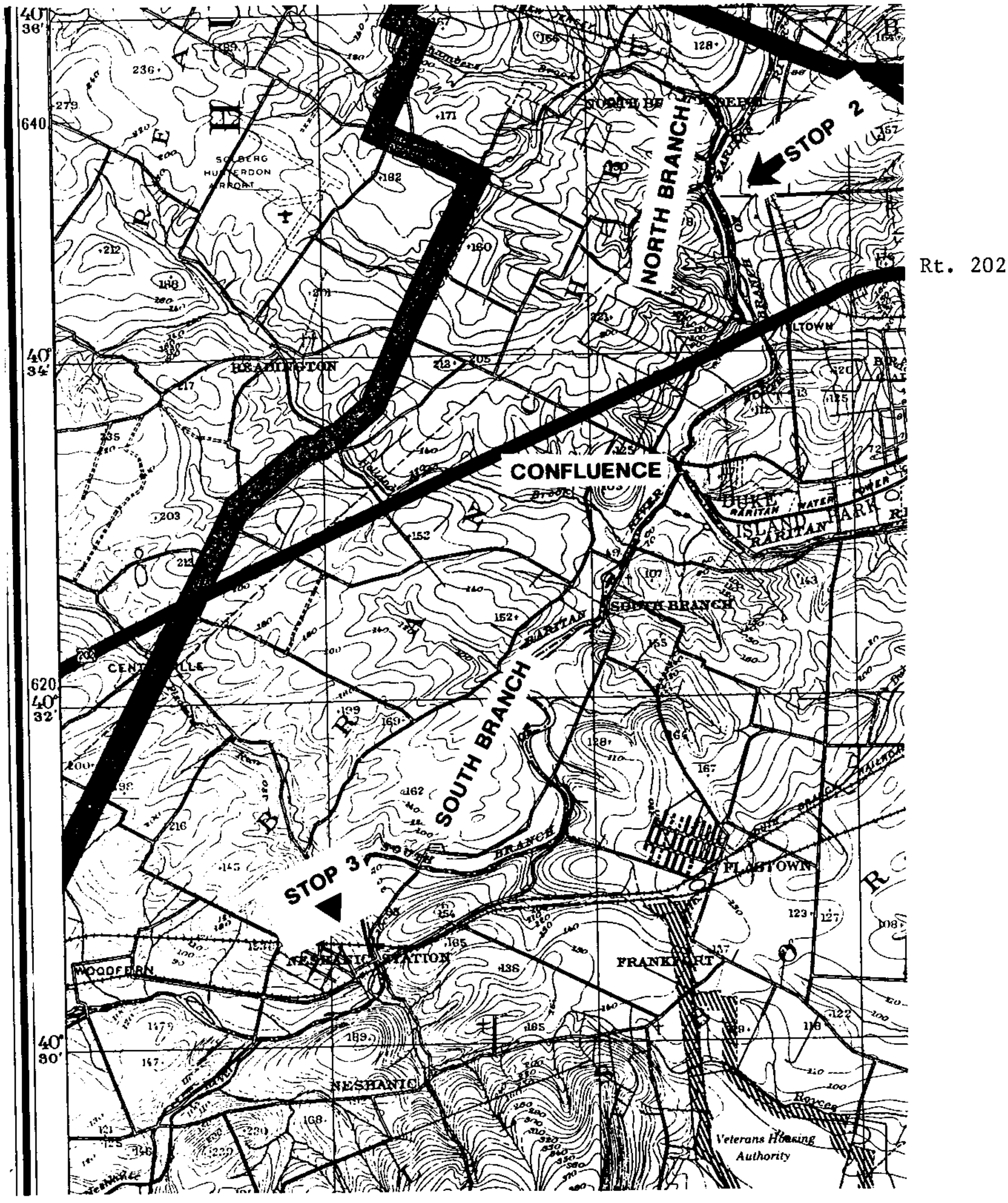


Figure 2-1 Locations of confluence of North and South Branches and **Stop #2 and Stop #3**. NJ Atlas Sheet 25, topographic series. Scale 1 mile to the inch.

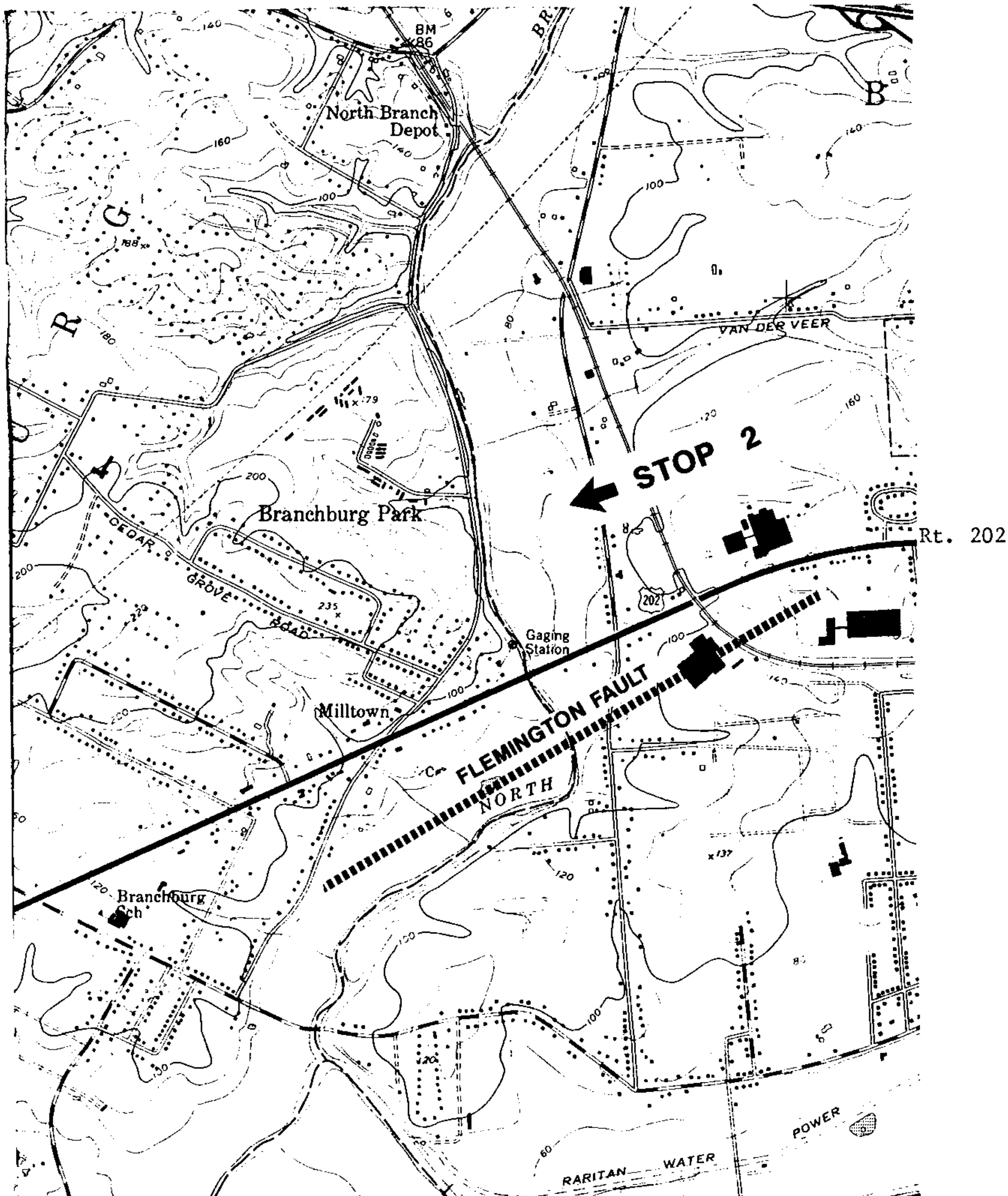


Figure 2-2 Topographic map of **Stop #2**, North Branch County Park. USGS Quad. map, 7.5 min series, Raritan quad. 1:24,000.

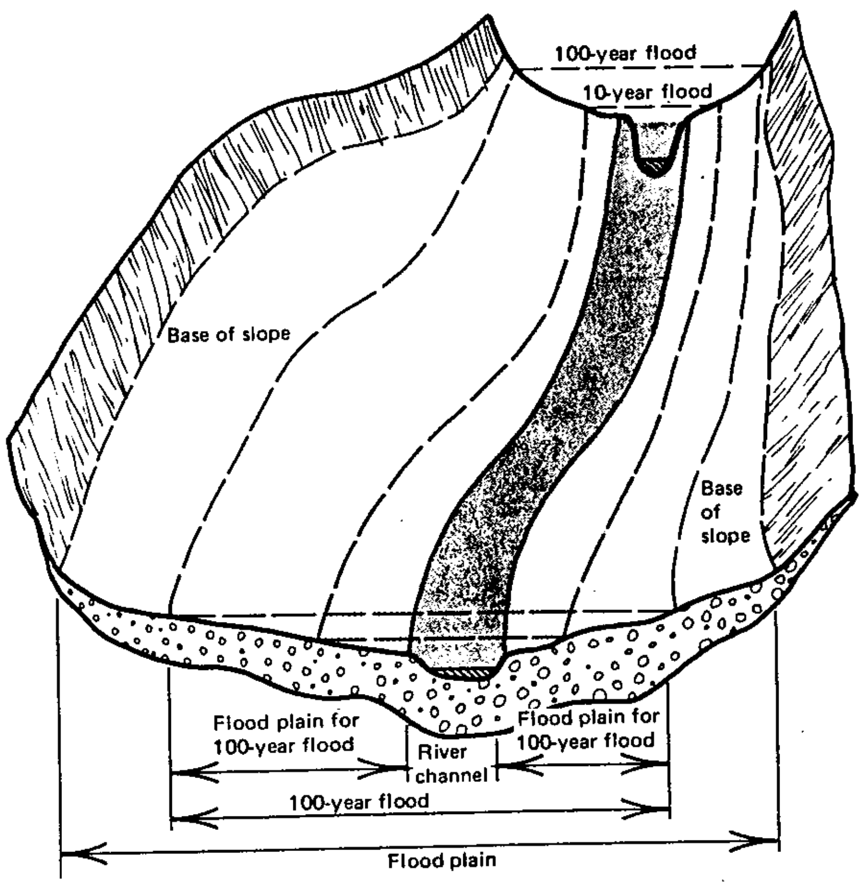


Figure 2-3 Diagram showing the relationship between a river, its flood plain and the area covered by large infrequent floods.

STOP #3 South Branch Tribuary, Neshanic Station

The South Branch originates from Budd Lake, elevation 933 ft (284 m) and joins the South Branch at elevation 50 ft (15 m). The tributary drains 722 km2 and has a mean annual discharge of 6.3 m3 sec-1 supplying 25% of the total flow of the Raritan River. **Stop #3** at Neshanic Station (Fig. 3-1) is located 6 kilometers upstream of the confluence with the North Branch (Fig. 2-1). The channel meanders through a relatively wide flood plain. Land use is mainly agricultural with about 35% forested and minor 10-15% urbanization.

Figure 3-2A shows the tributary system of the South Branch and North Branch and the location of the USGS gauging stations. Two large resevoirs are filled with water pumped from the South Branch.

The typical hydrograph of the South Branch (UR on Fig. 1-4) shows a quick rise to peak flow because of steep channel gradients, particularly in the headwaters. However, due to its large area and rural character, lag times are greater and falling limbs are less steep, than the urbanized Green Brook. The relaxation period is long due to upstream routing effects and short-term storages. Flood stages tend to be slightly higher in the North and South Branches compared to lower portions of the Raritan. This is likely due to relatively high channel slope and large areas of impervious bedrock (7.6% of drainage area) in the Highlands Province which can increase runoff rates to downstream reaches.

Suspended sediment (Fig. 3-2B) is transported directly through the river to areas downstream except during floods where some may accumulate on the flood plain. Bedload moves only during high discharge events and is stored as bars in between the infrequent floods.

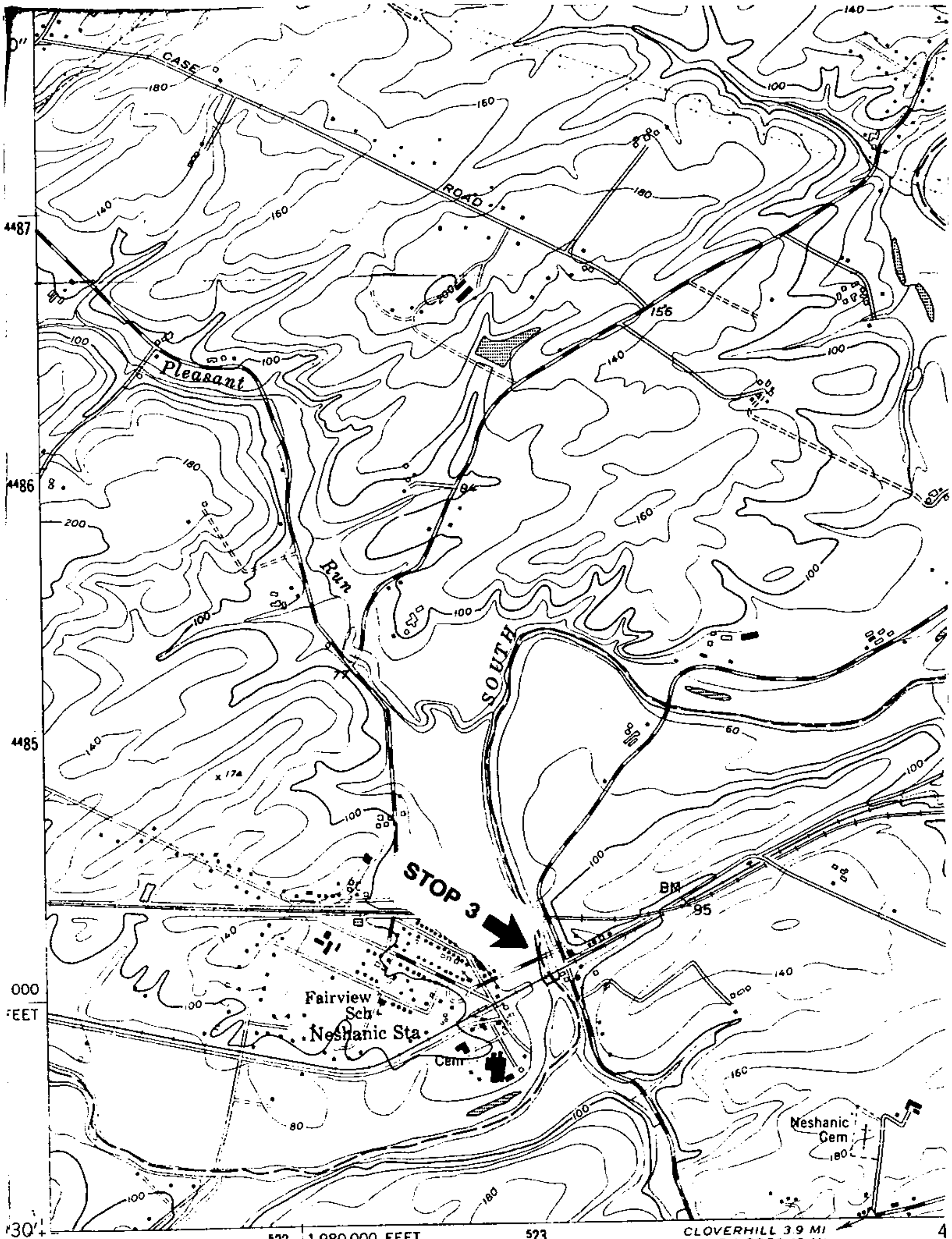
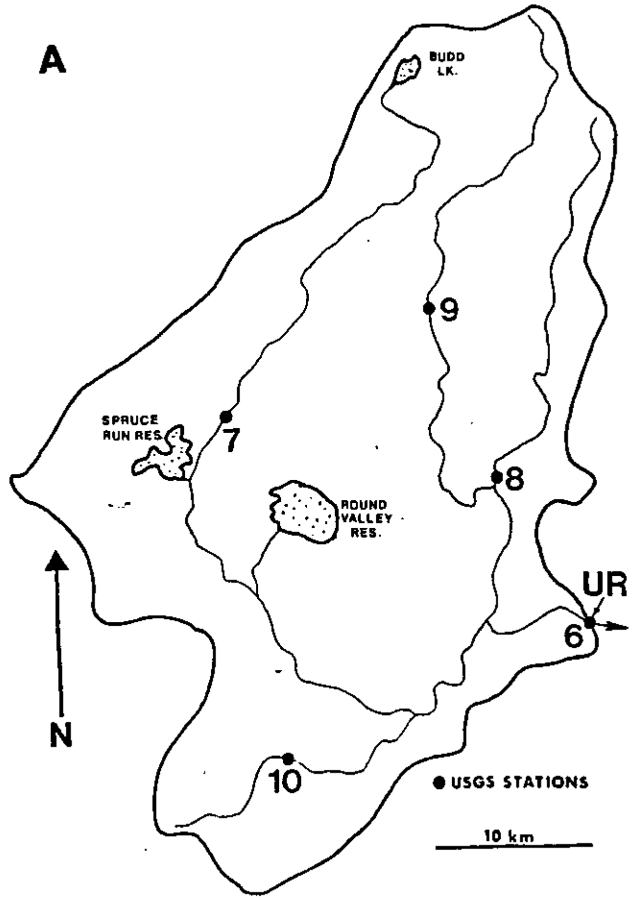


Figure 3-1 Topographic map of **Stop #3**, South Branch, Neshanic Station. USGS Quad. map, 7.5 min. series, Raritan quad. 1:24,000.

A



B

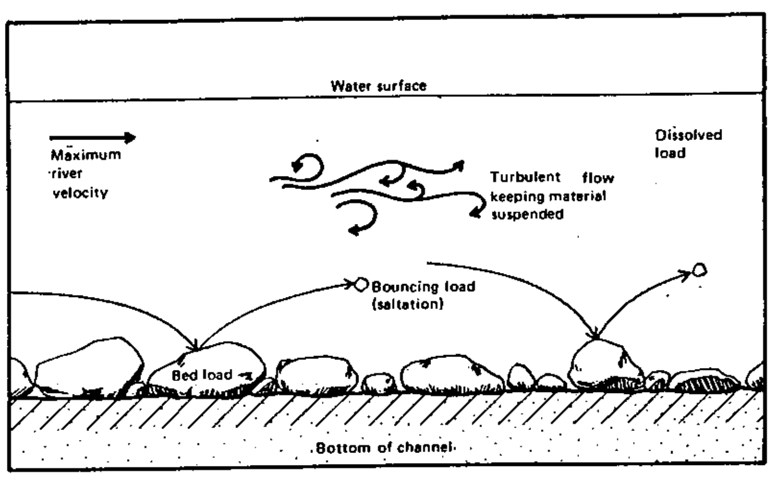


Figure 3-2 A. Tributary basin map for North and South Branches (Upper Raritan) showing location of gaging stations. B. Diagrammatic sketch parallel to flow showing types of sediment load.

STOP #4 Carnegie Lake, (Millstone Tibutary), Kingston, NJ

Carnegie Lake is a relatively narrow and shallow impoundment. It was formed by the construction of a dam on the Millstone River at Kingston in 1907. The lake has a surface area of about 1 km^2, a length of 5.5 km, and a mean depth of 1.2 m. At its outlet, the lake drains 445 km^2 which represents 63% of the Millstone Basin. The lake receives most of its runoff from the Stony Brook and the Upper Millstone sub-basins. The mean annual discharge at the USGS gage near Kingston (just below the outlet of the lake) is 7.8 m^3/s or 18.2 $l/s/km^2$. The volume of Carnegie Lake varies due to dredging and ranges from 1.2-2.7 million m^3. This capacity corresponds to 2 to 4 days of flow of the Millstone River at Kingston. The period of highest discharge tends to be during the winter and spring seasons (Table 1). Water is diverted between Carnegie Lake and the Delaware and Raritan Canal for water supply purposes. During the past 6 years, about 3% of the discharge at the outlet has been transferred from the canal to the Lake. Canal-to-lake diversions occur in all months and are greatest during the winter months. Lake-to-canal transfers only represent about 11% of the total diversions and occur primarily in the spring and summer months.

Carnegie Lake acts as a sink for suspended sediments that originate from upstream sources. Mansue and Anderson (1974) report the results of four bathometric surveys of Carnegie Lake taken in 1907, 1950, 1959, and 1968. These surveys were used to estimate the amounts of suspended sediment trapped by the impoundment during each inter-survey period (Pavlowsky 1989). Drainage area-corrected sedimentation rates calculated for each period are: (1) 1907 to 1950, 31.7 $Mg/km^2/yr$; (2) 1950 to 1959, 18.1 $Mg/km^2/yr$; and (3) 1959 to 1968, 71.0 $Mg/km^2/yr$. The average amount of sedimentation in Carnegie Lake during the 61 year period was about 35 $Mg/km^2/yr$. When these sedimentation rates are compared to the average sediment yield of the Stony Brook basin during the same period of 78 $Mg/km^2/yr$ (Mansue and Anderson 1974), the sediment trap efficiency of the Lake averaged about 44% with a range between 23% and 91% annually. These figures probably underestimate the actual trap efficiency of Carnegie Lake, since over one-half of its drainage includes coastal plain areas. Coastal plain basins tend to have sediment yields much lower than those reported for the Stony Brook basin which drains the piedmont (Hindall and Jungblut 1980). Given the analysis above, Carnegie Lake traps about one-third of the suspended sediment load of the entire Millstone basin (drainage area of 702 km^2) annually.

The water quality characteristics of Carnegie Lake tend to reflect a mixture of runoff from both piedmont and coastal plain areas (Table 2). Piedmont surface waters are relatively basic. The weathering of the shale and basaltic rocks underlying the basin release high concentrations of calcium, magnesium, sodium, and potassium base cations. The high sodium levels may also be related to road salt inputs. Coastal plain surface waters have low pH values and very low alkalinity, indicating that these waters are

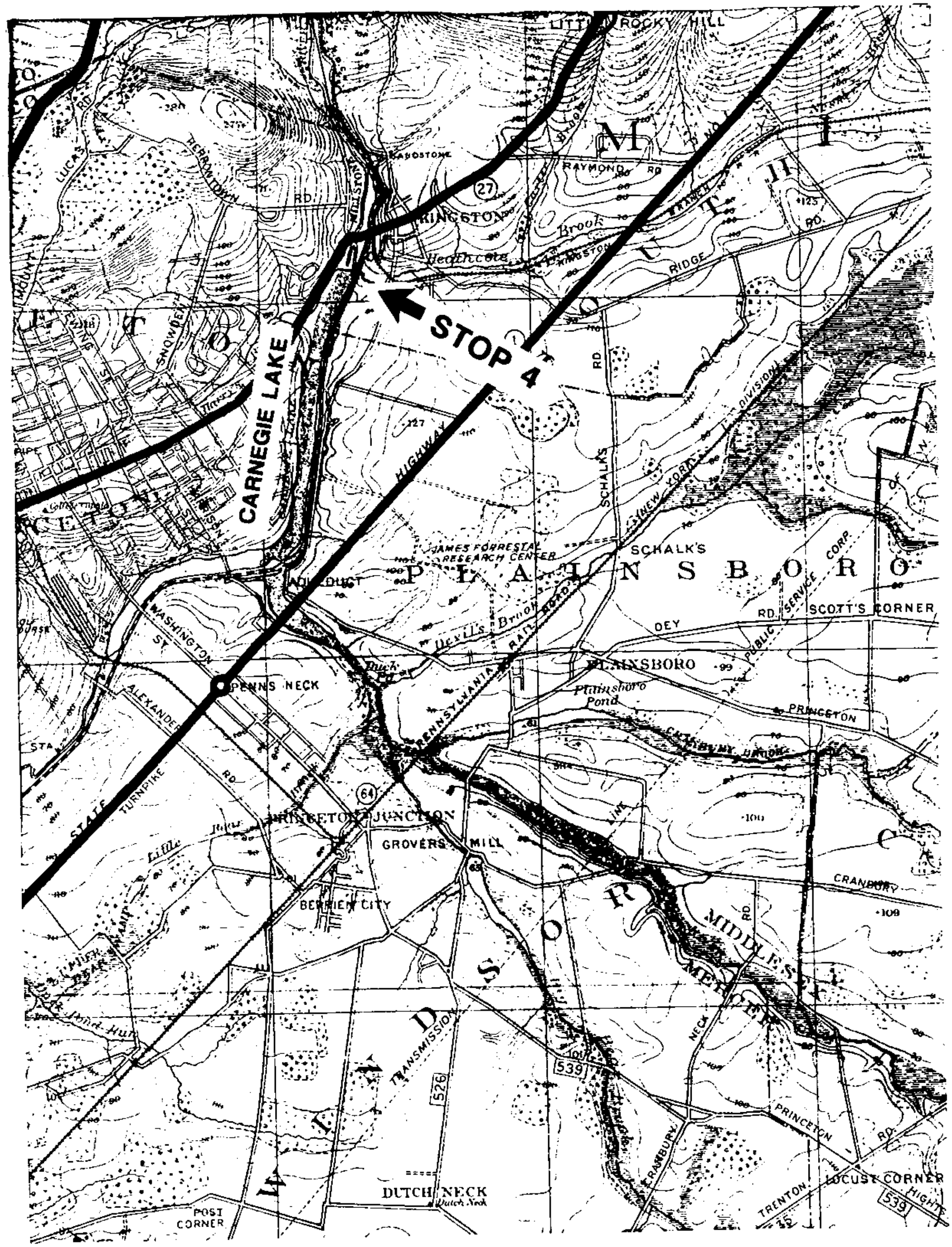


Figure 4-1 Location of **Stop #4** at Carnegie Lake. Dam impounding the Millstone River is located at northern end (Kingston, NJ). NJ Atlas Sheet 28, topographic series, Scale 1 mile to the inch.

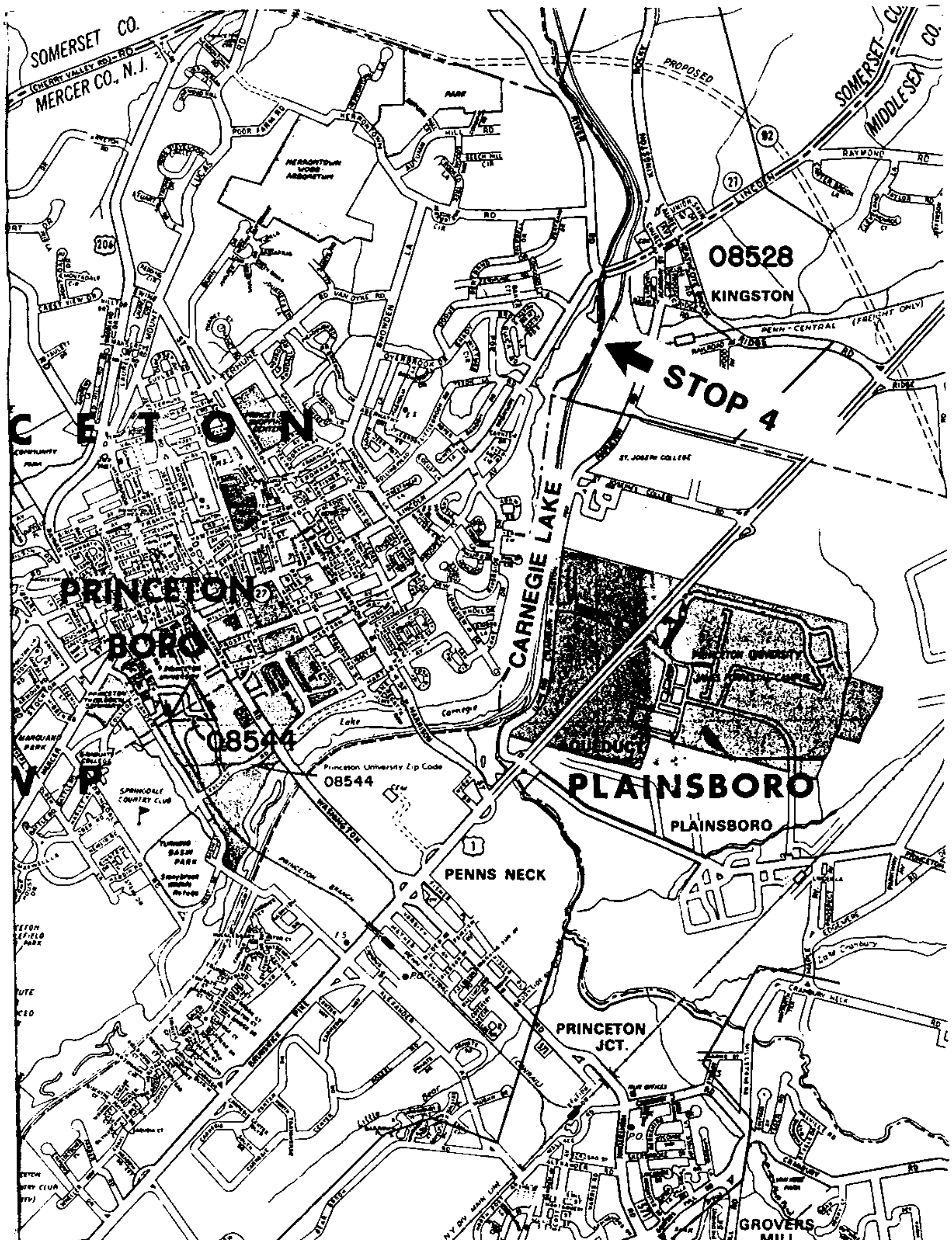


Figure 4-2 Mercer County map. 1.35" to a mile.

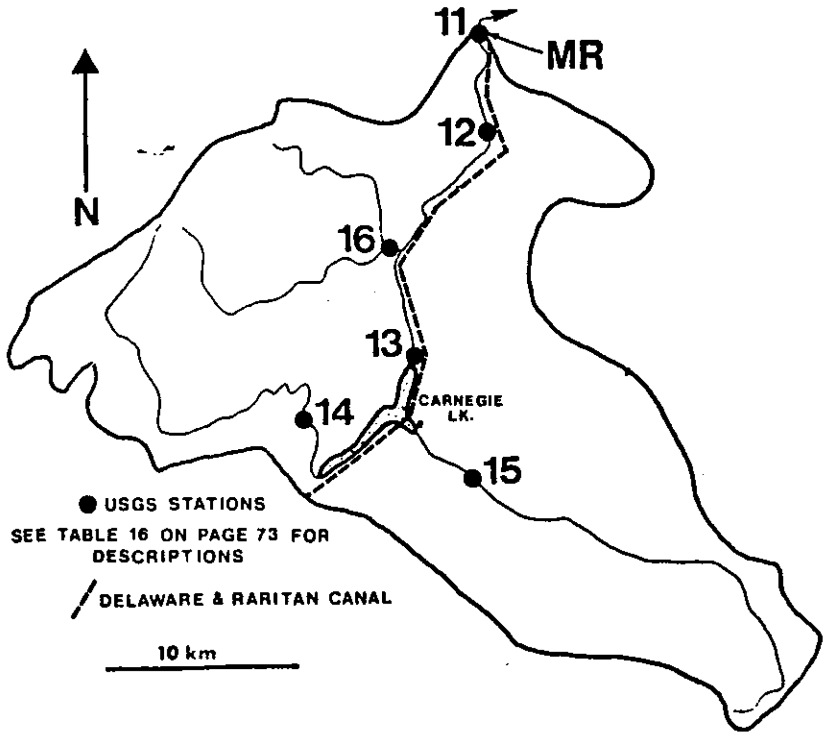
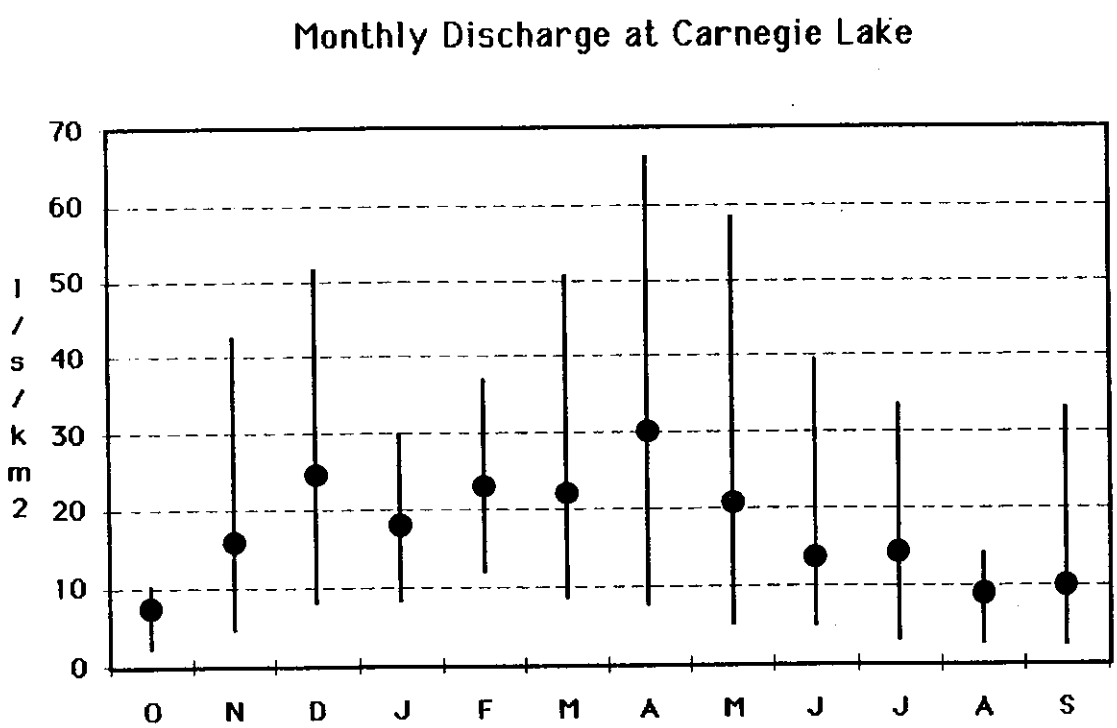


Figure 4-3 Location of U.S. gaging station on the Millstone tributary (Pavlowsky, 1989).



poorly buffered. This analysis suggests that the Upper Millstone has been affected by municipal and/or agricultural pollution. In both the summer and winter seasons the water at the Grovers Mill station tends to have high potassium, nitrogen, and phosphorus concentrations (Table 2). Further, Upper Millstone water contains low dissolved oxygen levels, particularly in the summer months. Since Carnegie Lake is not very deep or wide, runoff is transported through the impoundment quickly. Hence, it generally it appears to have little if any negative influence on water quality at the outlet. However, some pollution problems probably exist in the Lake. Besides the possibility of sediment-associated pollutants being concentrated to toxic levels in lake bottom sediments, higher concentrations of organic carbon leave the lake than enter it. This may indicate high rates of eutrophication in response to nutrient pollution from the Upper Millstone basin. Additionally, levels of some dissolved constituents at the lake outlet are lower than expected as in the cases of sodium, sulfate, and silica during the summer. It is hard to interpret this observation given the limited analysis reported here. Nevertheless, these results exemplify the differences between piedmont and coastal plain surface water quality and show that nutrient pollution has affected Carnegie Lake to some degree.

References:

Hindall, S.M., and D.W. Jungblut, 1980. Sediment yields of New Jersey streams. USGS Open-File Report 80-432, Trenton, NJ.

Mansue, L.J., and P.W. Anderson, 1974. Effects of land use and retention practices on sediment yields in the Stony Brook Basin. USGS Water-Supply Paper 1798-L, Trenton, NJ.

Pavlowsky, R.T., 1989. Trace metal yields and sources in the Raritan Basin, New Jersey. Unpublished Masters Thesis, Dept. of Geography, Rutgers University, New Brunswick, NJ.

Table 1: Monthly Discharge at Carnegie Lake. The data represent 6 years of record during the 1980s at the USGS gage on the Millstone River at Carnegie Lake, at Princeton. Discharge units are in $l/s/km^2$.

Season	Mean	Minimum	Maximum
October	7.3	2.4	10.1
November	15.8	4.6	42.5
December	24.5	8.1	51.4
January	18.0	8.3	29.8
February	23.0	12.0	26.8
March	21.9	8.5	50.5
April	30.1	7.6	66.2
May	20.6	5.1	58.2
June	13.5	4.8	39.4
July	14.1	3.1	33.5
August	8.7	2.6	14.0
September	9.9	2.4	32.9

Table 2: Carnegie Lake Water Quality Characteristics. Average values for the last 6 years of data collected at USGS water quality monitoring stations as follows: P= Stony Brook Station draining the piedmont; CP= Grovers Mill Station draining the coastal plain; and O= Kingston Station at Carnegie Lake outlet.

PROPERTY	SUMMER			WINTER		
	P	CP	O	P	CP	O
sample size (n)	25	23	22	15	12	12
Discharge ($l/s/km^2$)	3	10	7	17	26	22
Specific Conductance (us/cm)	251	178	173	196	204	186
pH	8.1	6.8	7.9	8.0	6.8	7.2
Alkalinity (mg/l $CaCO_3$)	59	15	27	32	10	21
dissolved O (mg/l)	10.2	4.9	8.5	13.9	11.0	12.4
dissolved Ca (mg/l)	18	11	12	13	11	12
dissolved Mg (mg/l)	7.9	4.2	4.8	5.9	4.4	4.9
dissolved Na (mg/l)	17.5	11.7	10.8	13.3	16.1	14.3
dissolved K (mg/l)	2.8	3.7	3.2	1.9	3.4	2.3
total N (mg/l)	1.0	3.9	2.2	1.3	3.8	2.3
total P (mg/l)	0.08	0.36	0.14	0.06	0.23	0.11
total Organic Carbon (mg/l)	4.6	5.9	7.4	3.9	4.3	4.1
SO_4 (mg/l)	25	19	19	23	25	23
dissolved SiO_2 (mg/l)	5.8	7.5	5.6	10.7	7.6	8.7

STOP #5 Head-of-Tide, (Lower Raritan), Johnson Park, Piscataway, NJ

The furthest extent of tidal effects on riverine processes varies with the magnitude of the tide (spring vs. neap) and the magnitude of the river discharge. Consequently, the head-of-tide on the Raritan is not one specific spot, but a ~4 km reach of river located near New Brunswick....from about 19 km to 23 km above the river mouth (Fig. 5-1). The **Stop #5** location is shown on Fig. 5-1 and Fig. D5 (Ashley and Renwick, 1988).

The south side of the river has been used for the construction of the Delaware-Raritan Canal and thus the south bank is high modified. The D&E Canal, built in the 1820s, served as a primary transportation route across central New Jersey for much of the 19th century. The canal is now used as a source of drinking water.

During excavation of the Raritan Landing archaeological site (located just north of the Landing Lane Bridge) gravel beds were exposed below fine-grained flood plain deposits. Based on this we interpret that the river has migrated in a southerly direction away from the resistent red sandstone outcrop (site of Rutgers Stadium) to its present position.

The river is a single channel floored with bedrock and patches of gravel <u>above</u> the head-of-tide, composed of multiple gravel channels (braided) <u>within</u> the-head-of-tide, and sandy meandering <u>below</u> the head-of-tide. There is a steep channel slope in the bedrock reach and high velocities cause rapid tranport of sediment downstream. Only coarse sands and gravels are stored in this reach, and these are only temporarily stored in small volumes. The flow is slowed or "stopped" during high tide and as a result sediment is deposited and stored in large gravel bars in the braided reach (Fig. 5-2). There are indications that the gravel bars have grown substantially in recent years because of construction (John Lynch Bridge and Landing Lane Bridge). Their prominance may have been somewhat enhanced by these activities, but their existence and location are a function of tidal hydraulics.

The Lower Raritan exhibits a comparatively moderate level of heavy metals in the water column, with average bioavailable concentrations of lead

(17ppb) and arsenic (5.1 ppb) above drinking water and surface water standards at median flow conditions. In the Lower Raritan, wastewater effluent appears to be the most important contibutor of metals during low flow and urban runoff the most significant source of metals during high flow events. Overall, chromium, nickle, and cobalt appear to have primarily derived by natural weathering and the other metals (zinc, lead, copper, arsenic, cadmium, silver, and mercury) have anthropogenic sources.

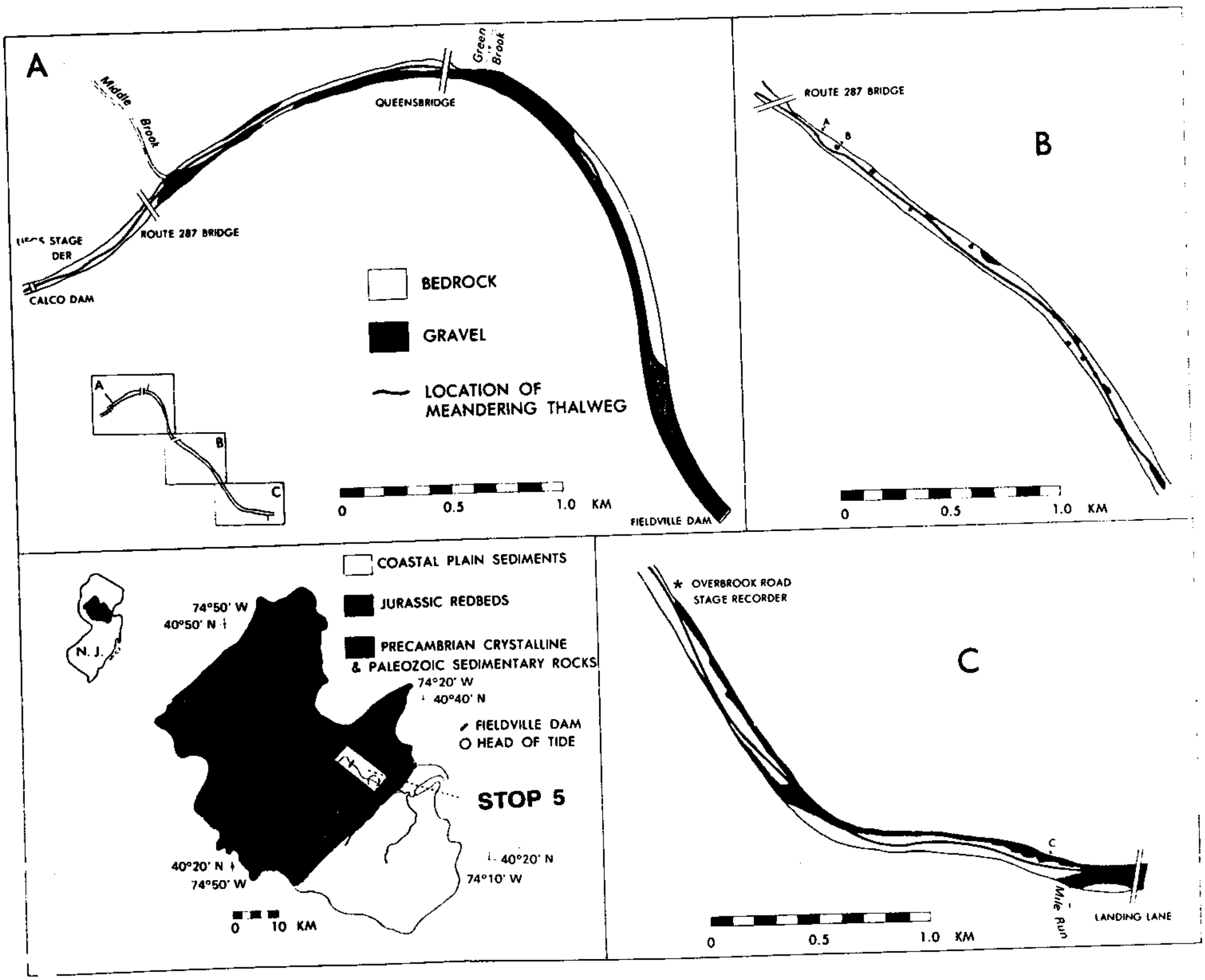


Figure 5-1 Location map for **Stop #5**. Diagrams A, B, C, illustrate patchiness of gravel in this bedrock reach.

Figure 5-2 An oblique air photo of the braided reach shows a large gravel bar exposed at low tide just downstream of Landing Lane Bridge.

STOP #6 Raritan Estuary, Edison, NJ

The contact between the Piedmont Province and the Inner Coastal Plain is upstream at the Rt. 1 bridge. A geologic section across the estuary shows that the Piedmont redbeds (the Newark Group) are only about 20 m below the coastal plain sediments (Fig. 6-1). The estuary is tidal and changes flow directions four times a day as the tide floods and ebbs. The water here is a mixture of salt and fresh water with salinities ranging from near 0 at the surface during high-runoff events to nearly 20 ppt at the bed during moderate runoff conditions when salt water penetrates further inland. The turbidity maximum characteristic of many estuaries is only weakly developed in the Raritan, but is most evident in this area (Fig. J5). The beds and banks of the river are composed mostly of fine-grained sediment, although there are occasional gravel clasts in the thalweg. **Stop #6** is at the transition between the upper estuary (muddy-gravel reach upstream) and middle estuary (the muddy-sand reach downstream) (Fig. 6-2). Fine sediment and associated organics, as well as any contaminants are transported from the upper portions of the watershed and from outside the estuary (Raritan Bay and Arthur Kill). The suspended sediment is moved landward and then seaward and mixed before deposition along the margin the channels and in the overdeepened dredge channel. Attempting to trace the path of pollutant migration in an estuary is difficult, if not impossible.

Most of the wetlands have been severely altered by human activity (Fig. 6-3). Filling has been carried out for a variety of purposes, including land reclamation, dredge spoil disposal, and solid waste disposal. Most of the marsh has been ditched for mosquito control. Two of the more obvious landfills visible here are the Kin-buc landfill on the north bank and Edgeboro landfill to the south. Kin-buc is a toxic waste landfill that operated in the mid-1970's. In the late 1970's and early 1980's closure operations were carried out, including placement of a clay cap on the top of the fill. Because of its proximity to the river leachate from the landfill is rapidly diluted and mixed with pollutants from other sources, and there is little clear evidence of

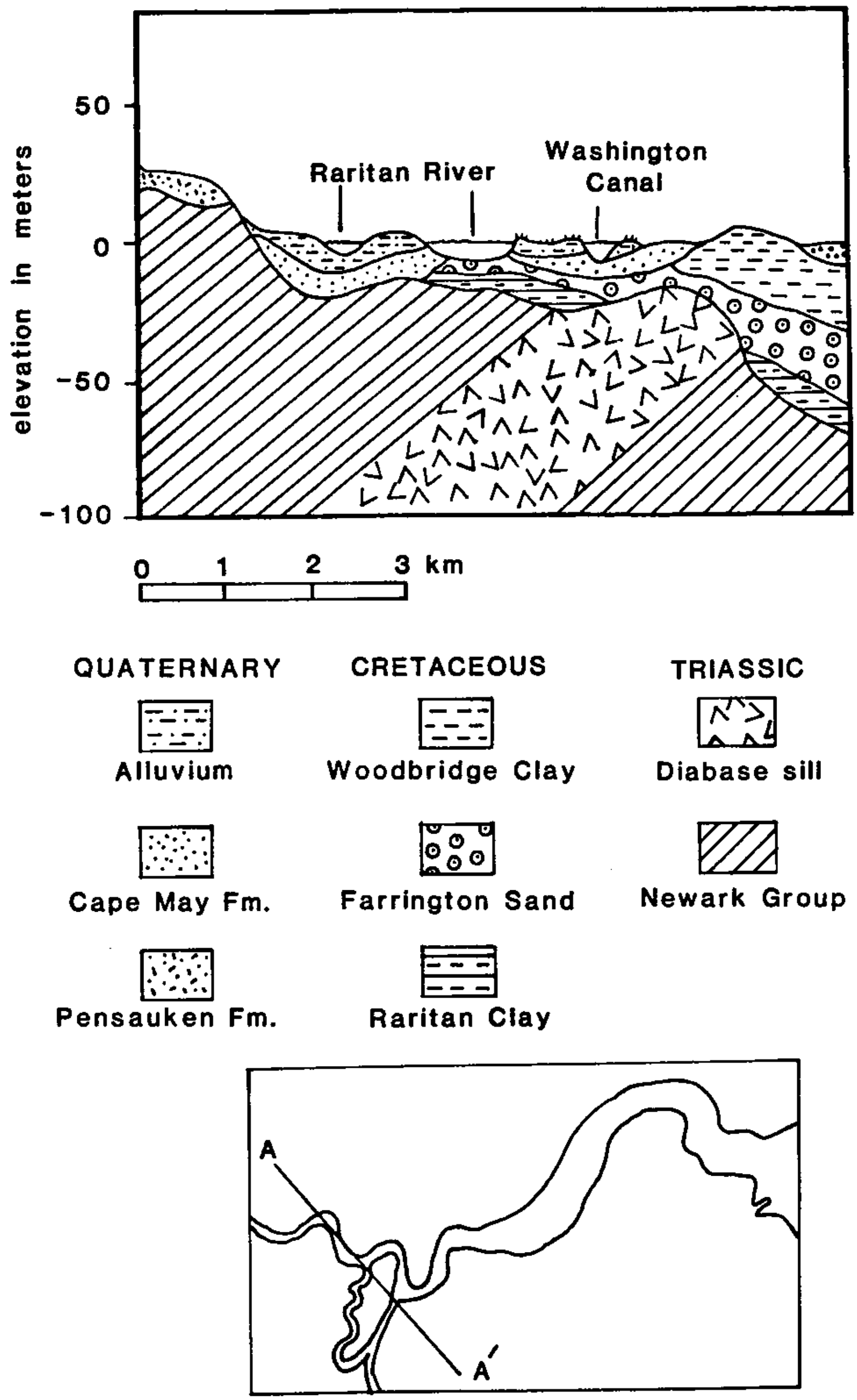


Figure 6-1 Generalized geologic cross-section NW-SE.

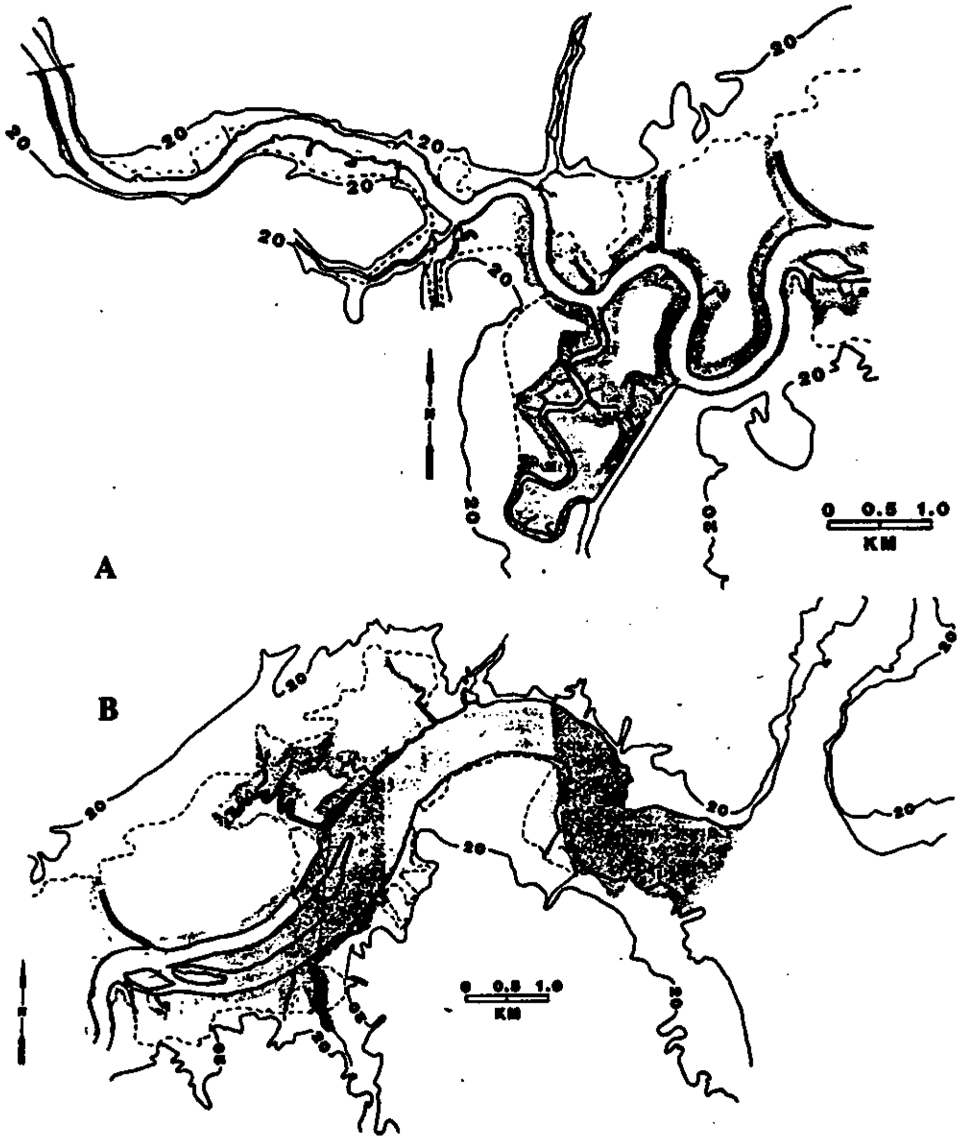


Figure 6-2 Map of areas fine-grained sedimentation. A. in upper and middle estuary and B. lower estuary.

Figure 6-3 Aerial photograph showing the highly modified saltmarsh of the Raritan River estuary.

water quality impacts of the landfill at the present time. The Edgeboro landfill is the only operating solid-waste landfill in Middlesex county.

An important thing to note regarding the estuary is that local point sources do not produce localized concentrations of pollutants in sediments because of the thorough mixing by tidal currents. In addition, although major sediment imputs are from landward sources, large imputs of sediment of ~100,000 tonnes a year from beyond the mouth of the estuary mean that there is potential for contamination of estuarine sediments from seaward sources in the Hudson-Raritan Bay system, as well as from the Raritan drainage (Section J, Table I). The estuary is serving as a sediment and pollution sink, accumulating at a rate of 1.5 to 3.4 mm yr-1 (Renwick and Ashley, 1984).

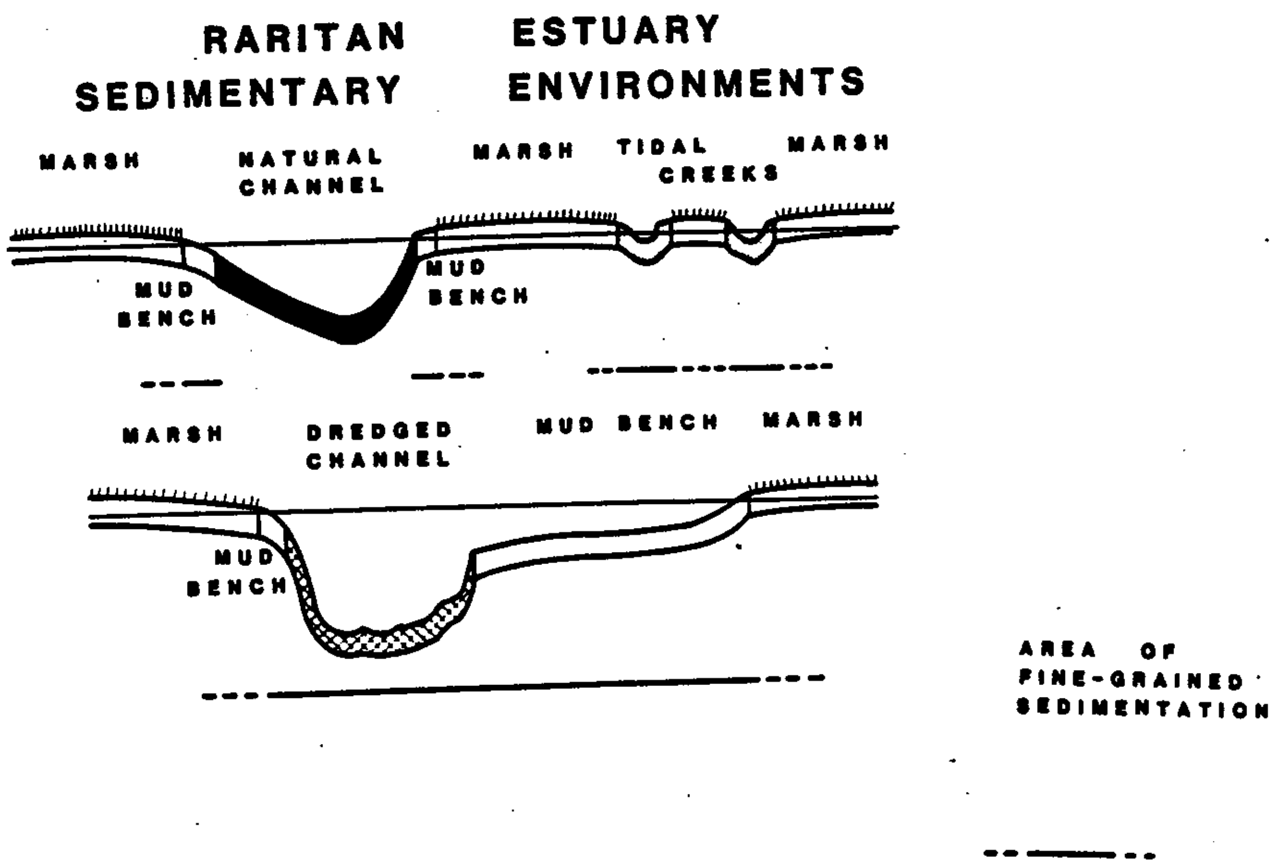


Figure 6-4 Cross-sectional diagrams of sedimentary environments.