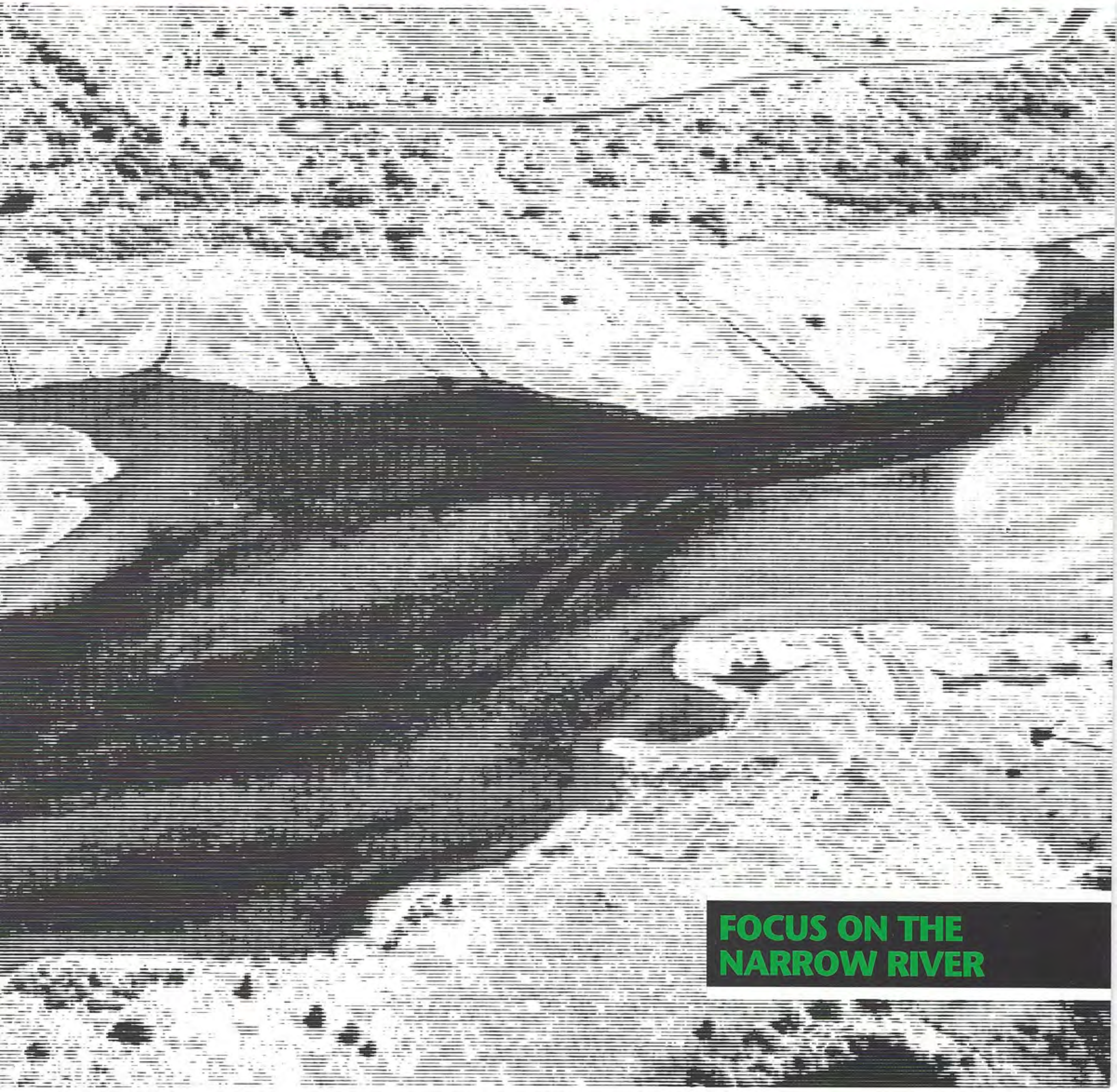
maritimes
THE UNIVERSITY OF RHODE ISLAND • GRADUATE SCHOOL OF OCEANOGRAPHY
MAY 1991



FOCUS ON THE NARROW RIVER

maritimes VOLUME 35 NUMBER 2 MAY 1991

CONTENTS

Cover: From an aerial photo of Narrow River. Middlebridge Bridge is on the back cover.
Photo by Jon C. Boothroyd.

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Maritimes is published by the Office of Marine Programs and coordinated by Sara Hickox, Director.
Address correspondence to Office of Marine Programs, Marine Resources Building,
URI Narragansett Bay Campus, Narragansett, RI 02882-1197.

(USPS 330-020) US ISSN 0025-3472

Published quarterly by The University of Rhode Island in February, May, August, and November.
Second-class postage paid at Wakefield, RI 02880.

URI Publications Office 5/91

The Narrow River

Laboratory for Science and Management

I left the surface and descended into the unknown, the sound of bubbles from the air regulator ringing in my ears, a knot of apprehension in my stomach. Almost immediately, a brownish horizon appeared below. Penetrating the horizon, the light turned red, like blood, then black. Even though I breathed air from SCUBA tanks, I could smell the stink of sulfide gas. Icy coldness began to numb the skin around my face mask. I was in a place burgeoning with invisible life-forms that do not need oxygen and never see the sun. This was not the moon, nor the bottom of the sea. It was a small brackish pond in the Narrow River and I was collecting mud samples for my dissertation.

Another time, I probed a marsh with lengths of narrow steel pipe. Below the surface I could feel resistance, quite irregular, defining a spongy buried log. Exploring the unseen surface embedded in peat, I pulled up bits of wood. Beneath this sunny marsh lay an ancient fallen forest, invisible and unknown, a remnant of lower stands of prehistoric times. This was not the Amazon delta. It was a saltmarsh along the Narrow River.

Arthur G. Gaines, Jr.
Research Specialist,
Marine Policy Center, Woods Hole Oceanographic Institution

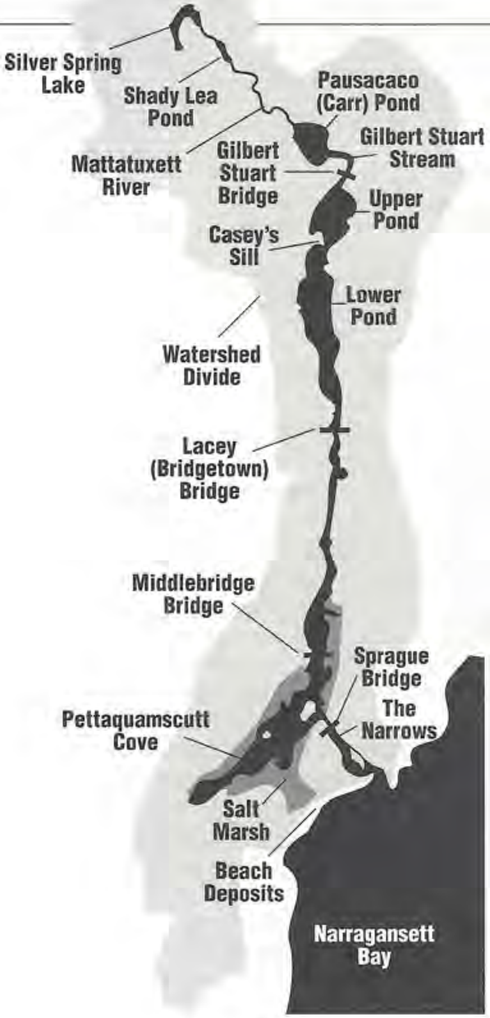
Many similar stories could be told, yet it is hard to say why the Narrow River is special. Why did I devote six years to writing a dissertation about it? Why is the river worth a special issue of *Maritimes*? For each person—scientist, fisherman, resident—the river is special for different reasons.

The Narrow River displays most of the post-glacial history of southern New England. A 10-mile trip from its tidal inlet at Narragansett Beach in the south, to beyond its headwaters in the north, represents a trip backward in time; from the marshes, flats, and estuarine lakes of the southern area ("recently" flooded by the sea) to the ponds of the central portion that are still freshwater, to the dry kettle holes in the north, yet to be filled either by rising groundwater, or the rising ocean.

The Narrow River links us to the past. The marshes we stand on today record our footprints as the latest event in a story that goes backward through our own lives and history, to the post-glacial history captured in deposits left 10,000 years ago.

The Narrow River watershed is a sharply defined natural system, in which the organization and flux of energy and materials important in the natural sciences can often be defined and measured. The geomorphologist can ask questions in the context of structure, process, and time; the sedimentary geologist in terms of sources, pathways, and fates; the geochemist in biogeochemical cycling; and the ecologist in ecosystem modeling.

The Narrow River amplifies many natural processes and provides ready access for research. Hydrogen sulfide gas accumulates in the bottom water of brackish ponds in the Narrow River to about 10 times the concentration in the Black Sea (a water body famous among geochemists for its anoxic bottom water). Accumulation of chemicals such as plant pigment derivatives and sulfur compounds in sediments of these lakes is pronounced. Distortion of the daily ocean tides, propagated through the channels, flats, and basins of the river is dramatic. Stratification of water and microbes in the brackish lakes is sharp, and natural bacteria, only indirectly detectable in other water bodies, visibly discolor the water in the Narrow River.



How should ethics and aesthetics enter a deliberation on protection of ecosystems?

An important opportunity in studying the Narrow River is the integration of natural sciences: the interactions among tidal, wind, and gravitational forces; glaciation; sunshine, rainfall, and climate; biological speciation, evolution, and behavior; chemical properties and processes; erosion and deposition; hydrodynamics; and many other processes known and unknown. Equally fascinating are the qualities that are difficult to understand in conventional scientific terms, as the "nonlinearities" of the physicist, or the "emergent properties" of the systems ecologist. These are characteristics that cannot readily be explained. How is it that salt marshes grow upward to match the rate of sea level rise? How are inlet geometry and distortion of the tidal wave determined?

During the decade I spent in Rhode Island (1964-1974) I knew the last of the river men (Thad Holburton; the Yoman brothers; Eban Carr; and especially Bill Lacey), whose lives and livelihoods were closely connected with the river. They caught fish and blue crabs, oystered (pronounced "ice'ted"), rented boats, and kept vegetable gardens. Their cottage industry, smoking the migratory river herring (alewife or buckey [*Alosa pseudoharengus*]), gave rise to the local appellation "Buckeytown" for the Bridgetown area of the river.

As the river is a geological sediment trap, so it also trapped something of the ethnic past through generations of river men who spent much of their lives within its steep walled valley. Their works are evident in structural relics along the shores of the river: archaeological sites and middens near Pettaquamscutt Cove; the Bull garrison destroyed in 1675 during King Phillip's indian war; remnants of the smelt weir at Upper Pettaquamscutt Pond; the saw pit foundation left by John Aldrich Saunders, who built coastal schooners during the early 19th century. Along the Mattatuxet River you can still see the system of dams designed to extract water and energy from the river's flow for use in manufacturing, textile, fulling, saw, and snuff mills dating back to before 1690.

The river system is less isolated than it used to be. Residents now work outside the river, but leave their residues within the system. Fertilizers, pesticides, and other domestic chemicals drain into the river through runoff. Structural damage to the system includes loss of vegetation, paved surfaces, diverted fresh water, and alterations to the shape of the river itself.

Many questions concerning man's use of natural coastal systems can be addressed at the Narrow River. For instance, what kind of chain reaction does human activity or perturbation cause in a natural system? How do nutrients added by man affect ecosystem organization and biological productivity, and is that production algae, shellfish, or fish?

The Narrow River watershed prompts equally difficult social questions, in which science plays only a partial role. Where do the individual property rights of a landowner end when damage to the larger natural system is threatened, and how is such a threat documented? How should ethics and aesthetics enter a deliberation on protection of ecosystems?

The papers that follow in this special issue of *Maritimes* illustrate some of the remarkable aspects of the Narrow River, and hint at some of the many remaining opportunities to address important problems of oceanography and management of our coastal assets. ❖

Dr. Gaines lives near Woods Hole with his wife, Jennifer (who grew up along the banks of the Narrow River), and two daughters, Sarah and Hannah.

The Geologic History of Narrow River

The view looking northwest of the flood-tidal delta sand shoals. The northern end of Pettaquamscutt Cove is partially filled with marsh. Overlying glacial river and lake deposits are open fields (top) and marsh (upper left). Middlebridge Bridge is at the upper right; Sprague Bridge is at the lower right.

Rhode Island began as a series of volcanic islands that formed along the coast of Africa before 600 million years ago (Late PreCambrian time). These volcanic islands were on a tectonic plate that collided with Africa (during an event called the Avalonian Orogeny). The granite in parts of the upper watershed of Narrow River formed at this time. Between 600 and 300 million years ago, a small slice of continental rocks drifted away from Africa, much as Madagascar is doing today. This slice (the Avalon tectonic plate) existed in the early Atlantic Ocean (the Iapetus Ocean). Pulling apart of this slice led to the fomation of the Narragansett Basin and the sedimentary rocks that underlie most of the Narrow River watershed.

Jon C. Boothroyd
Professor of Geology

The Avalon tectonic plate moved away from Africa because of several processes. The Iapetus Ocean first grew larger and then began to close as the ocean basin was consumed by a subduction zone along the North American tectonic plate. Eventually, Rhode Island collided with New England

An aerial view of the southern portion of the Narrow River and Pettaquamscutt Cove. Sprague Bridge is just visible on the right and marks the entrance to Narragansett Bay. Photos by Jon Boothroyd.

about 275 million years ago. The continent of Africa followed and further crunched Rhode Island in a scraping motion. Granite formed during this event now borders the Narrows and the south side of Pettaquamscutt Cove. At the end of this series of collisions (called the Alleghanian Orogeny), Rhode Island was probably a rugged mountainous barrier separating Africa from North America.

The high mountains were eroded to lowlands by the time the opening of the present Atlantic Ocean began between 220 to 150 million years ago. The lowlands were uplifted several times in response to complicated plate motions. The last time was probably 20 million years ago. Sediment deposited in ancient lowlands during these episodes is now missing on mainland Rhode Island but can be seen in isolated bluffs on Block Island and Martha's Vineyard. The valley that contains Narrow River probably came into existence when erosion lowered the landscape following the last uplift.

Narrow River proper and the upper ponds are underlain by sedimentary rocks that have been changed by heat and pressure. These schists, phyllites, and slates contain some interbedded graphite that originated as coal. Several small mines were established during colonial times to obtain graphite for use in the manufacture of gunpowder. Bedrock, including older granitic rock, is near or at the surface over much of the steeply sloping watershed, and the resistant granite of the Narragansett Pier Formation forms the entrance to Narrow River at Cormorant Point. The Narragansett Pier granite also pokes up through the Narragansett Basin rocks at Pettaquamscutt Rock.

An ancestral river coursed through the present location of Narrow River, eroding a valley in the bedrock and depositing sediment on a river flood plain. All evidence of this earlier river sediment has been removed by subsequent glaciation during the last one to two million years.

The glacial history of Narrow River began one to two million years ago with the first advance of a continental ice sheet. Ice covered Rhode Island and then retreated and advanced several times as the climate warmed and cooled. Each time the ice advanced, it removed the original river sediment and later glacial sediment, and redeposited it as a thin layer of till on the uplands, and as thicker river and lake deposits in the lower areas. Thus we see only the record of the last glacial advance and retreat. However, it is this last glacial episode (the Wisconsinan Stage) that truly dominates the landscape of Narrow River.

The glacial sediment now in the Narrow River valley began to be deposited about 16,000 BP (years before present). A glacial river and lake deposit (called the Saugatuckket morphosequence) filled the lowermost Pettaquamscutt valley and created a sediment dam in the area between the present Silver Lake and Sprague Park in Narragansett. With the retreat of the glacier up the valley, a glacial lake formed behind the dam. Ice blocks, detached from the active ice front, were later buried by a delta, that advanced southward into the lake filling the Narrow River valley. This interpretation of delta sedimentation is different than that shown on published surficial or glacial geologic maps; coring by myself and graduate students in support

At the end of the Alleghanian Orogeny, Rhode Island was probably a rugged mountainous barrier separating Africa from North America.

of Sea Grant studies by Dan Urish of the Department of Civil Engineering recovered glacial delta and lake floor sediment at depths of three to seven meters below present mean sea level (MSL). This shows that a lake did occupy the valley even though the maps show only river deposits.

The gently sloping, glacial delta plain dips below present sea level south of Middlebridge Bridge, thus the glacial lake level was lower than present sea level. The lake probably drained through low areas in the till-covered uplands, perhaps into a larger lake, that is now overlain by Narragansett Beach. Glacial deposition in the Pettaquamscutt valley ceased when meltwater from the glacier was directed elsewhere by ice retreat from the northern topographic divide of the valley. The meltwater was then directed toward the present Narragansett Bay through Hamilton and Bissel Coves.

Melting of ice blocks created depressions where organic sedimentation in freshwater wetlands or ponds was initiated by 11,300 BP according to work by Arthur Gaines. These wetlands and ponds were probably connected by a series of small streams, much like Gilbert Stuart Stream, at the head of the valley, is today. Saltwater incursion into the valley occurred between 4,750 BP and 1,700 BP, based on work by R. McMaster, when rising sea level overtopped the low bedrock sill in the vicinity of the Narrows. The present system of flood-tidal delta shoals, tidal flats, and salt marsh became active at that time.

The Pettaquamscutt or Narrow River estuary, trending north-south, is 10km long and ranges from 100-700m in width. A separate, 1.25km long segment (the Narrows) forks from the main estuary and serves as the present tidal inlet. Tidal range in the lower estuary is 45cm, decreasing to 10cm at the head. The present estuary occupies ice block depressions at the northern end, but at the southern end, marine sediment has filled the depressions and extended laterally over the glacial delta plain.

Narragansett Beach, a 1.6km long, 200m wide barrier spit, is anchored to a till bluff on the southwest and extends northeast to restrict the entrance of the Narrow River estuary. Mean tidal range in the open Rhode Island Sound is 1.2m. The beach fronting the barrier spit was eroding at the rate of 0.4 to 0.7m per year between 1939 and 1975 as determined by master's thesis work of Margaret Dein-Bradley (of URI's geology department). The direction of sediment transport on the beach is to the northeast, thus the beach serves as a source of sediment for the Narrow River estuary.

The lower Narrow River is geologically complex. The seaward portion of the tidal inlet (the Narrows) is filled by a flood-tidal delta and various other sandy intertidal-to-subtidal shoals. A second, more complex, flood-tidal delta is present at the junction of the Narrows with the main body of the estuary. This tidal delta, with many lobes, has moved across the estuary to separate the southern deeper-water area (Pettaquamscutt Cove) from the rest of the estuary. Most of the flood-tidal delta is subtidal, but less than 1m below MSL. The tidal delta extends northward to Middlebridge Bridge, where construction of the causeway and resulting narrow constriction has allowed a series of subtidal shoals to form north of the bridge. Salt marsh is moving outward over these tidal flats, gradually constricting the river.

Sea level is presently rising at a rate of 27cm per century as measured at the Newport tide gauge. The present rate of rise is matched by the upward growth of salt marsh peat so that the high marsh surface is level with spring high water. However, the present rate of sea level rise is raising the ground water table in the glacial river sediment along the river. This elevated water table adds to the problem of failing septic systems.

Future sea-level rise will gradually inundate, from south to north, the gently sloping glacial delta plain particularly in the Middlebridge Road area of South Kingstown. Accelerated sea level rise due to global warming will, of course, hasten this process. ❖

Dr. Boothroyd, Professor of Geology and Chairman, is primarily a field geologist specializing in coastal, glacial, and braided river environments. He has 25 years of field experience in New England, South Carolina, Florida, Alaska, Iceland, Saudi Arabia, Madagascar, and Ecuador. He serves as an advisor and expert witness on coastal zone management issues to various state agencies and towns in Rhode Island as part of his Sea Grant advisory work.

Narrow River Phytoplankton

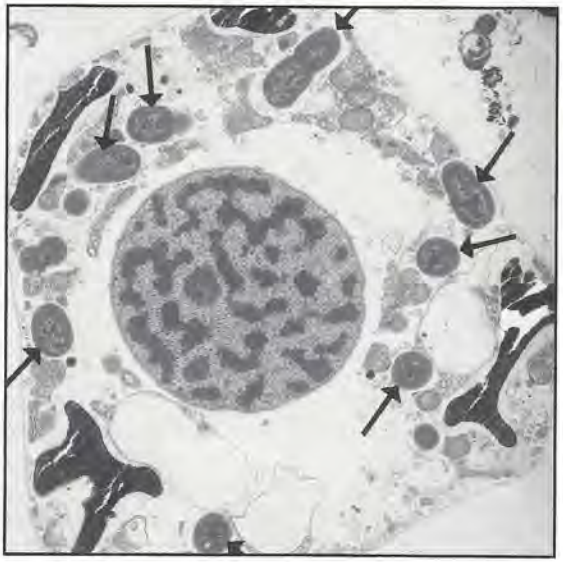


Figure 1. (Above) The silica skeleton of *Hermesinum* in the scanning electron microscope. Length is 0.04 millimeters.

Figure 2. (At right) An ultrathin slice of *Hermesinum*, perpendicular to the view in Figure 1. The four peripheral black structures in the transmission electron microscope are slices of the skeleton; the nucleus is the round object in the center; and *Synechococcus* cells are shown by arrows.

Unique is a word often used to describe the jewel of an estuary whose proper name is the Pettaquamscutt River, referred to locally as Narrow River. There are many other small embayments throughout the world with fairly similar geomorphic and hydrodynamic characteristics, but there are no other similar places nearby. The multitude of unusual and fascinating biological and mini-oceanographic features found here could occupy entire careers of URI's marine scientists while keeping them within a few miles of home and lab.

A particularly fascinating collection of creatures inhabits the upper part of Narrow River in the lakes called the upper and lower basins. These creatures, invisible without the aid of a microscope, are part of the incredibly diverse and abundant phytoplankton population. These two small basins contain more phytoplankton species than the combined number of bird and tree species in Rhode Island. The exact number is unknown, since some are new species and have yet to be formally described, and other species are discovered every year which were previously unknown in this region. Although invisible to the naked eye, they cover a considerable size range. The largest are about half the width of a human hair, but it would take about a hundred of the smallest laid end-to-end to equal the same size. Most come and go as the seasons wax and wane, but a few are there throughout the year, varying only in their abundance.

Paul Hargraves
Professor of Oceanography
and Botany

The number of creatures in the water is highly variable. When an event such as mixing of oxygen-free water from the deeper parts of the basins disturbs the normal flow (described elsewhere in this issue), two major occurances impact the phytoplankton. First, the oxygen-free water with high amounts of hydrogen sulfide kills off billions of the phytoplankton cells (most phytoplankton exist as single cells or as loosely associated colonies of cells). This mass death is most obvious in the location where mixing takes place and is accompanied by the strong smell of hydrogen sulfide. Second, a growth explosion takes place somewhat downstream in the days following the sulfide "ventilation." This mass growth is caused by the transport of nutrients into the surface water where the surviving phytoplankton, in the presence of light and the absence of grazing animals (killed by sulfide), can photosynthesize, grow, and reproduce (by cell division) causing a "bloom." Under the most favorable circumstances, one cell can produce up to several thousand cells in about a week. For example, in the fall of 1990, three "ventilations" of the upper basin occurred. By November, the bloom had reached such a level that a coffee cup full of river water contained as many cells as three times the population of Rhode Island. Cells of this kind may eventually

Figure 3. (At left) A living *Mesodinium*, which has harpooned a cryptomonad (which appears as a small white bean-shaped cell). One of the two-pronged harpoons is also visible next to the cryptomonad.

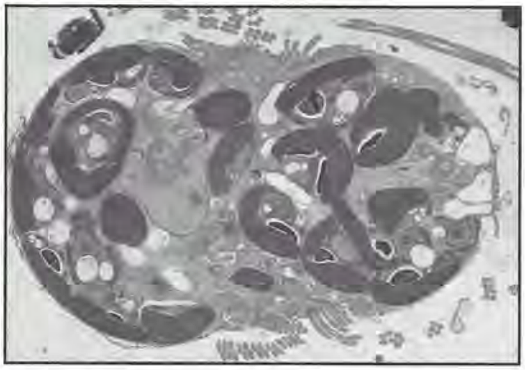


Figure 4. (At right) Transmission electron microscope image of an ultrathin slice of a *Mesodinium* with about 16 cryptomonads inside (appearing as dark bean-shaped objects in this photo). Length of *Mesodinium* is about 0.02 millimeters.

wash out into Rhode Island Sound, be eaten by planktonic animals or benthic shellfish in the river, or die and sink into the oxygen-free waters where bacteria will recycle them into nutrients to await the next ventilation.

Among the most intriguing organisms in the river are symbiotic organisms ("symbiosis" means the "living together" of two organisms: parasites and their hosts are symbiotic; an association where one organism benefits while the other is mostly unaffected is "commensal symbiosis"; if both organisms gain, the association is "mutualistic symbiosis"). Several symbiotic associations have been found in the river during the past year which have never been seen before. Research on two of these relationships, probably mutualistic, illustrate how Narrow River acts as a natural laboratory.

Hermesinum is one of the last two survivors of a group of organisms whose abundance peaked about 50 million years ago. It is found living in less than 10 places in the world, one of which is Narrow River. One peculiar characteristic of *Hermesinum* is that its skeleton is composed of silica (essentially, glass) which is shown in Figure 1. It swims slowly through the water with its heavy glass skeleton, eating the bacteria it encounters. *Hermesinum* attracted my interest because it has an unusual cell nucleus. Looking at extremely thin slices of *Hermesinum* cells in the electron microscope, something even more interesting than the nucleus appeared. Instead of digesting all of the bacteria it ate, it allowed some of the bacteria to live. Moreover, it allowed only the photosynthetic cyano-bacteria called *Synechococcus* to live as sort of an internal garden (Fig. 2). The *Synechococcus* cells all appear quite healthy, and in some cases, were growing inside the *Hermesinum*. This is a pretty good deal: when its food is scarce, *Hermesinum* can swim toward the optimum light and nutrient conditions, encouraging *Synechococcus* to grow faster, and share in its photosynthetic harvest. *Synechococcus*, for its part, is somewhat protected from the harsh environment (unless *Hermesinum* gets eaten). As is usual in science, this discovery raises lots of new questions: how and why does *Hermesinum* choose to keep only *Synechococcus* alive internally? When *Hermesinum* divides, do *Synechococcus* cells go to each of the two new *Hermesinum*? Since *Hermesinum* disappears from Narrow River every October and reappears every July, where does it go, and do its *Synechococcus* cells go with it? These questions represent a few years of research and show how Narrow River research could comprise a career.

Another case of mutualistic symbiosis, discovered in Narrow River last year by Paul Johnson and Percy Donaghay, involves two completely different organisms. *Mesodinium* is a voracious predator of phytoplankton in coastal waters throughout the world (mostly along the Pacific coast of North and South America and the Atlantic coast of Europe). Sometimes when *Mesodinium* feeds on a reddish-colored phytoplankton from the group called cryptomonads, it keeps some cryptomonad cells alive in its body and *Mesodinium* becomes red. The full name of this predator is *Mesodinium rubrum*, which means the "red mid-sized whirling one." In Narrow River there lives a predator that looks very much like *Mesodinium*, but is a brilliant blue-green color. With two forked harpoon-like appendages, it catches and eats blue-green cryptomonads. An ultrathin slice of this *Mesodinium* (Fig. 4) reveals up to 20 cells of the cryptomonad living inside. One presumes the advantages to these partners are the same as for *Hermesinum* and *Synechococcus*, and the same sorts of research questions apply. But there are others: can we call this predator *Mesodinium rubrum* if it is blue-green rather than red? Is the cryptomonad an entirely new species? (I believe it is.) Why doesn't *Mesodinium* keep

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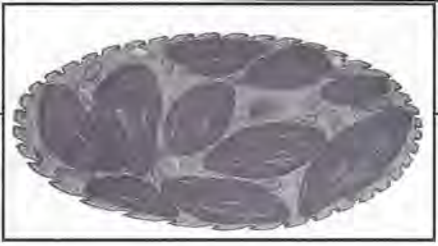

The Pettaquamscutt Lakes

A Captive Estuary for Studying Global Warming

Figure 4. These dominant forms found in the pycnocline include the oxygen-producing alga *Euglena proxima* (20 x 70 µm cell with chloroplasts) at top, and the anoxygenic spiral-shaped photobacterium above, which uses hydrogen sulfide rather than water for photosynthesis (in the photosynthetic chlorosomes in the periphery of this 2 µm diameter cell).

We have made great strides in recent years in understanding microbes and their processes in the upper levels of the ocean. There has been growing recognition that microbes play a major role in producing and consuming not only major gases like oxygen and carbon dioxide, but trace gases as well, including methane and hydrogen sulfide. These non-CO_2 radiatively important trace gases (RITG) play a role in the apparent warming trend of the global climate. The RITG have been all but ignored as significant greenhouse gases in the upper ocean. This was because they were thought to exist only in anoxic habitats (lacking oxygen) such as tundra, the rumen of cows, and in sea floor and lake bottom sediments well removed from the atmosphere. Recently, however, it has been recognized that less than 10 percent of upper ocean productivity falls to the sea floor. This implies that at least 90 percent of this debris must decay in the upper ocean and turn into anoxic microsites where the end products of decay (carbon dioxide, hydrogen sulfide, and methane) accumulate in the pycnocline. This is the boundary between the surface mixed layer and deeper water marked by a sharp increase in water density of stratified oceans and lakes (see Fig. 1).

John McN. Sieburth
Professor of Oceanography and Microbiology, Project Director for Sea Grant/EPA-AERL Projects

The presence of these greenhouse gases in the upper water column was largely ignored as an exotic phenomenon. They are now, however, being recognized as the "tip of the iceberg." During seasonal stratification, debris that would normally settle to the sea floor is trapped in the denser waters of the pycnocline. These processes are hard to follow in open ocean and coastal waters, due to the dynamic nature of the unfettered sea. In contrast, the two anoxic basins in the upper Pettaquamscutt Estuary (Narrow River) offer captive, stratified estuarine water for studying the processes diagrammed in Figure 1. Here, in the Pettaquamscutt, the processes taking place in open and coastal seawaters are greatly amplified due to the poor exchange between the oxygenated upper water and the lower anoxic water mass. These macrocosms, each with different salinity, sulfide, and microbial contents, have deep 15m and 20m water columns which are isolated by shallow sills from freshwater input and tidal exchanges of seawater from lower Narragansett Bay. This isolation prevents ventilation by oxygen below a depth of 4m (approximately 12 feet). These deep water columns, therefore, include the extreme conditions of oxic to anoxic. They also maintain a spectrum of microorganisms that have evolved from the ancient anoxic oceans of 3.5 billion years ago to today's largely oxygenated oceans which offer only microparticulates as a refuge for anaerobic bacteria.

Percy Donaghay and I initiated a Rhode Island Sea Grant project in 1987 to study the stratification and processes involving the microbes found in the Pettaquamscutt basins. Figure 2 shows our profiling and sampling platform moored in the lower anoxic basin. We use an instrument, developed by Donaghay, which obtains high-resolution profiles of both the physical and chemical parameters needed to describe the water column's vertical stratification. A representative profile is shown in Figure 3. Such profiles help us choose the depths from which to obtain discrete samples for microbiological analysis and more sensitive chemical analysis.

The most interesting site is in the pycnocline just below the oxic/anoxic interface at 4m. Here, in the slightly denser waters, debris and the associated microbes accu-

Figure 2. The 1990 profiling and sampling crew on the platform in the lower basin of the Pettaquamscutt Estuary, after a nocturnal station.

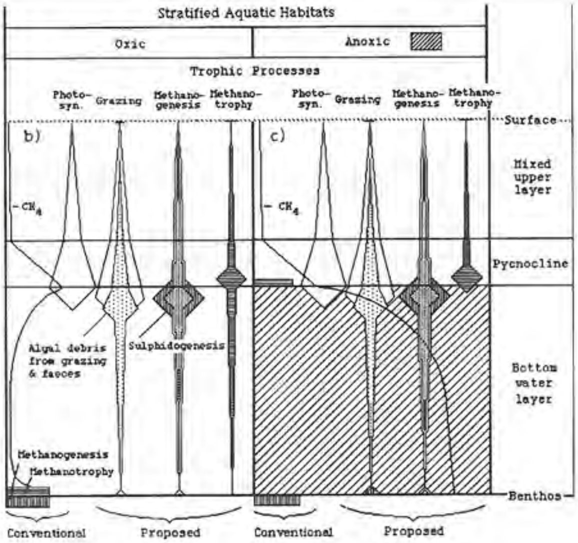

Figure 1. A proposed paradigm explaining the processes in the oxygenated pycnocline and how, with eutrophication and poor ventilation, the waters below the pycnocline can become anoxic (shaded area). The kite diagrams show relative activity on a vertical scale. The phototrophs responsible for photosynthesis are grazed by the zooplankton, forming fecal debris. In contrast to conventional concepts, it is hypothesized that the maximum production of methane and hydrogen sulfide occurs in the pycnocline and throughout the water column rather than being restricted to anoxic sediments.

mulate and cause turbidity (indicated by a decreased transmissivity of light) and fluorescence (a measure of photosynthetic microorganisms). Our study has shown that marked primary productivity occurs in this highly turbid zone, as indicated by fluorescence and the presence of the phototrophs shown in Figure 4. This is also the zone of decay which produces hydrogen sulfide and methane. Thus, stratification in the water column largely transfers decay processes from the sea floor to the upper water column as hypothesized in Figure 1. This is contrary to conventional wisdom and has been difficult for most oceanographers and atmospheric chemists to accept.

Having developed our methodology for profiling and sampling with a resolution of 1cm (rather than the usual 1m to 10m resolution) and having spent three years characterizing how physical and microbial factors control inorganic and organic chemical species, we had a basis to study whole system dynamics. We learned how storm and tidal perturbations affect the water columns. We made both daytime and nighttime observations (diel studies), which allowed us to compare light and dark processes. Our comparisons have shown us the susceptibility of anaerobic processes (like methane production) to photosynthetically produced oxygen in the anoxic zone. With these data, and well-rehearsed field procedures, we were ready for the storms and exceptionally high tides that occurred in the fall of 1990. These disruptions to the system apparently caused the seawater incursions and anoxic water displacement postulated by Arthur Gaines almost 20 years earlier. Water rich with hydrogen sulfide was pushed into the oxic zone and formed milky clouds of microscopic sulfur particles. These particles blocked the sunlight, interfering with the major photosynthetic alga and bacterium shown in Figure 4.

Now that we have observed the influence of diel cycles, seasonal cycles, and storm fronts, we are preparing for the second year of

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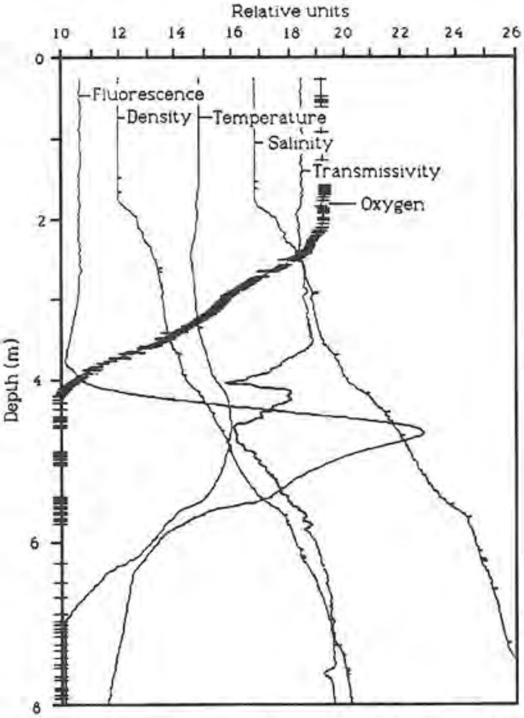

Figure 3. A centimeter-scale profile of the upper 8m of the lower anoxic basin of the Pettaquamscutt Estuary. Note the sharp drop in oxygen to form the oxycline, and two discrete maxima in turbidity (as indicated by transmissivity), the lower coinciding with the fluorescence maxima dominated by the photosynthetic forms shown in Figure 4.

Metal Pollution Recorded in Pettaquamscutt River Sediments

Two basins in the upper reaches of the Pettaquamscutt River estuary provide a unique environment for establishing the recent environmental history of Rhode Island. Each basin has a stratified water column resulting from the contrasting density between the lighter, lower salinity river water flowing out from the north over the top of the incoming denser sea water. This relationship creates a lens of fresh water that caps the denser salt water beneath it, limiting the ability of oxygen to penetrate to depth. The inability of oxygen to mix downward causes oxygen depletion, or anoxia, in the bottom waters of the Pettaquamscutt River.

This anoxic condition produces several important effects in the sediment column that mark the Pettaquamscutt River as a valuable site for reconstructing the recent environmental history of Rhode Island. The first important effect is the formation of annually layered sediments formed by seasonal variations in the sediment that is deposited. These annual layers are usually destroyed after deposition by the burrowing activities of bottom-dwelling organisms. However, anoxia at depth precludes the presence of bottom-dwelling organisms and, consequently, limits biological mixing which could disturb the record in the upper sediment layers. Accurate age determinations can be made using these sedimentary layers in the same way that age can be determined by the annual growth rings of trees.

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A second effect is that anoxia tends to immobilize chemical species, particularly trace metals, in the sediment column. Normally, a strong gradient exists between oxygenated bottom waters, surface sediments, and anoxic sediments deeper in the sediment column. This gradient allows trace metals to migrate freely through the sediment column and confuse the pollution record. However, the elemental sulfur associated with anoxia combines with the positively charged metal particles to form highly insoluble metal sulfides which are virtually immobile once deposited. For this reason, the annually layered sediment sequences, and the heavy metal concentrations associated with them, can be a powerful tool for investigating the history of marine pollution in the Narragansett Bay region.

Research on the river is particularly important because one cannot assess the current status and long-term trends in environmental quality of the river without sufficient historical data on pollution. The environmental impact of humans is recorded in the trace metal concentrations of the sediment. Our study will quantify the record of sediment contamination within the undisturbed sediments of the Pettaquamscutt River.

Sediment cores taken in the middle basin of the river were analyzed for heavy metal concentrations, grain distributions according to size, and age of the sediment. The Pettaquamscutt River sediments reflect the history of pollution inputs beginning in the 1700s. The increases beginning in the mid-1800s correspond to the end of the Civil War, a time of tremendous growth in industrial activity and in Rhode Island's population.

The distribution of lead in the river is one example of the influence of post-European settlement (Fig. 1). The period prior to the early 1800s shows little variation in metal concentrations and reflects the natural occurrence of the metals in the sediment prior to human impacts.

Since then, lead inputs have increased, largely due to the combustion of fossil fuels. After the 1920's, increased lead inputs have been traced to the use of lead-containing fuel additives. Today, about 98 percent of the lead contributed from the atmosphere can

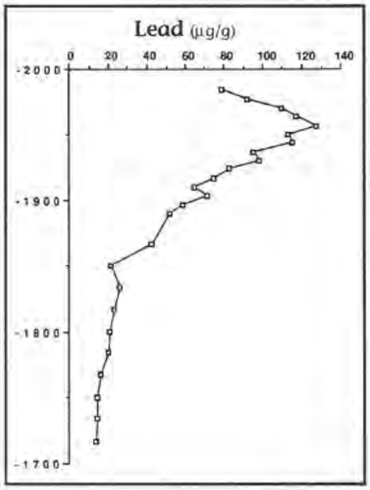

Figure 1: Lead concentrations versus age in Pettaquamscutt River sediment cores.

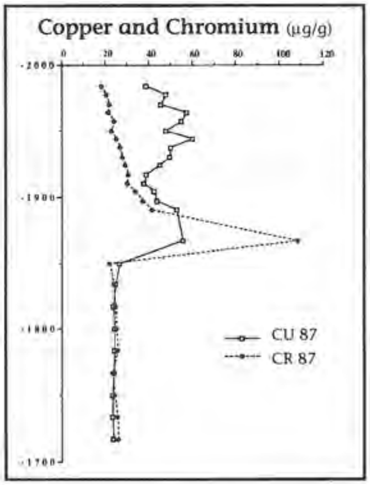

Figure 2: Chromium and copper concentrations versus age in Pettaquamscutt River sediment cores.

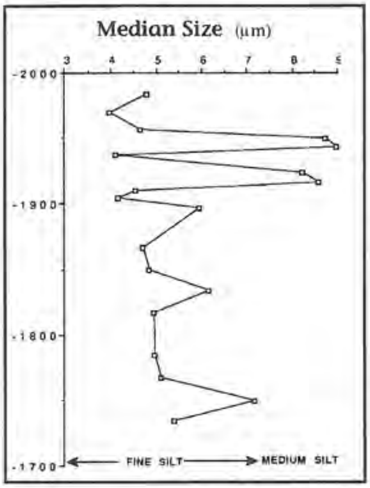

Figure 3: Median grain-size distributions versus age in Pettaquamscutt River sediment cores.

be traced to the combustion of gasoline. The plots of lead in the river show this increasing trend through the 1950s and into the early 1970s, when consumption of lead-containing fuel was at its maximum (National Research Council, "Lead," 1972). The regulation of lead additives in the 1970s resulted in decreased consumption of leaded gas which is reflected in the core data. Other possible lead sources in the river sediments are runoff from the land and industrial effluents. The runoff can be enriched in lead from housing pipes and leaded paints as well as gasoline and automotive fluids that leak onto the roads and wash into the river.

Other heavy metals analyzed in this study include cadmium, chromium, copper, iron, silver, manganese, nickel, and zinc. The chromium and copper records (Fig. 2) show further evidence of human influence on the study site. Chromium shows a large spike in the 1850s. Textile mills were established along the shores of the Pettaquamscutt River during this period, and these mills produced dyed cloth through the 1860s (Pettaquamscutt Historical Society, 1963). The color treatment of these textiles involved the bonding of the color to metals, most often chromium (National Research Council, 1974). The copper trend is similar to that of chromium, with a spike appearing near the 1850s. Copper may have been associated with the mills along the river, but may also be attributed to the Pettaquamscutt shipbuilding industry and the use of copper nails.

The second part of the study focused on obtaining the grain-size distribution down the core in order to relate the accumulation of fine particles with the metals electrically attracted to them. Three trends are apparent in the grain-size data (Fig.3): the deeper part of the core contains fine-sized particles, whereas the interval between about 1900-1960 contains coarser sediment. The coarsening trend in the data relates to increased land use adjacent to the basin. Vegetation lost due to land development causes increased runoff and erosion and an influx of coarser sediment into the basin. Subsequent to 1960, the pace of development adjacent to the basin slowed and finer sediments were deposited.

This study emphasizes variation in the sedimentary record and in the heavy metal concentrations with time. Further studies are underway to accurately count the laminations observed in the cores and to study the history of environmental change at the site since the time of the last glaciation. ❖

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Jeff Corbin received his bachelor of science degree from the University of South Carolina in 1986. He completed his master's degree in geological oceanography at GSO in 1990 and is currently working as a chemist for Scientific Applications International Corporation in Narragansett.

Freshwater Inflow to the Narrow River

Gilbert Stuart Stream provides freshwater inflow to the Narrow River.

Much of the ecological makeup of an estuary can be attributed to the characteristics of the freshwater inflow and groundwater seepage along its coastal margin. These determine an estuary's salinity characteristics and, to a large extent, its flushing potential. This is especially true in the deep upper ponds of the Narrow River where the incoming freshwater flows on top of the denser and deeper saline anoxic water.

Incoming fresh water also transports most of the pollutants entering the Narrow River, including salts, hydrocarbons, and heavy metals from highways and roads; nutrients, pathogens, and harmful chemicals from residential sewage disposal systems; nutrients, pesticides, and herbicides from agricultural activity; and hydrocarbons from fuel storage tanks. All of these byproducts of man's activity eventually move into the flowing waters of the Narrow River.

The Narrow River (Pettaquamscutt) Watershed is a 14.4 square mile (37.3 sq. km.) valley lying in a north-south trend along the western margin of the Narragansett Basin in southern Rhode Island. The watershed is approximately 10 miles long (16km) and ranges from 5,000 feet (1,500m) to 14,000 feet (4,300m) wide. Elevations range from near sea level at the estuary outlet (to Narragansett Bay) to 250 feet (73m) at the northwest watershed divide. The watershed is bounded on its long sides by ridge lines underlain by shallow bedrock, with the valley sides dropping steeply to relatively flat lands of highly permeable glacial sediments bordering the estuary.

Some 27 percent of the watershed is developed residential land. The rest is categorized as forest (46 percent), wetlands (19 percent), or open water (8 percent). In order to adequately describe the watershed, it has been subdivided into a data base composed of 99 subbasins, each distinctively identified by physiographic, hydrogeologic, and land-use characteristics. This data base can then be used to evaluate and model freshwater inflow quantity and quality. These subbasins, shown in Figure 1, are coded and keyed to 22 distinctive characteristics ranging from point and non-point source pollution factors to infiltration and evapo-transpiration characteristics.

In a typical year, 43 inches of precipitation falls on the watershed. Approximately 14 inches of precipitation flows to the Narrow River as surface water or groundwater, and the rest returns to the atmosphere as evapotranspiration. Surface water runoff moves relatively quickly through the system after a storm, within a matter of a few days at most. In contrast, the rain that soaks into the ground and becomes groundwater moves much more slowly. A drop of

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groundwater, for example, originating at the eastern boundary of the watershed may take well over a year to reach the estuary as groundwater seepage. Thus, groundwater continues to replenish the streams that feed into the Narrow River and provide shoreline seepage even during a dry summer.

There are 10 perennial streams that enter the Narrow River. The principal streams are Gilbert Stuart Stream, which discharges into Upper Pond in the north, and Crooked Brook and Mumford Brook, which discharge into Pettaquamscutt Cove in the south. The other regions receive the majority of their freshwater inflow as groundwater seeping out along the coastal margin. Gilbert Stuart Stream, the major freshwater stream in the entire watershed, contributes about 34 percent of the total freshwater flow to the watershed. The combined flows of Crooked Brook and Mumford Brook represent about 19 percent of the total freshwater inflow.

The quality of stream water directly reflects land use. The highest concentration of minerals was found in runoff from the densely developed Narragansett region, which is drained by Crooked Brook and Mumford Brook. Some water samples from Crooked Brook show chloride concentrations as high as 1,200 mg/l, almost 100 times groundwater concentrations.

The results of field observations from a 1988-89 Sea Grant study and associated model simulation show that most of the freshwater inflow reaches the estuary as groundwater outflow from the surrounding watershed, either directly as groundwater seepage, or as stream base flow, also derived from groundwater. During this study, the groundwater contribution averaged 65 percent of the total freshwater inflow to the Narrow River. Groundwater inflow is especially significant along the central part of the Narrow River where an estimated 73 percent of the fresh water entering the Narrow River goes through the highly permeable sands and gravels along the shoreline. This is also a region of dense residential development so the groundwater carries relatively high levels of chemical constituents.

The quality of the groundwater varies greatly depending on the associated land use. During the Sea Grant study, groundwater sample concentrations of nitrate, a common cause of eutrophication in coastal waters, were as high as 72 mg/l in residential areas with on-site sewage disposal systems. In pristine areas, the concentration was typically less than 0.5 mg/l. While the study did not directly evaluate biological contributions to the Narrow River, groundwater level records show that many sewage disposal systems are nonfunctional due to a high water table and, at times, they are completely flooded to the ground surface. Thus, in many instances, direct inflow of untreated sewage effluent is likely.

A summary of the range of freshwater inflow into the Narrow River is contained in Figures 3A through 3C. These are idealized diagrams which show the general location of

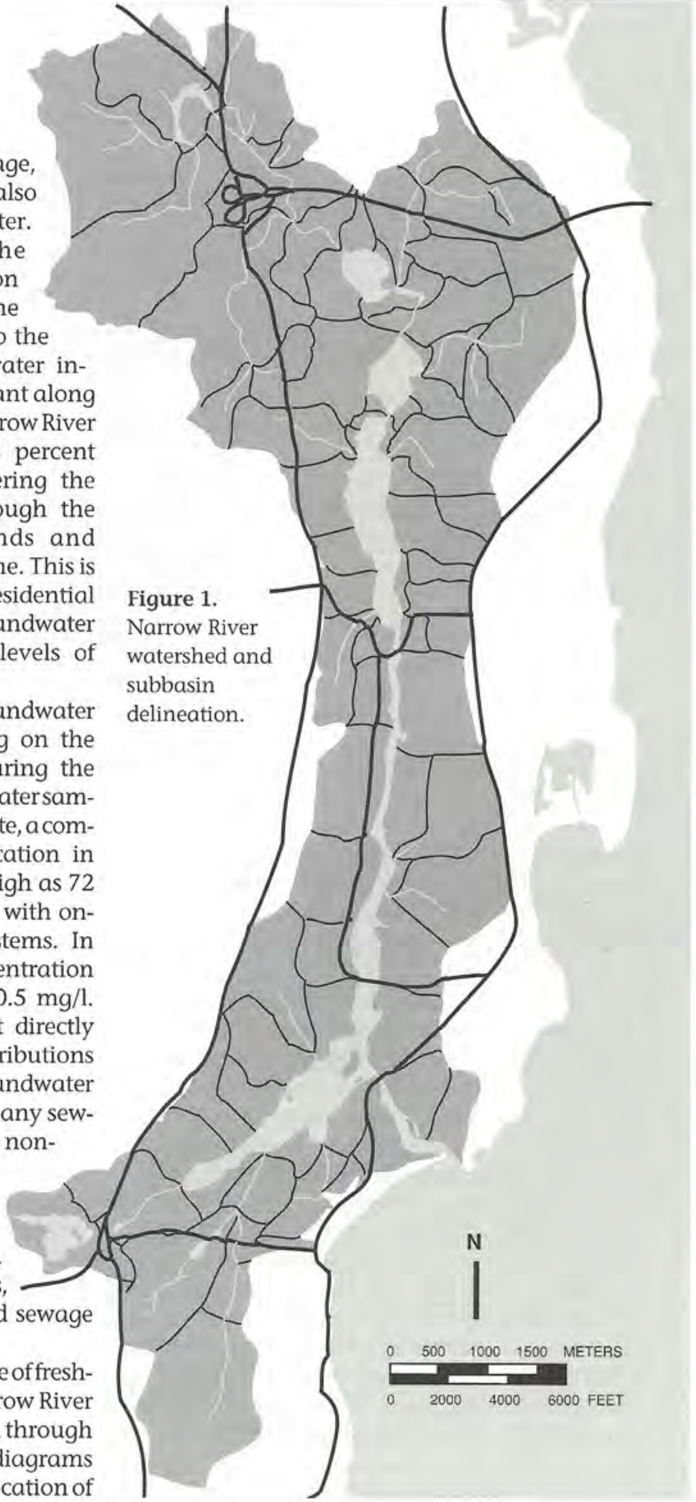

Figure 1. Narrow River watershed and subbasin delineation.

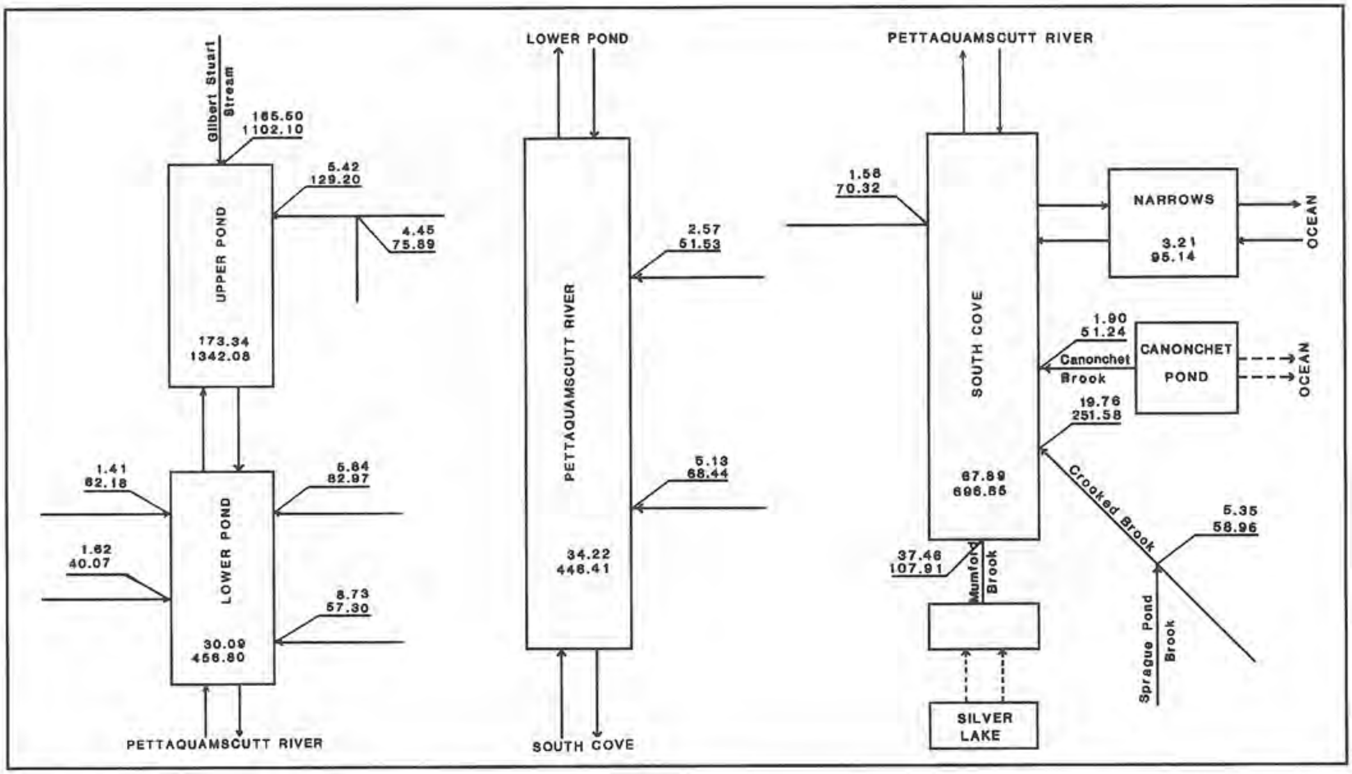

Figure 3. Schematics of freshwater inflow to the Narrow River. The figures at the lines represent low and high values for stream flow, and the figures in the boxes include both stream flow and groundwater seepage for the river section indicated. The values are represented in thousands of cubic feet per day.

freshwater inflow as well as high and low flow values experienced from 1988-89. As a point of reference, precipitation in 1988 was 43 inches, fairly close to the long-term average. Precipitation in 1989, a wet year, was 56 inches. The arrows in the figures indicate perennial stream inputs. The upper number of each set is the daily low flow in thousands of cubic feet per day and the lower number is the greatest dry weather flow experienced during the study period. These are average daily flows and do not reflect higher short-term peak flows which would result from storms. Finally, the values in the boxes that represent Narrow River segments are total inflows to that segment, including shoreline groundwater seepage.

Knowledge of the quantity and quality of freshwater inflow to the Narrow River is essential to understanding and controlling human activities in the watershed. By separating freshwater inflow into definitive components of surface water and groundwater, we can better track and control various pollutants. Modeling is now underway to link the freshwater inflow from the watershed with the dynamic system of the estuary itself. ❖

Dr. Urish is a professor of civil and environmental engineering at the University of Rhode Island. He received his bachelor of science degree in civil engineering from the University of Illinois in 1954, his master's degree in hydrology from the University of Washington in 1964, and his doctorate in ground water hydrology from the University of Rhode Island in 1978.

He is a registered professional engineer in California and Rhode Island, and a professional hydrogeologist certified by the American Insititue of Hydrology. His research and consulting work includes groundwater resource evaluation, geophysical exploration, pollution monitoring and detection, environmental impact investigations, and seawater intrusion evaluation.

Restoration of the Narrow River

Initiatives and Cost

Shoreline development: This area, located about a mile south of Middlebridge Bridge, is developed far beyond capacity. The sediment is not able to process the amount of effluent that is produced by the surrounding homes. The result is that septic systems drain directly into the river. Photo by Jon C. Boothroyd.

The Narrow River, flowing through North Kingstown, South Kingstown, and Narragansett is an unusually diverse body of water because of its geology, hydrology, ecology, and recreational and aesthetic value. This estuary has suffered serious degradation in water quality, fisheries, and recreational utility.

These conditions can be reversed with a proper mix of pollution control strategies and funding. For many years, town governments have tried to identify and pursue the ways and means to clean up the river. Towns such as Narragansett, South Kingstown, and North Kingstown used to look to the Environmental Protection Agency for grants to provide up to 75 percent of the funding needed to alleviate water pollution problems. In the past decade, however, financial responsibility has been shifted to states and municipalities and these towns must search for their own means to address environmental problems. The major pollution control initiatives currently under consideration involve three strategies: to extend sewer lines into densely developed and unsewered areas, to create programs ensuring septic system maintenance, and to develop effective means of dealing with storm water-borne pollutants entering the river.

Clarkson Collins
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South Kingstown and Narragansett propose to extend regional sewer system collectors along the east (Narragansett) and west (South Kingstown) sides of the river. Between 1991 and 1997, the two projects are planned to connect 1,846 existing dwellings resulting in a decrease of roughly 75 percent of the sewage input into the surface and groundwater in the watershed of the two towns.

The anticipated cost of these systems is considerable. The South Kingstown extension will cost up to $2.6 million, while the larger Narragansett project is now estimated at $9.8 million. The state is providing $2.2 million of support for these projects which means that the net construction costs on a per house basis will probably range from $5,500 to $6,000. The actual homeowner's yearly costs may vary considerably. Costs will depend on what the Town Council determines is the level of the general fund versus rate payer support of construction and finance costs, costs of debt service, and individually financed costs to tie in the sewers. While towns must shoulder more responsibility in paying for sewer extensions, one promising development is the establishment of the Rhode Island Clean Water Financing Agency which can provide below-market

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financing rates for towns to undertake water quality improvement projects. Over the life of a bond, such low interest financing may save the towns millions of dollars.

The second approach to reducing the rate of septic system failure, and associated pollution to the Narrow River (currently under consideration by the Narragansett Conservation Commission and town staff) is to adopt regulations for district management of wastewater. Under legislation passed by the state legislature in 1987, towns are empowered to establish special mangement programs for Individual Sewage Disposal Systems (ISDS) requiring, among other things, regular pumping, maintenance, and repairs. The program would be supported by a yearly fee covering pumping and administrative costs. Homeowners whose systems are inoperative would be obliged to bear their individual repair costs. This program would probably result in more frequent repairs, but it would also result in an improvement in the sewage systems' performance throughout the watershed.

Preliminary estimates indicate that a wastewater management program in Narragansett would cost the homeowner approximately $50 to $75 annually. While annual costs of an ISDS maintenance program are considerably lower than sewer costs, replacement of a failed ISDS can cost as much or more than a sewer assessment. In the long run, the investment in sewers is probably a more effective and economic means of pollution control in densely developed neighborhoods. On the other hand, wastewater management districts appear to be a viable option in areas where sewering is not currently available or is impractical due to unfavorable site conditions.

A third step necessary to restore water quality to the Narrow River is the development of effective storm water management systems. Many communities have spent millions of dollars in sewering and wastewater treatment only to have poisoned urban and residential runoff from roads, lawns, and other development degrade local bodies of water. This danger is particularly present in the Narrow River, where slope and soil conditions increase the risk of pollutants entering the river via storm water runoff. In order to address this problem, the towns of North Kingstown, South Kingstown, and Narragansett have been granted $275,000 from the Aqua Fund to study the runoff pollution threat in the Narrow River watershed and devise methods of addressing associated pollution problems.

It is anticipated that the costs of implementing the study and adopting appropriate management techniques may be as expensive as the sewer extension project. Town councils must decide whether costs will be covered by general taxes, or whether special storm water management districts and fees should be devised to support pollution control. Based on experiences in other municipalities nationwide, annual storm water district fees may range from $40 to $80 per household.

These three approaches to the Narrow River pollution problem will result in improvements in water quality. The average annual household cost of such a program, however, may approach $1,000 per year or a 50 percent increase in the average household's outlay for town taxes and fees. Given the upward spiral of other municipal costs, a watershed-based fee system supported by local homeowners will generate strong debate on cost-sharing options and test the collective willingness to pay for improvement in environmental quality.

Practical means of attaining environmental quality in the Narrow River have been identified, and concrete steps are being taken to realize them. However, finding ways to finance restoration of the river presents perhaps the greatest challenge to town residents and government. We stand at the brink of success. We must confront this final and most rewarding phase with enthusiasm, resourcefulness, and determination. ◆

Clarkson A. Collins has worked in environmental planning and community development for the Town of Narragansett since 1985. From 1979 to 1984 he worked as a marine resource specialist at the URI's Coastal Resources Center concentrating on environmental management issues as part of the URI Salt Ponds Project. He received a master's degree in marine affairs in 1985 from URI.

Phytoplankton

continued from page 6

and store any of its other prey in the same way? Some of these questions involve speculation about the way in which the two organisms and their mutualism have evolved and provide plenty of grist for the mill of "thought experiments."

The phytoplankton of Narrow River inspire countless research questions. Why, for example, are species that are known to cause shellfish poisoning in some parts of the world completely nontoxic in Narrow River? Since some species can live only in a narrow range of low-salinity water and can't survive in the higher salinity of Narragansett Bay, how did they get into Narrow River? What mechanisms make it possible for species which require oxygen to live in the oxygen-free sulfide-rich lower depths of the basins? Because there are hundreds of species in Narrow River, each with its own peculiarities, there will always be plenty of intriguing problems to solve. Periodic events such as last fall's sulfide ventilation, while discomforting to many residents, provided scientists with new opportunities to dig a little deeper into the hidden community just below the water's surface. ❖

Dr. Hargraves has been studying the phytoplaknton of Narragansett Bay for over 25 years, first as a URI student and for the last 20 years as a member of the oceanography faculty. In that time, he has more than doubled the number of species known from the Bay, and described over a dozen new species and varieties.

Pettaquamscutt Lakes

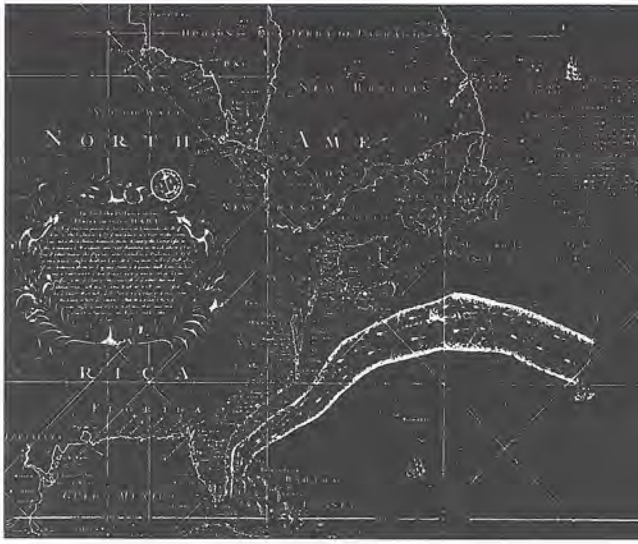
continued from page 9

our AERL study. In July 1991, we will measure the flux rates of RITG and observe the factors that control them. For the third year of the RITG study, we will use deep stratified tanks in an attempt to induce the microbes and processes that occur in oxic waters as well as reproduce the anoxia in basins such as those in the Pettaquamscutt Estuary (see comparison in Fig. 1). By varying parameters such as salinity and temperature in these controllable tanks, we hope to determine how resistant or susceptible the system would be to a global warming of 5°C or 10°C. ❖

This work was started with a development grant from Sea Grant and is being continued by a RITG grant from EPA, Athens (AERL 9005). The co-principal investigators are Percy L. Donaghay and Alfred K. Hanson, Jr., for Dana R. Kester. Other participants include Jeff Hughes, Paul W. Johnson, Ken M. Johnson, Dan O'Sullivan, Kathy Hardy, Adam Cantu II, Bill Miller, Jennifer E. Prentice, Bob Campbell, Candace Oviatt (GSO); Mary I. Scranton and Xiao-Hua Yang (SUNY, Stonybrook), Joel Radford-Knoery and Greg Cutter (Old Dominion); Doug Capone (Horn Point); John Stolz (Duesquene Univ.); Dennis Bazylinski, (PI&SU); Robb Mason and Bill Fitzgerald, (Avery Point); Maureen Keller (Bigelow).

Dr. Sieburth, trained as poultry microbiologist, was introduced to sea microbes while studying penguins and their food web in Antarctica during the 1957-1959 International Geophysical Years. He joined the Narragansett Marine Laboratory in 1960 and has been active in characterizing marine microbial food webs with emphasis on algal-bacterial interactions.

A Red Herring?



The Gulf Stream charts attributed to Benjamin Franklin and reproduced in the February 1991 issue of *Maritimes* are not what they seem, wrote Philip Richardson, a physical oceanographer at Woods Hole Oceanographic Institute (GSO, Ph.D. 1974). The illustration above is a true depiction of the original Gulf Stream chart drawn by Benjamin Franklin and Timothy Folger in 1769-1770. It was "lost" for nearly 200 years until Richardson found it in 1978 at the Bibliotheque Nationale in Paris. Despite the importance of the Franklin-Folger chart, which continues to be a good summary of the Stream's strength, course, and breadth, in Colonial times, it became quite rare. Consequently, Richardson said, the chart most people associate with Franklin is actually a copy of a copy. The chart on page one of that same issue is also misleading, he said. It is, in fact, an illustration of the migration of herring described in a paper written by John Gilpin (*Trans. Am. Philos. Soc.*, 2, 236-239, 1786.) and was printed as an inset in a version of Franklin's chart engraved by James Poupard. Publishing the two maps together with Franklin's written description of the Stream, presumably to economize on costs, (pages 294-329 of the same volume) helped create the mistaken identity. ❖

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