BENTHIC REPOPULATION OF THE RARITAN RIVER ESTUARY FOLLOWING POLLUTION ABATEMENT[1]

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ABSTRACT

A total of 69 samples of benthic animals was taken in the lower 20 km of the Raritan River estuary from 1957 to 1960. During 1957, under heavily polluted conditions, no freshwater species were discovered. Of the 17 marine species found, the barnacle *Balanus improvisus* extended 8.5 km above the river mouth; the remaining species were confined to the seaward 4.6 km of the river.

In January 1958, a trunk sewer system began operation in the lower Raritan Valley, and pollution was abated in the river. Rapid repopulation of the estuary occurred. The sequence and numbers of freshwater and marine species invading the estuary and colonizing the bottom sediments were followed in the samples of 1958, 1959, and 1960.

The most obvious change in 1958 was the distribution and density of *Balanus improvisus*. These barnacles coated all firm substrata in the previously uninhabited section, extending upriver to the limit of salt penetration. The 12 stations sampled in both 1958 and 1959 yielded 6 freshwater and 21 marine species in 1958 and 8 freshwater and 28 marine species in 1959. In 1960, freshwater species continued to increase, but there was a slight decrease in the number of marine species. Dominant components of the freshwater fauna were the oligochaetes *Limnodrilus* spp., the leech *Erpobdella punctata*, and the bivalve *Sphaerium* sp. A density of 7,102 organisms/m^2 was found at one of the freshwater stations in 1960.

Marine species that invaded the river following pollution abatement are placed in five groups—three of pioneers, one of secondary invaders, and one of progressive penetrators—on the basis of their year of arrival, penetration, and length of stay.

By the end of the study, biotic recovery had so progressed that a plot of the quantitative distribution of species illustrated the classic V-shaped curve for estuaries. A similarly shaped curve was obtained for the distribution of population densities.

INTRODUCTION

Much attention has been given to the qualitative and quantitative distribution of biota in polluted and unpolluted freshwaters (Klein 1957) and estuaries (Alexander, Southgate, and Bassindale 1935; Filice 1954*a*, *b*, 1958; Hedgpeth 1957). Relatively few studies, however, have dealt with biotic changes following pollution abatement. Carpenter (1924) and Laurie and Jones (1938) followed biotic recovery of freshwater streams after cessation of lead mining operations, and Reish (1957) made similar studies of conditions of temporary pollution reduction in the marine environment. No investigations of this type have been reported from an estuary. Opportunity to study such a situation was afforded in the Raritan River–Raritan Bay estuary during and following 1957. This report concerns the changes in the Raritan River.

The Raritan River, with a drainage area of 2,862 km^2, is the largest intrastate river system in New Jersey. There is a gradual transition from the rapid, trout-supporting streams of its headwaters to the slow-moving river in the lower Raritan Valley (Fig. 1). In its last 16.7 km, it meanders through a tidal marsh. At its mouth, it broadens into the shallow and approximately triangular Raritan Bay. The river is subject to tidal effects for about 33 km above its mouth, although the penetration of saline

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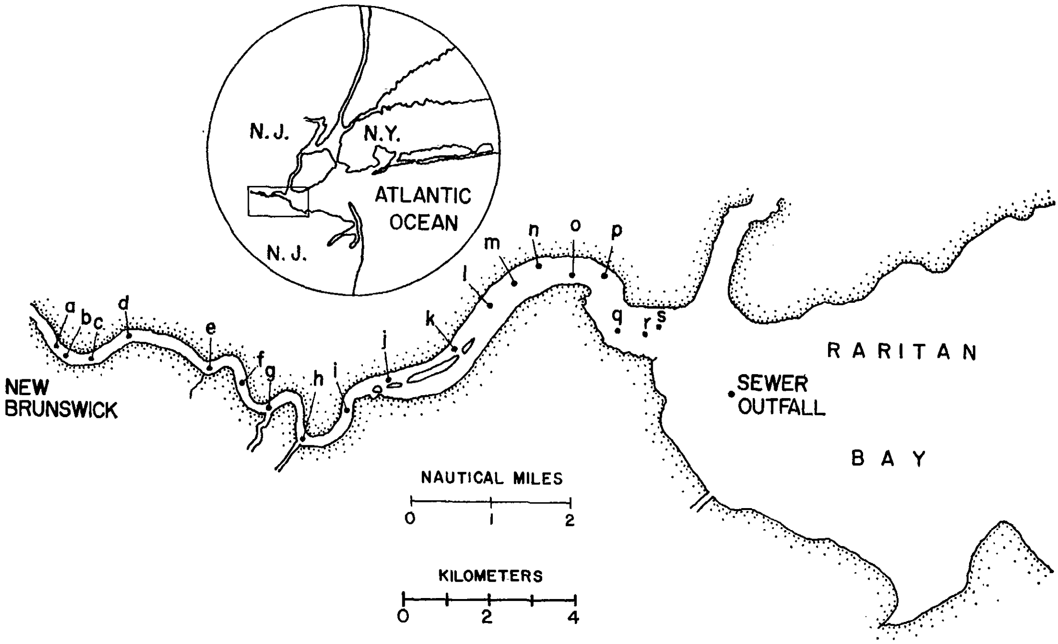

FIG. 1. Chart of Raritan River showing location of Stations *a* to *s*.

water does not extend more than about 19 km above the mouth even under extreme drought conditions.

The development of pollution in the Raritan River from the time the water was considered suitable for drinking purposes to the state of heavy pollution has been reviewed by Rudolfs and Fletcher (1951). An indication of the degree of pollution is shown by their analyses of certain industrial wastes being dumped into the river: phenols, 1,087 ppm; formaldehyde, 1,960 ppm; copper, 5.8 ppm; and arsenic, 375 ppm. They concluded that organic pollution existing in the river in 1950 was equivalent to raw sewage discharged by more than 750,000 persons. Rudolfs and Fletcher also reported that pollution increased progressively downstream and reached a maximum below New Brunswick. Seaward of this point, the pollution concentration decreased owing to dilution with salt water and stream self-purification. These conditions were highly unfavorable for benthos in the Raritan River.

A major trunk sewer system, which began operation in the lower Raritan Valley in January 1958, gives primary treatment to both domestic and industrial wastes. Chlorinated liquid effluents are discharged into the head of the bay (Fig. 1), while the removed solids are transported out to sea by barges. The change in the environment brought about by pollution abatement afforded the opportunity to follow repopulation of the bottom sediments by both freshwater and estuarine fauna.

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METHODS

Samples were taken during the summers of 1957 through 1960 and during November 1958 and March 1959. Nineteen sampling stations, *a* through *s*, were established in the river from New Brunswick to the river mouth (Fig. 1). Sixty-nine benthic samples were taken during the four-year period at these points. Some stations were sampled only once, while others were sampled up to six times. Except as noted below, all sampling was done from a chartered 43-ft (13-m) boat. Petersen or Van Veen grabs were used to obtain quantitative samples, and a crab dredge was used for qualitative samples. It was necessary to anchor the boat while quantitative and hydrographic samples were taken. To anchor, the crab dredge was lowered and towed under power with the current until the boat was on station. With the power in neutral, the crab dredge acted as an anchor and held the vessel stationary in the current. Stations *q*, *r*, and *s* were located by triangulation with sextants; all other stations were found by ranges on fixed landmarks. At four upriver points during the summer of 1958, and during the surveys of November 1958 and March 1959, samples were taken using an Ekman grab and a small dredge towed behind a skiff. The combined factors of the grab's lightness, strong tidal currents, and the extensive hard bottom made the Ekman grab unsatisfactory for quantitative work in this environment. Hence, all samples taken from the skiff are treated as qualitative only.

The sample at each point consisted of three to six pooled grabs, depending upon the type of sediment, apparent number of organisms, and available time. The samples were washed through a graded series of screens, the finest mesh being 1.5 mm, and all macroscopic organisms were picked from the screens and preserved. Full-strength formalin was added to the sample jars to give approximately a 10% mixture. The specimens were identified and counted later. On occasion, weather and lack of time prevented field separation of animals from sediment and debris remaining on the fine screen. In these cases, the material, or an aliquot, was preserved for later separation in the laboratory. Screens were scrubbed and washed between stations. About 0.5 liter of sediment from a separate quantitative haul at each point was saved for mechanical analysis of the sediments.

Surface and bottom salinity determinations and temperature measurements were made at each station. Beginning in 1958, dissolved oxygen content was determined. The Knudsen or Harvey methods were used to determine salinity. The unmodified Winkler method was used for the analysis of dissolved oxygen. Procedure for hydrometer and screen analysis of sediments was modified from ASTM Standard D 422-51. The method described by Shepard (1954) was used to classify sediment types.

No chemical or bacterial analyses (other than dissolved oxygen) were made in this study to assess the degree of pollution abatement. However, unpublished data, courtesy of the Middlesex County Sewerage Authority, on changes in most probable number of bacteria, biochemical oxygen demand, and dissolved oxygen indicated a marked reduction in pollution.

RESULTS

Salinity

Differences between surface and bottom salinities seldom exceeded 1‰ except at the deeper seaward stations, *m* and *p*, where differences approached 9‰. Bottom salinity ranged from about 24‰ at the mouth of the river to 1‰ at New Brunswick (Table 1). Salinities during the unusually dry summer of 1957 were much higher than in the following three years. The salinities observed in 1958–1960 show, in general, a range less than 4‰ at any station. One exception, Station *m*, has a range of 12‰. This station is located at a split in the channel, and the salinity variation observed might be due to current shifts.

Our observations on the distribution of salinity agree with those of Ketchum, Ayers, and Vaccaro (1952) except for the uppermost reaches. They found higher salinities near New Brunswick than were found in 1957, even though riverflows were

TABLE 1. *Station characteristics, 1957–1960. Arrows show change in sediment type. Co = cobble; Gr = gravel; Sa = sand; Si = silt; Cl = clay*

Station	Distance above mouth (km)	Depth at mean low water (m)	Bottom salinity (‰)			Sediment
			1957	1958–1960		
				Min	Max	
a	20.4	2.1	1	1	1	Co and Gr over Cl
b	19.8	3.0	1	1	1	Co and Gr
c	18.9	5.2	2.3	1	2.3	Gr→Sa→Si
d	18.0	3.7	4.0	1	3.9	Gr→Cl-Si
e	15.9	3.7	8.2	1	3.9	Gr→Sa-Gr
f	14.6	3.7	—	—	—	Gr
g	13.7	3.7	14.0	2.5	4.5	Gr
h	11.5	8.5	18.3	5.6	9.9	Co and Gr
i	10.2	3.7	—	7.5	8.7	Si-Sa
j	8.5	4.9	21.9	8.3	9.7	Sa
k	6.9	5.2	22.7	10.3	13.3	Si-Sa→Cl-Si
l	5.4	5.5	—	—	—	Si-Sa
m	4.6	8.5	23.4	9.7	21.6	Cl-Si
n	3.9	3.4	—	—	16.4	Cl-Si
o	3.1	2.1	—	—	16.8	Cl-Si
p	2.4	7.6	24.4	20.5	22.0	Si-Sa→Sa-Si
q	1.3	2.7	—	18.5	20.7	Cl-Si
r	0.7	4.3	24.3	21.5	22.9	Si→Cl-Si
s	0.4	2.7	27.0	21.2	24.1	Sa-Si-Cl→Si-Sa

approximately the same for the two periods. The most extensive salinity records available are those of Jeffries (1962), whose 16-month study in 1957 and 1958 was one aspect of this pollution abatement project. His Station 1 at the head of Raritan Bay coincides with our Station *s*. The salinities found at Station *s* fall within the summer salinity ranges given by Jeffries for his Station 1.

Dissolved oxygen

The change in the dissolved oxygen concentration since the start of the survey has been striking. As noted by Jeffries (1962, p. 25) in August 1957, "No oxygen could be detected in surface and bottom samples taken 3.8 and 7.4 miles upstream from the river's mouth." The distributions of dissolved oxygen for the summer surveys of 1958, 1959, and 1960 and the November 1958 cruise are shown in Fig. 2. In the summer of 1958, dissolved oxygen concentrations at the bottom were 36% of saturation or greater at almost all stations in the river. Bottom dissolved oxygen during the November 1958 sampling was much higher, ranging from 44 to 92% of saturation. Dissolved oxygen concentrations throughout the river during the summer sampling of 1959 did not exceed 30% of saturation—far less than the preceding summer.

The Middlesex County Sewerage Authority (unpublished data) sampled at several of their river stations on both flood and ebb phases of the tide at an interval of five hours. They found that dissolved oxygen concentrations in the surface waters may differ by as much as 1.6 ppm at a given station. Should this variation apply to the bottom waters as well, it might be significant in the distribution of benthic animals in the river, especially since the amount of dissolved oxygen in the water

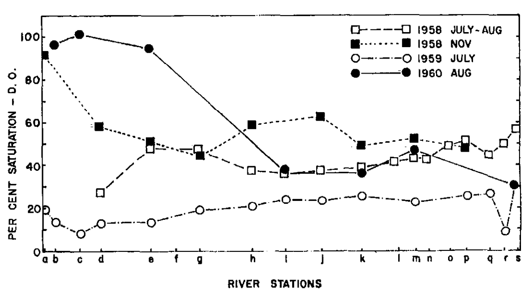

FIG. 2. Per cent saturation of dissolved oxygen in the Raritan River during the surveys of 1958–1960.

TABLE 2. *Qualitative and quantitative distribution of macrobenthic animals, summer 1957.* X = *species obtained from qualitative sampling; numbers following station letter show number of hauls taken with sampler; tabulated values are no./m². Sampling dates: 19 June, 2 July, and 20 August*

Freshwater species	Stations							Marine species
	a–h-3 or more	*j*-3	*k*-3	*m*-3	*p*-3	*r*-3	*s*-6	
					21	X	3	*Sagartia* sp.
						X		*Rhynchocoela* unident.
						3		*Eteone alba*
							X	*Eumida sanguinea*
				9	159	12	48	*Neanthes succinea*
							X	*Neathes* sp. A
				3	24	X	X	*Polydora ligni*
				150			X	*Streblospio benedicti*
				3				*Lacuna vincta*
							X	*Modiolus demissus*
				X				*Mytilus edulis*
				15	9		13	*Macoma* sp.
					6		55	*Mya arenaria*
		X			660	X	X	*Balanus improvisus*
							13	*Cyathura polita*
					3			*Ampelisca sp.*
				X			3	*Limulus polyphemus*
Total no./m²	0	0	0	180	882	15	135	
No. species quantitative	0	0	0	5	7	2	6	
Total no. species	0	1	0	7	7	6	12	

is very low and is probably near the threshold for many organisms.

Sediments

Sediments of the Raritan River tend to decrease in mean particle size from New Brunswick to the river mouth (Table 1). From New Brunswick to the Washington Canal (Station *h*), cobble and gravel cover finer material. Seaward from the Washington Canal, the sediments grade from sand to silty sand to clayey silt. Near the river mouth, the particle size increases again through silt to sand-silt-clay or silty sand.

During 1957, between Stations *a* and *h*, no surface sediment was found that could be classified as being finer than gravel. The investigations of 1958, 1959, and 1960 revealed larger amounts of decaying plant material on the bottom, as well as increasing amounts of sands, silts, and clays.

Sediment samples from all parts of the river in 1957 emitted droplets of oil when brought on deck. Samples smelled of oil or tar, and at some stations chunks of tar and oily debris were found. Samples from subsequent years had less oil smell, although at Station *i* the smell still persisted strongly in 1960.

Biota

The qualitative and quantitative distributions of animals found in the river during 1957–1960 are reported in Tables 2–7. In 1957, no freshwater species was found (Table 2). Seventeen marine species were recorded. One, the barnacle *Balanus improvisus*, extended 8.5 km above the mouth. The remaining 16 species were confined to the seaward 4.6 km of the river. The dominant fauna were: the polychaetes *Neanthes succinea, Streblospio benedicti,* and *Polydora ligni*; the lamellibranchs *Mya* and *Macoma*; and the cirripede *Balanus improvisus.*

The distribution of benthos the following summer, 1958, is shown in Table 3. Although the three uppermost river stations were not sampled, 5 freshwater species were found at Station *d*, 6 at Station *e*, and 1 at Station *g*. The pioneering freshwater fauna included 2 species of oligochaetes, 2 species of pulmonate gastropods, and 2

TABLE 3. *Qualitative and quantitative distribution of macrobenthic animals, summer 1958.* X = *species obtained from qualitative sampling;* Q = *qualitative sample only; number of Petersen hauls taken follows station letter; tabulated values are no./m²*. *Sampling dates: 28 July and 15 August*

Freshwater species	Stations																Marine species
	d-Q	*e*-Q	*f*-Q	*g*-Q	*h*-Q	*i*-6	*j*-6	*k*-6	*l*-6	*m*-Q	*n*-6	*o*-Q	*p*-3	*q*-3	*r*-3	*s*-3	
												X	X			X	*Sagartia* sp.
			X		X								X			X	Turbellaria unident.
							X	X	X	X		X		X		X	*Eteone alba*
			X	X	X	X	X		X	X	3	X	10	10	15	25	*Neanthes succinea*
		X															*Neanthes* sp. A
						3											*Glycera americana*
			X	X	X		X	X	3	X	3	X	10	X	10	X	*Polydora ligni*
			X	X			X	X			X	X		X		X	*Streblospio benedicti*
						5											*Heteromastus filiformis*
													5				*Cistenides gouldi*
Limnodrilus sp.	X																
Oligochaeta unident.	X	X		X													
									X								*Urosalpinx cinerea*
Helisoma trivolvis	X																
Physa sp.		X															
						8		13	5		3	X					*Macoma* sp.
									X	X	120	X	60	20	25	225	*Mya arenaria*
	X	X	X	X	X	10	X	X	X	X		X	X	X	X	X	*Balanus improvisus*
				X									5			15	*Cyathura polita*
						3											*Ampelisca* sp.
					X				X	X						X	*Carinogammarus mucronatus*
													5				*Crago septemspinosus*
															X	X	*Callinectes sapidus*
Diptera larvae	X	X*															
										X		X					*Membranipora lacroixi*
													X				*Bugula turrita*
Total no./m						29	0	13	8		129		95	30	50	265	
No. species quantitative						5	0	1	2		4		6	2	3	3	
Total no. species	5	6	5	6	5	6	5	5	8	7	5	9	11	6	5	11	

* Two species.

species of insect larvae. At Station *e*, living barnacles coated pilings, and freshwater physid snails moved about on an adjacent mud flat. The marine species in the river had increased to 22. The same 3 species of polychaetes that were dominant in the lower part of the river the previous year remained as dominants and extended their distribution to Station *f*, 14.6 km above the river mouth. In addition, *Eteone alba* extended its distribution up the river more than 7.4 km. *Heteromastus filiformis* was recorded for the first time from the river and appeared at Station *i*. Sets of *Macoma* and *Mya* extended their river penetration by 5.6 and 3 km, respectively. *Urosalpinx* and its egg cases were found at Station *l*. The amphipods *Ampelisca* and *Carinogammarus* and the isopod *Cyathura* penetrated to Stations *i*, *h*, and *g*, respectively. The most surprising change was that of *Balanus improvisus*; these barnacles seemed to coat all the firm substratum from Station *i* to Station *e*.

Qualitative sampling in November 1958 and again in March 1959 was done to assess gross changes in faunal distribution (Tables 6 and 7). Although these surveys extended seaward only to Station *p*, a distinct change was apparent in the river benthos. In November, there was a general but progressive decline in the number of marine species (compared with the summer distribution) from Station *f* to Station *p*. Station *e* showed a slight increase. At Station *d*, the total number of species, both

TABLE 4. *Qualitative and quantitative distribution of macrobenthic animals, summer 1959. X = species obtained from qualitative sampling; Q = qualitative sample only; number of Petersen hauls taken follows station letter; tabulated values are no./m². All samples were taken on 20 July*

Freshwater species	Stations															Marine species
	a-5	*b*-Q	*c*-6	*d*-6	*e*-3	*g*-6	*h*-Q	*i*-6	*j*-6	*k*-3	*m*-3	*p*-3	*q*-3	*r*-3	*s*-6	
Cordylophora lacustris					X											
											X	X	X	X	28	*Sagartia leucolena*
						5	X	X								Turbellaria unident.
							X				X	X	X		3	*Eteone alba*
					5	8	X	X	X	X	X	5		X	3	*Neanthes succinea*
													X	X	15	*Neanthes* sp. A
															3	*Glycera dibranchiata*
													5			*Haploscoloplos fragilis*
					5	15	X		10	5	X	10	5	10	50	*Polydora ligni*
										5				10	8	*Spio setosa*
											X	10			35	*Streblospio benedicti*
															8	*Tharyx* sp.
										20		5			5	*Cistenides gouldi*
									X							Polychaeta pieces
Dero obtusa		X														
Oligochaeta spp.		X*	920†	295‡												
Erpobdella punctata	9		X													
										5						*Lacuna vincta*
															10	*Nassarius obsoletus*
															3	*Acteon punctostriatus*
Helisoma trivolvis	3		X	10												
Lymnaea sp.		X														
Physa sp.	3	X	X	X												
Sphaerium sp.	36	X		3												
								10	3	20						*Macoma* sp.
															3	*Ensis directus*
													5	10	30	*Mulinia lateralis*
									3	10	290	14,200	2,500	12,400	8,458	*Mya arenaria*
					15	140	X	5	75	10		X	X	5	20	*Balanus improvisus*
					150	15	X	X				15		5	8	*Cyathura polita*
												X			3	*Edotea triloba*
												X			X	*Carinogammarus mucronatus*
					X	8	X	X	3	X			X		3	*Rhithropanopeus harrisi*
Diptera larvae			X	3												
														5		*Limulus polyphemus*
											X	X	X			*Membranipora lacroixi*
										X		X	X			*Molgula manhattensis*
Total no./m²	51		920	311	175	191		15	94	75	290	14,245	2,515	12,445	8,696	
No. species quantitative	4		5	6	4	6		2	5	7	1	6	4	7	19	
Total no. species	4	9	9	7	6	6	7	6	7	10	7	13	11	10	20	

* Predominantly *Tubifex tubifex*; approximately 4 other species including *Limnodrilus hoffmeisteri.*

† Predominantly *Limnodrilus hoffmeisteri* although *Tubifex tubifex, Limnodrilus* spp., and 2 other undetermined species were noted.

‡ Predominantly *Limnodrilus hoffmeisteri; L.* sp. plus an undetermined species.

freshwater and marine, was more than double that of the previous summer. By the next spring, the benthos from Station *f* to Station *p* was essentially unchanged, while that at Stations *d* and *e* returned to the levels of the previous summer. The only marine species remaining at Station *d* in the spring was *Balanus*, and at both Stations *d* and *e* many barnacles with decomposing meats were found. Not found in the spring of 1959 were: the polychaetes *Spio setosa, Heteromastus filiformis,* and *Arabella iricolor*; the isopod *Erichsonella attenuata;* and the caridean *Crago septemspinosus.* Changes in the freshwater benthos were also noted. Colonies of the fresh- and brackish-water hydroid *Cordylophora lacustris* were found for the first time. These colonies, however, were partly decomposed. Live limpets and physid snails were not found. The finding of physids with rotting meats and partially decomposed hydroid colonies indicated a winter kill-back. Larvae of three orders of insects were present in the spring but had not been found in the fall.

TABLE 5. *Qualitative and quantitative distribution of macrobenthic animals, summer 1960.* X = *species obtained from qualitative sampling; number of Petersen hauls taken follows station letter; tabulated values are no./m². All samples were taken on 10 August*

Freshwater species	Stations							Marine species
	b-6	*c*-6†	*e*-6	*i*-6	*k*-3‡	*m*-3	*s*-6	
Cordylophora lacustris			5					
						X		Hydroid unident.
							10	*Sagartia leucolena*
						X		Anemone unident.
						X		Turbellaria unident.
						5		*Neanthes succinea*
						X	15	*Polydora ligni*
			130					*Polydora* sp.
							3	*Spio setosa*
				15				*Spio filicornis*
							5	*Streblospio benedicti*
							3	*Tharyx* sp.
			3					*Amphicteis gunneri*
Peloscolex multisetosa		5						
Oligochaeta spp.	6,648*	2,405*						
Erpobdella punctata	13	220	8					
							3	*Acteon punctostriatus*
Helisoma sp.	5							
Lymnaea sp.	15							
Physa sp.	115	43						
Sphaerium	278	1,675						
				8		25	5	*Macoma* sp.
				3		55	1,238	*Mya arenaria*
			568			X		*Balanus improvisus*
Amphipoda unident.	3							
	20	140	75	3	5		28	*Cyathura polita*
				3				*Crago septemspinosus*
			5	15				*Rhithropanopeus harrisi*
Diptera larvae	5	33						
Odonata larvae		3						
Coleoptera larvae		3						
							3	*Bugula* sp.
			5					*Bowerbankia gracilis*
Total no./m²	7,102	4,527	799	47	5	85	1,313	
No. species quantitative	14	14	8	6	1	3	10	
Total no. species	14	14	8	6	1	8	10	

* Predominantly *Limnodrilus* spp. *L. udekemianus, L. claparedianus,* and *Tubifex tubifex* were identified in the samples. Approximately 3 additional undetermined species were also noted (*see* text).
† Shells of *Helisoma antrosa, H. trivolvis,* and *Lioplax* sp. were noted.
‡ Stunted shells of *Mya arenaria* were found.

In the summer of 1959, 15 stations from *a* through *s* were sampled and a total of 28 marine and 13 freshwater species was found (Table 4). Of the 15 stations, 12 (*d, e, g, h, i, j, k, m, p, q, r,* and *s*) had been sampled in 1958. These 12 stations yielded totals of 6 freshwater and 21 marine species in 1958, and 8 freshwater and 28 marine species in 1959. It is interesting that the freshwater and marine species increased proportionately in abundance.

Several significant changes in the marine fauna were noted in the 1959 summer survey. *Spio setosa,* found in November at Stations *d* and *g,* was present at Stations *k, r,* and *s.* Both *Mulinia lateralis* and *Molgula manhattensis* were found at 3 stations, *Edotea triloba* at 2, and *Rhithropanopeus harrisi* at 8 stations. *R. harrisi* had not been found in the river until November 1958, and then at Stations *h* and *k* only. By the following summer, *R. harrisi* was distributed from the mouth of the river to Station *e,* a distance of 15.9 km, and had attained a den-

TABLE 6. *Qualitative distribution of macrobenthic animals on 26 November 1958*

Freshwater species	Stations									Marine species
	a	*d*	*e*	*g*	*h*	*j*	*k*	*m*	*p*	
Turbellaria unident.		X								
					X		X			*Neanthes succinea*
			X							*Polydora ligni*
			X							*Polydora* sp.
		X		X						*Spio setosa*
		X		X	X					*Heteromastus filiformis*
		X	X							*Arabella iricolor*
Oligochaeta unident.	X	X*	X†							
Ferrissia sp.		X								
Helisoma trivolvis		X								
Physa sp.	X	X								
						X		X	X	*Mya arenaria*
		X	X	X	X		X			*Balanus improvisus*
		X								*Erichsonella attenuata*
							X			*Cyathura polita*
			X	X		X		X		*Crago septemspinosus*
					X		X			*Rhithropanopeus harrisi*
Total no. species	2	12	7	4	4	2	4	3	1	

* Two species of *Limnodrilus* plus 1 undetermined.
† One species of *Limnodrilus* plus 1 undetermined.

sity of 8 specimens/m^2 at Station *g*. At the most seaward station, *s*, 3 specimens of *Tharyx* sp. and 4 of *Nassarius obsoletus* were also noted as new additions to the marine fauna in the river.

Freshwater species were not found so far downstream in the summer of 1959 as in 1958. *Cordylophora lacustris*, found as decomposing colonies in the spring, grew in large abundant colonies at Station *e* in the summer. Oligochaetes were much more abundant than in the summer of 1958 or in the subsequent fall and spring surveys. Although several species of oligochaetes were found, there was a change in the relative proportion of species from Stations *b* through *d*. At Station *b*, *Tubifex tubifex* was the most abundant oligochaete, while at Station *c* its relative abundance decreased, and at Station *d* it was not found. The distribution of *Limnodrilus hoffmeisteri* was almost the reciprocal of *T. tubifex*, that is, present at Station *b* and increasing in relative abundance through Station *d*. The leech *Erpobdella punctata*, the gastropod *Lymnaea* sp., and the lamellibranch *Sphaerium* sp. were faunal components not found in previous surveys.

On the basis of three years of sampling experience in the river, sampling in 1960 was reduced to seven representative stations (Table 5). A total of 17 freshwater and 21 marine species was found in 1960, as compared to 13 and 25 species, respectively, for the same stations in 1959. The changes in total numbers of freshwater or marine species may not be so significant as the changes in species composition and population densities.

New additions of marine fauna to the river in 1960 were the polychaetes *Spio filicornis* and *Amphicteis gunneri* and the ectoproct *Bowerbankia gracilis*. It is ininteresting to note that these species appeared near the limits of saline penetration. Of the 12 marine species present in 1959 but not found in 1960, only *Cistenides gouldi*, *Neanthes* sp. A, *Eteone alba*, and *Mulinia lateralis* had occurred in any abundance or had been distributed at more than one of the stations sampled in 1960. It is unlikely that their disappearance can be accounted for by errors in sampling.

The distribution and abundance of *Neanthes succinea* underwent a marked change. From 1957 through 1959, *N. succinea* was one of the most abundant and widely distributed worms in the river. In

TABLE 7. *Qualitative distribution of macrobenthic animals on 23 March 1959*

Freshwater species	Stations *a*	*d*	*e*	*g*	*h*	*j*	*m*	*p*	Marine species
Cordylophora lacustris					X				
				X	X				*Neanthes succinea*
						X			Spionidae unident.
Limnodrilus spp.	X*	X							
Oligochaeta unident.	X		X						
Helisoma trivolvis	X	X							
								X	*Mya arenaria*
		X	X	X	X				*Balanus improvisus*
			X	X	X	X			*Cyathura polita*
					X				*Rhithropanopeus harrisi*
Diptera larvae			X						
Odonata larvae					X				
Coleoptera larvae		X							
Total no. species	4	5	4	3	6	2	0	1	

* Two species.

1960, however, only one specimen was found at one station. Three other species of polychaetes, *Polydora ligni, Spio setosa,* and *Streblospio benedicti,* were not found so far upriver as in 1959, and the latter was more seaward in its distribution than in the 1957 survey. The isopod *Cyathura polita* continued its river penetration to Stations *b* and *c*, tidal freshwater stations. At Station *c*, *C. polita* had its highest population density, 140/m^2.

At Stations *m* and *s* in 1960, there was a marked decrease in density as compared with 1959. The large difference can be explained by the poorer set of *Mya* in 1960. In both years, *Mya* was the most abundant form at these stations. At Stations *c*, *e*, and *i*, on the other hand, manifold increases in numbers/m^2 were recorded during 1960, and at Stations *b*, *c*, and *e* the number of species had increased. Although Station *b* was not sampled quantitatively in 1959, and numerical comparison cannot be made with the 1960 data, it was apparent at the time of sampling in 1960 that there had been a marked increase in the fauna. The only significant change in the species composition at the freshwater stations was the variety of oligochaetes. The number of oligochaete species is given in Table 5. The designation "approximately" (Table 5, footnote) is used because of limitations of time and patience. Specific identification of many oligochaetes is difficult and time-consuming, and so only an aliquot was examined for species composition. However, the number of oligochaetes collected was determined accurately, and worms that appeared different from those already identified were set aside for closer examination. In 1959, the dominant oligochaete at Station *b* was *Tubifex* sp., and at Station *c*, *Limnodrilus hoffmeisteri*. In 1960, however, *Limnodrilus* spp. dominated both Stations *b* and *c*; *L. hoffmeisteri* appeared to have been replaced by *L. udekemianus* and *L. claparedianus*. *Peloscolex multisetosa* and an unidentified amphipod were collected from the freshwater stations for the first time.

DISCUSSION

Under the conditions of pollution abatement, freshwater and marine (or estuarine) animals rapidly colonized the Raritan River estuary. Marine species that invaded the river can be placed in five groups on the basis of year of arrival, penetration in the river, and length of stay in or on the substrata newly available for colonization:

Group I—animals that are pioneers and remain as permanent residents: *Balanus improvisus, Mya arenaria,* and *Macoma* sp.

Group II—animals that are pioneers but remain only about two years (Fig. 3):

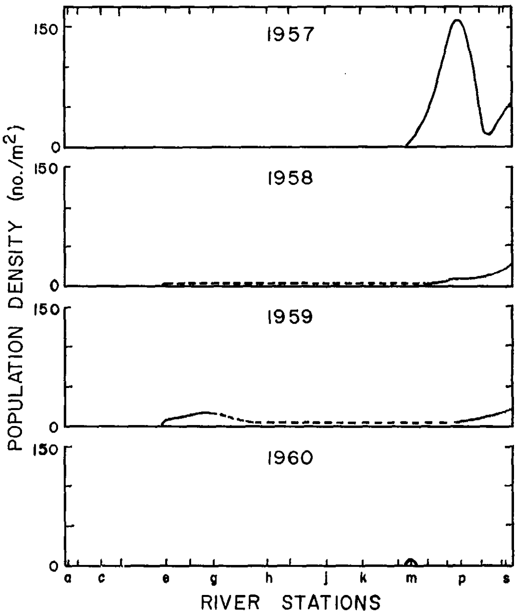

FIG. 3. Quantitative distribution of nereid polychaetes (*Neanthes succinea* and *N.* sp. A) in the Raritan River, 1957–1960. The pattern of distribution is typical for Group II organisms.

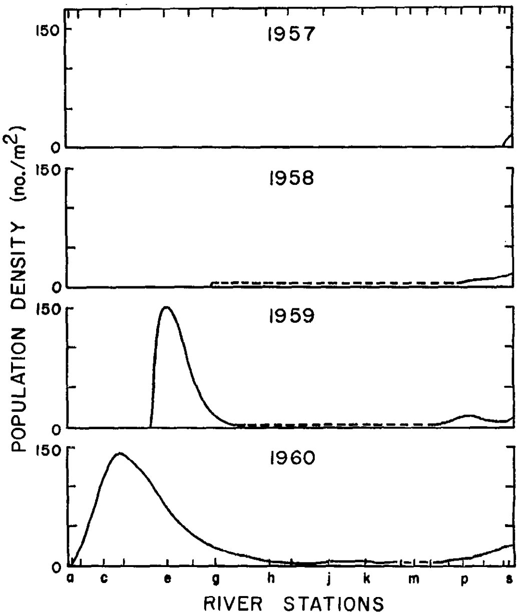

FIG. 4. Quantitative distribution of the isopod *Cyathura* in the Raritan River, 1957–1960. The smoothed curves illustrate progressive penetration of Group V organisms.

Neanthes succinea, *N.* sp. A, *Polydora ligni*, *Spio setosa*, *Streblospio benedicti*, *Eteone alba*, and *Cistenides gouldi*.

Group III—animals that are pioneers but remain one year or less: *Heteromastus filiformis*, *Amphicteis gunneri*, *Arabella iricolor*, and *Erichsonella attenuata*.

Group IV—secondary invaders: *Spio filicornis*, *Bowerbankia gracilis*, *Molgula manhattensis*, and *Edotea triloba*.

Group V—progressive penetrators (Fig. 4): *Cyathura polita* and *Rhithropanopeus harrisi*.

Data on the remaining species are considered inadequate to justify placement in the above groupings.

The change in distribution as shown by organisms of Groups II and III is difficult to explain. The fact that these forms inhabited lower saline waters successfully during their initial penetration into the river indicates that some factor other than salinity probably caused their disappearance or seaward regression. The worms of Group II, as well as *Heteromastus* and *Arabella* of Group III, are usual inhabitants of low-salinity waters (Rees 1940; Galtsoff et al. 1947; Hedgpeth 1950; Filice 1958; and others), and it would be expected that they would remain in the upper estuary after initial colonization. These worms are listed as deposit feeders (Sanders 1956; Savilov 1957), except for *Eteone*, which Savilov lists as a carnivore or scavenger. Sanders et al. (1962) conclude that *Eteone heteropoda*, however, is a deposit feeder. The feeding type of *Neanthes* sp. A is unknown. Sanders (1958) has shown a strong correlation between the detritus-rich, fine-particle sediments and the deposit feeding habit. The lack of such fine sediments in the upper estuary has probably been the most important factor in determining the relatively short stay of these forms. On the basis of similar reasoning, the stay of *Spio filicornis* (Group IV) can be expected to be short.

The polychaetes found in the upper half of the estuary are assumed to have arrived

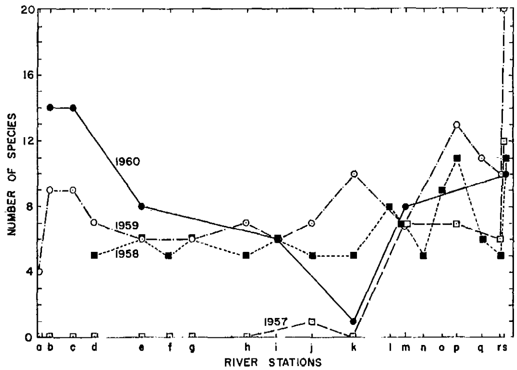

FIG. 5. Abundance of species in the Raritan River, 1957–1960. Number of species includes all species found regardless of sampling method.

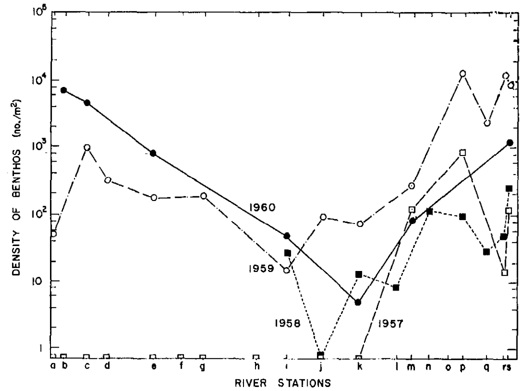

FIG. 6. Density of benthic animals in the Raritan River, 1957–1960.

as larval forms rather than by the migration of adults. Several juvenile worms found in this area support this assumption. One wonders why the larvae of these deposit feeders settled on a substratum of cobble and gravel. Larvae of a number of polychaetes are able to test the substratum and may even postpone metamorphosis until a substratum is found that is suitable for adult life (Thorson 1957). Thorson suggests that larvae may sometimes be deceived by a layer of soft substratum overlaying a hard bottom. However, at the upriver stations where the larvae of deposit feeding polychaetes had settled, the low percentages of fine particles in the sediment (at Stations *e* to *h*, for example) make this possibility remote.

The presence of *Erichsonella attenuata*, *Amphicteis gunneri*, *Arabella iricolor*, and *Spio filicornis* in the upper estuary is noteworthy. These species were found nowhere else in the Raritan River during the study; further, 178 sampling stations extending to the edge of the Atlantic Ocean failed to yield a single specimen of these species (Dean and Haskin, unpublished data). Estuarine ecology classes at Rutgers University have found all four of these species in the Navesink River, an estuary with a drainage opening to the Raritan Bay system near Sandy Hook. *Amphicteis gunneri*, found in the Raritan River at a salinity of less than 4‰, has been reported from various places including the abyssal zone (Kirkegaard 1954). A study of its larval stages, length of larval life, and sediment preferences should be rewarding.

The marked changes in the abundance of benthic species for the four summers of study are shown in Fig. 5. The distribution of species abundance in estuarine waters has been studied by several investigators (*see* Hedgpeth 1957; Filice 1958). The pattern of distribution in both polluted and unpolluted estuaries is relatively consistent: as the estuary is ascended from the sea, the total number of species decreases to a low point in the upper estuary and then increases as freshwater is approached and entered. Under the heavily polluted conditions in the Raritan River during 1957, the number of species diminished to a low level in the midsection of the river but did not increase again in the freshwater section. Following pollution abatement, the number of species in the less saline section increased each year. By the summer of 1960, approximately two and one-half years after the trunk sewer began operation, the classic V-shaped curve of species distribution was assumed.

The change in benthos densities is shown in Fig. 6. The increase in densities upriver from Station *k* is most striking. The pattern of distribution of benthos densities in the river shows a much lower density in the center section of the estuary than in either the freshwater or seaward sections. This pattern agrees with that reported by Caspers for the Elbe estuary (Hedgpeth 1957). In the Raritan River, the point of lowest densities fluctuates from year to year between Stations *i* and *k*. In view of this fluctuation, it would seem more appropriate to refer to a low region than to a low point. It is apparent from Fig. 6 that the classic V-shaped curve, used to describe the distribution of species in an estuary, also describes the distribution of benthos densities in an estuary.

It is tempting to conclude that succession occurred during the colonization of sediments following pollution abatement. The following population changes would support this conclusion: the pioneering organisms that remained only one or two years, the appearance of secondary invaders, and the progressive penetration by *Rhithropanopeus* and *Cyathura*. However, it is possible that these changes may have been caused by cyclic variations in abundance. Since data on such cyclic variation are unavailable for the area, a conclusion concerning succession would be speculative.

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