Section 6 Animal Waste

6.0 INTRODUCTION

Two water quality objectives defined by Public Law 92–500 are the elimination of the discharge of pollutants into navigable waters by 1985, and achievement, by 1983, of interim goals, which provide for the protection and propagation of fish, shellfish, and wildlife and provide for recreation in and on the water. Achieving these goals requires meeting the criteria for "fishable and swimmable water." The New York State Environmental Conservation Law calls for the promulgation of rules and regulations setting limits for total and fecal coliform bacteria, dissolved oxygen, copper, zinc, total dissolved solids and other parameters.

Other goals not specifically defined under the law but also of great importance are the reduction of sediment, the control of nitrogen and phosphorus, and the prevention of salt water intrusion into surface and groundwaters.

Inasmuch as animal wastes appear to contribute to the pollution of the Nassau-Suffolk surface and groundwaters, they must be considered in water quality management planning.

The purpose of this section is to define and identify the non-point sources of pollution that are caused by animal wastes in the bi-county area and to recommend appropriate actions.

Animal population, waste characteristics, waste impact and control are discussed in detail. General recommendations and specific recommendations for waste control are included.

Nassau and Suffolk are suburban counties, with a 1977 population of approximately 2.8 million. Although Suffolk leads all counties in the State in dollar income from farming, it has few farm animals other than commercial market ducks. However, the bi-county area has many pets, recreation horses, and wild animals. Except for market ducks, animal populations are generally widely scattered and dispersed, with few concentrations.

Estimates of manure production per animal or per 1,000 pounds of live weight vary widely as do the estimates for each component of manure. These factors vary as a function of animal species, breed, age, sex, type of feed, climate, and measurement methods. Table 6–1, which is based on average values, indicates the relative importance of different animal wastes in the bi-county region. Table 6–2 shows the daily production and composition of livestock manure (feces and urine).

The values in Table 6–1 represent only the solids portion of animal manure. The liquid portion, although not represented, also contains BOD, nitrogen and other components. The daily per animal values for BOD shown in Table 6–1 were calculated from pounds of BOD per day per 1,000 pounds of live weight, using average weights of 125 pounds for humans, 1,000 pounds for horses, four pounds for ducks, 1,350 pounds for cattle, 4.5 pounds for poultry, and 150 pounds for swine. The daily per animal value for dogs was derived from Table 6–5 and other sources. Wild ducks (not included

Table 6–1

SUGGESTED HUMAN AND ANIMAL WASTE PRODUCTION VALUES FOR BIOCHEMICAL OXYGEN DEMAND (BOD) AND BACTERIOLOGICAL CONTENT

		Daily Solid Weste Prod			Solid Waste Only			Solid Waste Bacteria Content (Million MPN/g)			
Biotype	Nassau-Suffolk Population (Numbers)	Single Animal (Grams)	Total Population (Pounds)	BOD per Animal Per Day (Pounds)	Human BOD Equiv.	Daily Total Human BOD Equivalent	Total Animal BOD Load (% Human)	Coliform Total	Coliform Fecal	Fecal Strepto-Cocci	FC/FS*
Human	2,735,637	150	903,000	0.17	1.00	2,735,637	100.0	NA	13.30	3.0	4.43
Dog	425,000	227	212,500	0.13	0.76	323,000	11.81	18.0	18.00	7,300.	0.002
Horse	30,000	16,100	1,063,875	1.40	8.24	247,200	9.04	NA	NA	NA	NA
Duck	750,000	336	400,000**	0.02	0.12	90,000	3.29	NA	32.70	53.6	0.61
Cattle	1,825	26,300	105,721	1.89	11.12	20,294	0.74	NA	0.23	1.3	0.18
Chicken	121,200	182	48,587	0.02	0.12	14,544	0.53	NA	1.30	3.4	0.38
Swine	635	2,700	3,776	0.34	0.20	1,270	0.05	NA	3.30	84.0	0.04

**Fecal Coliform-Fecal Streptococci ratio*

***Total volume of waste from market ducks adjusted for probable age distribution and does not include wild or semi-wild population.*

Sources: American Public Works Association; Water Pollution Aspects of Urban Runoff; USDI; Federal Water Pollution Control Administration; Washington, D.C.; January 1969. Anvik, J.O., E.A. Hyne, and A. Rahaman; "A Method of Estimating Urban Dog Populations and Its Application to the Assessment of Canine Fecal Pollution and Endoparasitism in Saskatchewan," Canadian Veterinary Journal; Vol. 15; No. 8; August 1974. Moore, J.A.; "Animal Waste Management to Minimize Pollution;" ibid. United States Department of Agriculture, Soil Conservation Service; Agricultural Waste Management Field Manual; Washington, D.C.; August 1975. United States Department of Commerce, Bureau of Census; 1974 Census of Agriculture Preliminary Report, Nassau County, New York; Washington, D.C.; June 1976. Wadleigh, C.H.; Wastes in Relation to Agriculture and Forestry; USDA, Misc. Publication 1065, Washington, D.C.; March 1968.

in this table), are about one pound lighter than market ducks. Information regarding cats, turkeys, wild geese and other animals was not available. However, geese can be roughly estimated at 4.5 times the duck figures (H.W. Oneth, November 30, 1976).

Coliform bacteria are a major component of urban and rural stormwater runoff and have been a factor responsible for the closure of portions of Great South Bay to shellfishing. Table 6–3 shows the total coliform and fecal coliform counts in stormwater runoff from four typical Long Island areas. Stormwater samples were collected by the Soil Conservation Service (SCS) staff during the spring, summer and fall of 1976 and analyzed by New York State Department of Environmental Conservation.

The values in Table 6–3 indicate that the suburban and agricultural areas contribute similar amounts of total coliform bacteria. High total coliform counts are expected from agricultural areas, since normal soil coliform bacteria, *Aerobacter aerogens,* are included as part of the total coliform count. They also indicate that agricultural watersheds contribute markedly fewer fecal coliform bacteria. Since the urban areas studied have sanitary sewers, it is logical to assume the probable source of their high fecal coliform counts is animal. Dogs were inventoried in approximately 35 percent of the households. The Baldwin site watershed drains directly into Baldwin Bay.

Table 6–2

DAILY PRODUCTION AND COMPOSITION OF LIVESTOCK MANURE (FECES AND URINE)
(Upper Figure is average; lower figures represent the range given in literature)
(Dashes indicate date not available or entry not appropriate)

	Dairy Cattle	Beef Cattle	Feeder Swine	Breeder Swine	Poultry	Ducks 1/	Sheep	Horses	Catfish	People
					lb/day/1,000 lb live weight					
Manure	85 72–90	62 41–88	69 50–90	50	53 32–67	–	36 30–40	50 40–60	–	31.2
Total Solids	9.3 6.8–13.5	8.9 6.0–11.1	7.2 6.0–9.0	4.3	13.9 9.0–17.4	2/ 24 2/ 13–31	9.5 8.4–10.7	17.5	3.1 2.8–3.5	3.4 2.4–4.4
Volatile Solids	6.9 5.7–7.9	6.9 4.8–8.2	5.7 4.0–7.0	3.2	10.8 8.0–12.9	2/ 14.5 2 8.7–17.5	8.0 6.0–9.1	–	–	2.0 1.1–2.6
BOD_5	1.4 0.8–1.8	1.5 1.0–1.8	2.3 2.0–2.8	1.3	3.4 1.6–5.5	5.1 4.1–7.6	0.8 0.7–0.9	1.4	2.3 1.1–4.9	1.36 0.6–2.10
COD	8.4 4.2–13.3	7.9 6.6–9.0	5.9 4.7–7.1	5.2	12.5 9.5–15.8	–	10.0 7.5–12.0	–	–	3.12 1.0–3.5
Total Nitrogen as N	0.37 0.29–0.51	0.43 0.30–0.58	0.45 0.20–0.70	–	0.86 0.45–1.50	1.42 1.17–1.62	0.40 0.34–0.45	0.30	1.6 0.7–2.5	0.20 0.14–0.26
Total Phosphorus as P	0.069 0.026–0.100	0.090 0.023–0.170	0.17 0.09–0.27	–	0.40 0.20–0.75	0.62 0.4–0.9	0.075 0.040–0.120	0.12	0.25 0.24–0.26	0.024
Total potassium as K	0.20 0.08–0.35	0.23 0.11–0.38	0.25 0.10–0.60	–	0.35 0.12–0.50	0.9 0.6–1.2	0.32 0.24–0.40	0.25	1.5 0.7–2.4	0.064

Although there are built up areas on Long Island that do not shed storm runoff to any surface waters, the densest population centers are located in watersheds that discharge directly to the marine edge and to inland lakes and ponds. These watersheds share similar topography and soil characteristics. Highways and local roads are mostly depressed below the ground level and serve as the principal drainage channels for runoff water. Hempstead, Babylon, Islip, and portions of Brookhaven and Southampton towns all drain into Great South Bay and its tributaries.

The residents in the Great South Bay watersheds use garden sprays and fertilizers, and pet populations are apparent. Some residents were observed dumping dog waste and oil into storm sewer inlets. When questioned, most people demonstrated little awareness of the environmental impact of these

practices.

In the past thirty years the introduction of the recharge basin, a form of large excavated pit vertical drain, has provided for storm water discharges from most new subdivisions in Suffolk County and many in Nassau. An evaluation of the impact of waste carried into these recharge basins and its possible effect on groundwaters is not included as a part of this report.

Dogs and semi-wild ducks were found to be major sources of non-point pollution in the bi-county area. Market, ducks, horses, cattle, wild ducks and geese may be major sources of pollution locally, but vary widely in both volume and characteristics of the waste material.

Other sources of non-point pollution such as deer, seagulls, and miscellaneous wildlife were not considered because adequate waste information was not available.

6.1 ANIMAL POPULATIONS

Agricultural animals in the bi-county region are generally found in small groups and in widely scattered locations. There are an estimated 500 dairy cows and 1,300 other cattle and calves; 121,000 chickens; 26,000 turkeys; and up to 750,000 market ducks. Sheep number 120; swine, 635; and horses on agricultural units, 550 (U.S. Department of Commerce, 1976). The recreational horse population is estimated at 30,000 and the dog population, at 425,000.

6.1.1 Cats

Cats outnumber all domestic animals except dogs. In the course of homeowner interviews in selected study areas in the two counties, it was found that there were about 2/3 as many cats as dogs. If this ratio is valid, the bi-county area contains an estimated 285,000 cats. Neither the existing literature nor the SCS interviews gave any indication that cat fecal waste poses a surface water pollution problem.

6.1.2 Dogs

Dogs are generally found in high concentrations in suburban and vacation-recreation areas. Nassau and Suffolk Counties follow this pattern, encountering problems of overpopulation and limited dog controls. The actual number of dogs in Nassau-Suffolk can only be estimated, because a reliable census count has not been compiled.

The following paragraphs discuss some of the common estimating methods and the results obtained when they are applied to the bi-county area.

The New York State Department of Agriculture and Markets licensed 135,143 dogs in Nassau in 1975 and 121,795 dogs in Suffolk. The two counties alone account for almost 25 percent of the total New York State dog registration. The number of dogs licensed in the bi-county area can be

Table 6–3

STORMWATER RUNOFF: TOTAL COLIFORM AND FECAL COLIFORM CONTENTS

Drainage Area	Land Use	Total Coliform (MPN/100ml)		Fecal Coliform (MPN/100ml)	
		Range	Median	Range	Median
Baldwin	Medium Density Residential	43,000–11,000,000	230,000	4,300–430,000	43,000
Lake Success	Low Density Residential	43,000–11,000,000	430,000	2,400–2,400,000	43,000
Sagaponack	Non-Irrigated Agricultural	2,400–24,000,000	230,000	3.0–230,000	4,025
Wildwood	Irrigated Agricultural	74,000–24,000,000	830,000	23.0–93,000	1,470

assumed to be considerably short of the actual total number of dogs for several reasons: first, only dogs over six months of age are licensed; second, owners caught with unlicensed dogs are usually required to obtain a dog license without penalty (newer dog owners questioned perceived not licensing their dog as a reasonable gamble); third, the present basis for dog licensing, *i.e.*, the dog census, taken by local municipalities to identify those homes having dogs, is conducted in a way that does not best serve the purpose of dog licensing controls. Dog owners may not be at home or they may not report their dogs completely. The per dog fee paid to enumerators for taking the census is too small to generate a vigorous search for even a majority of the dog owners. A total of 287,951 dogs were enumerated in the bi-county area in 1976.

According to New York State Bureau of Dog Licensing, less than two thirds of all dogs are actually licensed (Kehrer, 1976). Applying this ratio to the license figures results in an estimate of 385,000 dogs. If the same ratio is applied to the 1976 enumeration figures, the estimate is 462,000.

The dog population can also be estimated using interview material from the detailed study of watershed areas. Between 33 and 40 percent of the homeowners interviewed in the study of five sampled areas reported dog ownership. Among dog owners, one in five, or 20 percent reported more than

one animal. If it is assumed that ownership patterns in the sampled areas are representative of those in the Island as a whole, and that the Nassau-Suffolk Regional Planning Board estimate of a total of 750,000 households is correct, then the bi-county dog population comprises between 300,000 and 360,000 animals.

Still another method of estimating dog populations was used by Beck (A. Beck, 1973). He suggests that human population numbers can be used as a basis for predicting number of dogs. A ratio of 7:1 for urban and 5:1 for suburban areas should be used. On the basis of Beck's ratios, the estimated 2,736,000 bi-county residents could be expected to own between 400,000 and 470,000 dogs. Dr. R.W. Johnson (1975) estimated that in 1975, in Nassau County alone, there were approximately 350,000 dogs.

The canine population is increasing rapidly. In fact, the dog population on Long Island and in the nation is expanding more rapidly than the human population. Anvik (1974) estimates that the nationwide rate is 4.5 percent per year. Djerassi, *et al* (1973), estimated that 2,000 to 3,000 dogs and cats are born hourly in the United States. Others have suggested that hourly birth rates may be as high as 10,000.

The number of stray dogs in an area has a strong effect on the growth rate of the canine population. Strays are defined as any dogs running loose, whether licensed or not. Dogs released temporarily by their owners are technically stray dogs.

This impact of strays is discussed further, and in detail in *The Ecology of Stray Dogs: A Study of Free Running Urban Animals* by A. Beck (1973). Hummer (1975) reports that a single fertile stray female dog can generate more than 400 additional female dogs in five years under ideal conditions. Strays are more common in the more densely populated suburban areas, probably due to a greater availability of food.

Table 6–4 provides recent dog license and enumeration figures, which may be used to estimate dog populations in Long Island municipal subdivisions.

In summary, the dog population of the bi-county area is between 300,000 and 500,000. For purposes of this report, 425,000 has been selected as the most likely number. Canine numbers are increasing at an estimated rate of over four percent per year. Stray dogs play a major role in these increases.

6.1.3 Wildfowl

Certain wildfowl population figures are available from the New York State Department of Environmental Conservation Mid-winter Aerial Wildfowl Census. For the Long Island area in January 1975, diving ducks numbered 56,200; other ducks, 17,100; geese, 4,800; Brant, 24,000; swans, 700; and Mergansers, 6,700. In 1976 total counts declined slightly, while in 1977, the numbers of wildfowl enumerated returned to 1975 levels.

Table 6–4

DOGS ENUMERATED AND LICENSED: NASSAU AND SUFFOLK TOWNS, CITIES, AND SELECTED VILLAGES

Municipality	Enumerated 1976	Licensed 1976	Village	Enumerated 1976	Licensed 1976
Town					
Hempstead	59,995	50,682	Atlantic Beach	482	222
North Hempstead	21,957	22,573	Bayville	613	613
Oyster Bay	30,525	29,048	Bellerose	128	130
			Cedarhurst	553	535
Cities			Centre Island	113	117
			Floral Park	1,629	1,522
Glen Cove	2,418	2,064	Laurel Hollow	320	325
Long Beach	1,953	1,874	Freeport	3,916	3,336
			Garden City	2,002	2,332
Town			Hempstead	3,250	2,593
			Hewlett Bay Park	84	79
Babylon	27,515	21,564	Hewlett Neck	71	64
Brookhaven	35,324	26,372	Lynbrook	2,258	1,926
East Hampton	1,683	2,302	Malverne	1,021	1,005
Huntington	18,175	24,687	Massapequa Park	3,075	2,727
Islip	39,811	23,206	Mill Neck	291	269
Riverhead	2,674	2,824	Old Brookville	336	300
Shelter Island	378	1,597	Oyster Bay Cove	436	439
Smithtown	12,633	11,894	Rockville Centre	2,124	2,238
Southold	2,747	3,066	Sea Cliff	896	807
Southampton	6,500	4,283			

THE FOLLOWING WERE ENUMERATED IN 1974 AND LICENSED IN 1975:

Village			Village		
East Rockaway	1,535	1,153	Lawrence	798	693
Farmingdale	640	621	S. Floral Park	131	140
Hewlett Harbor	208	197	Stewart Manor	267	309
Island Park	526	524	Valley Stream	3,763	3,598
			Woodsburgh	105	88

Total Enumerations 287,951 **Total Licensed 256,938**

The Federation of New York State Bird Clubs (1976) reports about 6,500 wintering Canada and snow geese. If it is assumed that a typical goose (Oneth, 1976) is four to five times the weight of a duck and has similar waste characteristics, it can be estimated that 100 geese produce 330 pounds of manure in a 24-hour period. This means that the total average wintering goose population produces 21,450 pounds of manure daily. Much of this is discharged directly into surface waters or adjacent to them.

Canada geese located on ponds along Merrick Road and the Sunrise Highway in Nassau County are changing their migration habits and are becoming year round residents, according to Dr. R.W. Johnson (1975). This change, which may be the result of feeding by man, sharply increases the waste loading from geese on these ponds. The greenskeeper at the Lake Success Golf Course reports fairway grass heavily damaged by the droppings of Canada geese living on and near the lake. Crop farmers in the Mecox Bay area report that certain farm fields are heavily manured by geese in fall and winter. Geese are attracted to the fields by the winter cover crops. Some of these fields shed storm runoff to Mecox Bay.

6.1.4 Semi-wild Ducks

White Pekin ducks that have been released, abandoned, or have escaped, and their descendants that are produced from interbreeding between the White Pekins and wild ducks are sometimes called "Indian Runners". These semi-wild ducks also include crosses between Indian Runners and wild ducks. The first and second generation cross breeds are too heavy bodied, 4.3 pounds and up, to sustain prolonged flight. They usually have a light tan appearance, pinto coloration, and large white patches on the neck, breast and tail. The male Indian Runner-Mallard cross usually has a black head; the female cross is without the distinctive black mask on the beak.

An accurate count of the semi-wild ducks on Long Island's inland ponds is not available. White Pekin ducks have been observed in the bi-county area on many ponds including Hook Pond in East Hampton, Westhampton Sanctuary, Barry Road Pond, Wading River Pond, Blydenburgh Park Pond, Argyle Lake, Stony Brook Mill Pond, Setauket Mill Pond, Cowen's Lake and the Peconic River. (See map at the end of this section).

The origin of the semi-wild duck population is largely related to the practice of giving baby ducklings to children at Easter. Park employees interviewed reported noticeable increases in the white duck populations within two months after Easter. An inventory of semi-wild duck populations on fresh surface waters in Nassau is currently being conducted by the Nassau Health Department (Natural Resources Defense Council, Inc., 1975). Inventory data was not available at this writing. John Renkavinsky, Fish and Wildlife Division, New York State Department of Environmental Conservation, estimated the inland pond wild duck population for Nassau-Suffolk at 18,000 (Renkavinsky, 1976).

A count of the semi-wild duck population is essential to help educate the public as to the need for the control of pet duck sales and the release of pet ducks. The Federation of New York Bird Clubs and/or other organizations might include such a count when they make their next annual bird count effort.

6.1.5 Horses

The Nassau-Suffolk Horsemen's Association, Inc. estimates that there are approximately 30,000 horses in the bi-county area. However, the Association officials, concerned about regulations, have been reluctant to locate or identify horse concentrations. Prior to 1973, the Cooperative Extension Service office at Riverhead attempted to locate horseowners in order to control an outbreak of equine encephalitis.

Response was limited and counts have since been lost. In 1973 the Riverhead staff of the SCS, in attempting to locate concentrations of horses of ten or more animals, contacted most of the large animal veterinarians within the bi-county area. Good cooperation was received. Only 4,000 horses were located in concentrations of ten or more animals.

The 1974 *United States Census of Agriculture* (1976), lists 60 farms having nearly 600 horses and the telephone book lists 25 commercial riding stables in Nassau County and about 50 in Suffolk. Two racetracks, Belmont and Roosevelt Raceway, house about 2,000 horses in season and half that number when the racing season is closed. Veterinarians report local areas in both counties—Muttontown, Brookville, East Patchogue, Oakdale, and Sayville among them—where the number of horse owning residents is well above the Nassau-Suffolk average. Horseback riding is a popular family activity in the bi-county area. The presence of more than 75 commercial riding stables and of many private clubs and horse farms indicates a prominent future for the Long Island riding horse.

In summary, there may be 30,000 or more horses in the bi-county planning area, of which probably less than 5,000 are housed in concentrations of ten or more. Approximately 25,000 horses are owned and housed in singles, pairs or small numbers, as a widely dispersed population of large animals. The dispersion of the horse population suggests that there may be many small non-point equine waste pollution sources affecting Long Island surface waters.

6.2 ANIMAL WASTE CHARACTERISTICS

Waste composition varies with animal age, breed, sex, and feed (Moore, 1970). For example, ducks produce about twice the daily volume of waste of humans, but more than five times the fecal coliform bacteria and more than 36 times the fecal streptococci. Tables 6–1 and 6–2 provide additional details regarding this variability. The following paragraphs describe the waste characteristics of dogs, semi-wild ducks and horses:

6.2.1 Dog Waste

The volume or weight of waste generated by a dog population can vary according to size, age, diet, and level of activity. Johnson (1975), concludes that an average Nassau County dog will produce a half-pound of feces and 3/4 quart of urine daily. Kramer (1971), estimates that 500,000 New York City dogs produce 110,000 pounds of waste on a dry basis each day. The half-pound of waste per dog per day value is regarded as conservative by veterinarians (Oneth, 1976).

A study in Saskatoon, Saskatchewan Canada (Anvik, Hyne and Rahaman, 1974), estimated that the city's 13,200 dogs produced 7,260 pounds of solid waste per day. It also estimated that 29,300 pounds of dog solid waste were on the streets of Saskatoon on March 30, 1973. A detailed study of a sample area of twenty of the city's 1,400 blocks provided the basis for these figures. Beck has reported that a large dog will produce 50 percent more waste than the average sized dog under similar conditions (Beck, 1973). Using 425,000 as the most probable number of dogs for the bi-county area, the SCS estimates that the total daily yield of dog waste amounts to about 106 tons of feces and 80,000 gallons of urine. This would amount to approximately 38,700 tons and 29 million gallons annually.

More documentation of the composition of dog waste is needed in view of its impact on Long Island surface waters. Generally dog wastes are high in nitrogen and are a source of coliform bacteria. The results of laboratory analyses of three collections in the Chicago area are shown in Table 6–5.

Table 6–5

ANALYSIS OF DOG DROPPINGS

Item	1	2	3
Water Soluble, mg/100 ml	16.5	20.2	178.3
Volatile Water Soluble, mg/100 ml	10.3	15.9	145.8
BOD_5, mg/g	78	377.3	300
COD*	200.7	552	720
Coliform, MPN/g	16,090	16,090	1,400,000

**Source does not provide dimension, assumed to be mg/g.*
Source: American Public Works Association; Water Pollution Aspects of Urban Runoff; USDI; Federal Water Pollution Control Administration; Washington, D.C.; January 1969.

6.2.2 Duck Waste

Certain specific kinds of ducks, other than commercial ducks and wild ducks cause pollution of surface waters on Long Island. They are the semi-wild White Pekin ducks and their descendants that do not migrate.

The amount and characteristics of waste produced by semi-wild ducks is similar to that produced by White Pekin ducks. Variations are due to differences in feeding, activity and age (Moore, 1970). Domestic farm reared ducks are known to be heavy feeders. During the first seven weeks of their lives they can consume 21 pounds of concentrated feed. Young semi-wild ducks can be expected to consume even larger volumes of food, since the food they eat is not concentrated.

Best estimates indicate that 100 semi-wild ducks on a typical park pond can produce 74 pounds of duck manure per day or 13.5 tons per year (Geldreich, 1969 and Wadleigh, 1968). A group of 100 semi-wild ducks would contribute about 207 pounds of nitrogen, 90 pounds of phosphorus, and 130 pounds of potash to such a pond each year. Each duck adds eleven billion fecal coliform bacteria to its watery environment each day.

Table 6–6, which shows the average amounts of the major nutrients contained in the daily waste per 1000 pounds live weight of humans, ducks, and chickens, facilitates comparison of the nutrient loadings attributable to each of these sources.

Table 6–6

AVERAGE COMPOSITION OF DAILY WASTE PER 1,000 LBS. LIVE WEIGHT

Nutrient (lbs.)	Man	Ducks	Chickens
Total Nitrogen as N	0.20	1.42	0.86
Total Phosphorus	0.024	0.62	0.40
Total K	0.064	0.9	0.35

Source: United States Department of Agriculture, Soil Conservation Service; Agricultural Waste Management Field Manual; Washington, D.C.; August 1975.

Duck waste is a concentrated pollutant. Table 6–7 confirms that bacteria and nutrient levels of White Pekin duck waste are especially high in coliform and nitrogen and exceed those of humans and chickens.

6.2.3 Horse Waste

An average horse produces eight to eleven tons of feces and urine per year (SCS), or, stated somewhat differently, a 1,000 pound horse will average 0.9 cubic feet of waste per day of which 65 percent will be water (Parr, 1974). Given the estimated 30,000 horses kept in the Nassau-Suffolk area, the expected daily waste production would be between 660 and 900 tons. Yearly horse waste figures probably total 300,000 tons, exclusive of bedding straw, chips or hay. By comparison, a human population of 2,700,000 people produces an estimated human waste total of 1,725,000 tons yearly.

Table 6–7

ESTIMATED PER CAPITA CONTRIBUTION OF INDICATOR MICROORGANISMS

Animal	Daily Production Fecal Coliform, (Million)	Fecal Strep., (Million)	Ratio FC/FS
Man	2,000	450	4.4
Ducks	11,000	18,000	0.6
Chickens	240	620	0.4

As indicated in Table 6–8, horse waste is relatively low in five day biochemical oxygen demand (BOD_5) and higher in phosphorus than most other animal wastes.

Table 6–8

AVERAGE COMPOSITION OF ANIMAL MANURES
lbs/day/1,000 lbs. of live weight

	Horses	Ducks	Poultry	Cows	People
BOD_5	1.4	5.1	3.4	1.4	1.36
N-Nitrogen	0.30	1.42	0.86	0.37	0.20
P-Phosphorus	0.12	0.62	0.40	0.069	0.024
K-Potassium	0.25	0.9	0.35	0.20	0.064

Source: United States Department of Agriculture, Soil Conservation Service; Agricultural Waste Management Field Manual; Washington, D.C.; August 1975.

Horse feces generally contain a higher percent of undigested nutrients than that present in human wastes. The waste from a single horse contains eleven times the BOD of an average human. The 30,000 horses in the bi-county area produce waste having the equivalent BOD_5 of 330,000 people.

6.3 ANIMAL WASTE IMPACT

In any animal waste management planning and control program, careful attention must be paid to the extreme variability in both volume and characteristics of the animal waste in question. The following paragraphs discuss actual and potential impact of wastes from dogs, ducks, and horses in the bi-county area.

Burge (1974), in his consideration of health hazards associated with animal waste, concludes that the incorporation of manures into farm fields lowers the impact of animal wastes on the environment and provides a sound and reasonable disposition of animal waste. Feces deposited on grassy soil areas are reduced by sunlight and air, and are less likely to be washed away by storm water. Soluble pollutants and bacteria are more likely to be washed into the topsoil layer where pollutants are consumed, impounded and recycled.

Recent studies indicate that if proper management is followed, manures can be applied to land on a year-round basis to achieve a lowered environmental impact. Young and Mutchler (1976), report that less than three percent of the total nitrogen and four percent of orthophosphate in manure ran off of manured, sloping land during the winter when it was fall plowed preceding the application. This contrasted with sixteen to twenty percent of total nitrogen and orthophosphate in the runoff from similarly treated grassland. It is concluded that level, or nearly level, fall plowed cropland can effectively retain animal manures that are applied to frozen ground if such procedure is necessary to control or reduce pollution from animal waste accumulations over winter. At other times spreading and plowdown or soil injection of animal waste slurry is appropriate for land application of animal wastes.

6.3.1 Dog Waste Impact

Dr. P. M. Schantz (1976), of the Center for Disease Control, Atlanta, Georgia, has stated that there is "a potentially important public health problem as a result of the increasing numbers of stray dogs in urban areas..." Marron *et al.* (1974), found that at least thirteen diseases are transmitted to man by parasites in dog feces, including salmonelloses, tuberculosis, toxoplasmosis and visceral larval migrans.

Beck and others (Beck, 1973; Burge, 1974; and Johnson, 1975) have commented extensively on the problem of dog feces in public areas as it relates to pollution and health. Dogs assimilate only 30 to 50 percent of their food, providing food for rats in their excrement. Dogs are attracted to beaches and parks by the food scraps.

Dog urine causes cankers and other damage to trees and thus increases landscape maintenance or replacement costs (Hummer, 1975).

In 1973, James Redman (1973), Aquatic Biologist for New York State Department of Environmental Conservation (NYSDEC) at Stony Brook, reported that, "Storm water runoff has been directly responsible for most of the recent closures of shellfish growing areas. Results of these (urban land runoff) sample examinations demonstrated conclusively that this (runoff) material transports large numbers of organisms. Methods should be developed for diverting urban runoff from estuarine waters."

Redman analyzed a number of street runoff water samples for fecal coliform and fecal streptococci. Microbiologists generally agree that the fecal coliform content of human waste will be more than two times the fecal streptococci content. In animal waste, it is usually the reverse. A majority of Redman's samples showed the fecal strep to be more numerous, supporting the contention that animals are the major source of the fecal coli in storm runoff.

The example of a single southeastern Nassau village lends further credence to Redman's findings. Residents of Massapequa Park have 2,727 licensed dogs. Application of the previously described estimation techniques indicates that the total dog population comprises 4,090 animals producing some 373 tons of solid animal waste annually. This village sheds or diverts most of its storm drainage water to South Oyster Bay. Using the Saskatoon, Canada figures cited above (Anvik, Hyne and Rahaman, 1974), an estimated 9,000 pounds of solid dog waste is present at any particular time on the streets of such a village. Much of this will be flushed into the Bay by the next major rainstorm.

6.3.2 Duck Waste Impact

The duck waste impact includes pollution from domestic duck farm operations, from the White Pekin duck that has been released or abandoned, and from the wild duck population.

6.3.2.1 Duck Farm Operations. Major changes in duck farm operations are now taking place. Discharges of treated wastewater have decreased from more than 6,000,000 gallons per day in 1972 to less than one-third of that amount in 1976. Storm runoff which formerly flowed through the farms is now largely contained or will be by mid-year. A few farms have already eliminated wastewater discharges completely. Solid waste consists of sludge from treatment lagoons, scrapings from pens, and straw and manure cleaned from buildings. Building manure is taken or given to gardeners or spread on cropfields. The sandy pen scrapings are frequently used as fill within the closed system. Some farmers cover rather than scrape. Lagoon sludge is removed and trucked away by cesspool cleanout firms. The SCS believes that this sludge should be applied to agricultural land as a valuable soil amendment. However, specialized manure handling equipment is needed.

In the United States as a whole, land application of duck wastes, including partially treated duck process waste water, has been considered the generally appropriate and available method for waste disposal for the duck industry. However, on Long Island fewer than five farms have sufficient land for such a procedure. Only about half the duck farms are so located that nearby vacant land, which could be combined with owned land to provide sufficient acreage for irrigation of the waste water, is available for sale or lease.

If correct management is followed, animal waste can be disposed of by applications on a year-round basis without adverse impact on ground or surface waters. (Graber, 1974; Moore, 1970; Parr, 1974; SCS, 1975; Wadleigh, 1968; Young and Mutchler, 1976; and Burge, 1974). Because of variations in soil, slope and waste characteristics, adjacent land use, and other factors, each application site requires planning on an individual basis. Conservation plans, as prepared for farm operators by the SCS working through the Suffolk County Soil and Water Conservation District, can include such planning.

The SCS classifies soils by "hydrologic groups". Knowledge of these groupings can provide guidance for proper management of irrigation waste water. Soils in Group "A" are moderately rapidly permeable sands, have limited internal surface area, limited absorption capacity and base exchange capacity. Soils in Group "B" have 30 to 80 percent fines, are moderately slowly permeable and have greater runoff potential than the "A" soils. Soils in groups "C" and "D" are not common and are of little significance on Long Island. Although "B" group soils are present in the bi-county area, they are not usually found on or near existing duck farms, an important factor in planning waste application rates.

A combination of waste water management measures is probably the best approach to the achievement of zero discharge that is available to duck farmers today. These measures should include the treatment and recycling of wastewater in periods of no precipitation, and irrigation of wastewater on managed hayfields after storms. To accomplish this, water use flows must be cut to the minimum during and after periods of rainfall. Adequate storm water holding ponds or holding areas should be developed. Continued operation of present treatment systems would be necessary, but without discharges to receiving waters. In most cases irrigation equipment and land would have to be added.

Another option for waste waster disposal involves the use of the marsh-pond waste treatment system, pioneered by Maxwell Small of Brookhaven Laboratory and the Town of Brookhaven. Approximately sixteen of the present duck farms do have sufficient land for such a facility. Marsh-pond treatment is designed to produce a high quality effluent appropriate for high rate land application.

An additional and as yet unattractive alternative for duck farmers is duck production without waste water. So far, this has been tried without economic success, making this option uncompetitive and unsuitable at the present time. The nationally renowned Duck Research Laboratory at Eastport would be the logical institution to undertake further research on the question.

Relocation of duck farms to interior areas of Long Island has been suggested. However, studies to determine the impacts of such a relocation on the movement of nitrogen and other pollutants through the soil are needed before relocation can be endorsed.

If the completely dry operation concept were to become fully and economically feasible, relocation, if it were still necessary, would then become more realistic. Such an operation requires continuous housing, which has been particularly unsuccessful with the "breeder" ducks that produce the eggs for starting new ducklings every seven weeks.

6.3.2.2 Semi-wild Ducks. The White Pekin pet duck that has been released or abandoned onto a public pond is dependent on feeding by humans for survival. It is common to see parents bring their children to feed these ducks at local ponds. Unable to fly in search of food, the semi-wild duck

becomes an aggressive beggar, making the act of feeding more rewarding for children. Such feeding sustains high duck populations, promotes growth, and indirectly, pollutes the pond. The Nature Conservancy recognizes that the feeding of wildlife creates this kind of problem and prohibits feeding at its sites on Long Island. Artifical feeding also alters the eating and migrating habits of wild ducks that visit the pond.

Ducks have an aquatic orientation and their waste is deposited directly into or near surface waters. Ponds, especially in residential areas, are under particular stress. Extraneous inflows such as those from urban storm runoff are often rich in nutrients that stress the ecosystem. Any unnecessary duck waste can further upset a pond's nutrient balance and can be responsible for production of excessive algae and weeds and the presence of high coliform counts.

Numerous diseases are communicated to animals and man via waters contaminated with duck wastes. These duck related diseases include the following: Salmonella, Psittacosis or Ornithosis, Type A Influenza, Yoba I Virus, Eastern Equine Encephalitis (E.E.E.), Schisosomiasis (Swimmer's Itch) and New Castle Disease. All but Eastern Equine Encephalitis can be passed to humans through waste contaminated water (Burger and Maher, 1977).

Swimming at Hempstead Harbor beaches was recently jeopardized because of high levels of coliform (8,000–10,000 MPN/100ml) at the outfall of Rosyln Park Pond. The large duck population, over 500 birds on the pond, was deemed responsible for the high coliform counts. In addition to chlorinating the pond outflow, the town officials transplanted ducks from this pond to other town ponds. The population of "Indian Runners", sustained in large measure by hand feeding, had grown so rapidly that, in effect, a pollution problem was transplanted along with the ducks. The present resident duck population at Roslyn Park Pond is now estimated to include over 100 White Pekins.

6.3.2.3 Wild Ducks. The wild duck populations of Long Island are a cherished part of our wildlife heritage. Much of the general public is unsympathetic toward the duck hunter, insisting on strong enforcement of federal and state laws that limit duck hunting. These same protective attitudes toward ducks reinforce the concept of feeding semi-wild ducks on inland ponds.

To a degree, wild ducks pollute bays and ponds. Brandvold, *et al.* (1976), in their study of the influence of wild ducks and waterfowl on surface waters, concluded that large migrating populations increase the available nitrogen and phosphorus compound and cause increased oxygen demand.

6.3.3 Horse Impact

Although it is comparatively easy to prove that there are a large number of horses producing vast quantities of waste that constitute a serious threat to Long Island surface waters, it is not possible to criticize the average horse owner for waste mismanagement. The relatively few known concentrations of waste are managed relatively well, with most stable waste stored away from storm runoff wash, and most accumulations faithfully picked up by gardeners, farmers or trash collectors.

At Belmont and Roosevelt Raceways, stables are cleaned daily and a large amount of straw is used to absorb waste liquids. The waste is stored in bins, one for every 26 horses, and these are emptied twice each week. The manure is loaded on trucks and shipped daily to mushroom farms in Pennsylvania.

Commercial riding stables usually stockpile manure out of sight behind buildings and provide some rainfall runoff protection. Some owners lime the manure or use a fly repellent. The waste is given to gardeners, nurserymen or farmers. The demand seems to exist the year round. No large piles were observed at the stables visited.

There have been isolated instances of complaints about commercial stables and stable owners expressed concern over their neighbors' past complaints to the local health department. Such complaints had been followed by a visit from the health inspector, who provided guidelines for cleaning up the nuisance.

Most local governments issue a general business license to commercial stables. The license evidently has no connection with waste management or complaints. However, some riding stable owners expressed concern that the license might be used to limit their activities in the future.

During this study, horses were observed in a variety of locations—in garages, backyards, woodlands, near ponds in residential settings. In isolated cases runoff from small paved surfaces having horse waste was seen draining into surface waters. The field staff only occasionally observed situations where storm runoff washed horse waste onto the drainage ways of neighboring properties.

Manure applied to nearly level to gently rolling grasslands at the rate of ten to 30 tons of dry waste per acre per year presents little or no hazard from nitrate runoff or leaching. Applications in excess of 30 tons per year can result in potentially harmful nitrate leaching (Parr, 1974).

6.4 ANIMAL WASTE CONTROLS

The Federal Water Pollution Control Act, 1972 Amendments, (PL 92-500) and subsequent EPA guidelines and standards as published specify those animal feeding operations that are subject to permit regulations:

> "Only an animal feeding operation defined as concentrated animal feeding operations is subject to the permit requirements. Such an operation occurs where: (1) more than 1,000 animal units are confined and there is a discharge of pollutants more frequently than that resulting from a 25-year, 24-hour storm event; (2) more than 300 and less than 1,000 animal units are confined and there is a discharge of pollutants into navigable waters more frequently than that resulting from a 25-year, 24-hour storm event through a man-made device or directly into

navigable water flowing through a feedlot; (3) there are 300 animal units or less confined and the Director of the State Program, after an on-site inspection, determines that pollutants are discharged into navigable waters through a man-made device or directly into navigable waters flowing through a feedlot." (Final NPDES regulations from the March 18, 1976 Federal Register on concentrated animal feeding operations.)

The New York State Sanitary Code classifies animal wastes as both offensive material and sewage when the animal wastes are water borne. Section 17-0105, Article 17, of the State Environmental Conservation Law, defines sewage as the "water-carried human or animal wastes from residences, buildings, industrial establishments or other places together with such ground water infiltration and surface water as may be present...." This section of the law together with related health rules and regulations provides a limited basis for the control of animal waste pollution by designated state and local agencies. However, the definition of "sewage" does not specify a lower limit of animal waste concentrations. Street runoff carrying dog waste components may be "sewage" under the law.

California, Iowa, Maine, Nebraska and Ohio, states with substantial animal husbandry, have passed laws or rules and regulations controlling disposal of farm animal wastes and have developed guidelines for land disposal and/or irrigation of liquid manures. However, no state laws were found to deal with wastes from dispersed animal populations.

The California State Water Resources Control Board has issued guidelines for the disposal of animal wastes to protect water quality and prevent other problems. Storm water management devices must be designed to accommodate the flow from a 10-year frequency, 24-hour storm. Storm runoff must not flow through manure storage areas on farms or other animal enterprises.

Iowa considers land application of animal wastes the primary means of disposal. The Water Quality Commission has formulated a policy giving recommended application rates and time of application. It includes a procedure to be used on land near watercourses that are subject to ten year frequency flooding.

Maine has developed guidelines for animal waste disposal, which, although they do not have the effect of law, are cited as references in municipal ordinances. Conformance with the guidelines is required as a condition of approval for large farm development. The guidelines specify time and rates of application of waste and of waste spreading with regard to water courses or water supply sources. Soils and slopes receive special attention. Conditions for manure piling and lagoon liquid manure disposal by irrigation are covered. Commercial fertilizer relationships are suggested.

Nebraska has rules and regulations primarily addressing animal waste disposal from point sources with no consideration for waste from pastures or rangeland. Rule No. 20 of "Rules and Regulations Pertaining to Livestock Waste Control" focuses on proper storage and disposal concentrations of animal waste to prevent water and land pollution. It includes a prohibition of manure spreading on frozen ground, and, therefore, represents a degree of animal waste control that reduces non-point source pollution.

Ohio's sediment and animal waste control law provides for implementation of non-point source control through soil and water conservation districts and locally prepared conservation plans (Unger, 1976). A Livestock Waste Management Guide has been prepared to assist an owner in the selection of a waste handling system. It deals primarily with cattle and swine, but some mention is made of horses. Specific mention is made of rainfall runoff. The value of manure as a source of plant nutrients, *i.e.,* as fertilizer, is stressed.

Present New York State and local health regulations that permit the control of offensive material provide that upon receipt of a complaint, a health department representative may investigate and cause a hearing to be held relative to a "nuisance", and may subsequently require the abatement of such nuisance.

Except for the 28 duck farms, Suffolk and Nassau counties have fewer than twenty commercial livestock or animal husbandry farm operations. Very few abut surface waters. Accumulated animal wastes are managed in accordance with present controls. These controls appear to be sufficient to prevent serious or repeated animal waste pollution from livestock farm operations in the bi-county area. The following paragraphs describe existing and proposed controls affecting dogs, ducks and horses.

6.4.1 Dog Controls

The first New York State Dog Control Law was enacted in 1917. This law, which superseded local laws that were considered ineffective, was a licensing law intended to protect domestic animals from dogs and to create a fund to compensate the animal owners for damages caused by dogs (Kehrer, 1975 and Renkavinsky, 1976). The 1929 revision to the New York State Dog Control Law included authority to impose restrictions on the keeping and running of dogs at large. Dogs are the only animals required to have a license in New York State.

In 1973, the New York State Department of Agriculture and Markets proposed a revision of the 1929 dog licensing law to achieve more effective dog population control. Many of the suggested changes were strongly opposed by dog owners during a series of emotion-filled public hearings. Notwithstanding their apparent unpopularity, the same law change proposals have merit today. The 1973 proposed law included the following provisions, none of which were enacted (Kehrer, 1975):

1. Substantial increases in fees for fertile dogs, with moderate fees for sterilized dogs.
2. Ear tattoos for identification (as now used with cattle).
3. Electronic data processing for licenses and enumeration, to be sup-

plemented by the existing animal control officers, who would also register new dogs.

4. Provision to allow witholding of dog control funds from any municipality failing to adequately control and enumerate their dogs.

The shortcomings of the present law are revealed in part, by the above proposals for change. Local units of government are supposed to hire dog enumerators to canvas an area and to list all dogs. Dog census takers are paid 50 cents per dog counted. Dog owners may not be contacted, or may not acknowledge all their dogs, or the census taker may lose interest when not enough dogs are found per hour of work.

The Dog Control Laws enacted recently on Long Island deal primarily with the nuisance of dog waste on streets and lawns, and usually require dog waste clean up. Dog waste related complaints are common. Nassau County Health Department reported 550 animal waste related complaints during 1975, and an expenditure of $32,000.00 in salaries to service them (Cooperative Extension Service of Suffolk County, 1975).

Local leash laws are designed to prevent dogs from running loose, causing damage or a nuisance, or threatening the public. All towns and villages in Nassau and Suffolk counties except the Town of East Hampton reported having a leash law. East Hampton and Southampton Towns ban dogs from beaches and Hempstead Village, Valley Stream, and Roslyn exclude dogs from parks.

Dog curb laws may have a negative effect on the environment. East Hills and Rockville Centre have dog curbing laws requiring that owners walking dogs allow their pets to defecate only at or near the street curb. In theory, the waste will then be swept up by street cleaning operations. In fact, animal waste in or near the road is easily flushed into the storm drainage system by rainstorm runoff. The drainage system empties into bays and estuaries, recharge basins, etc.

Dog cleanup laws, discussed subsequently, are one alternative to simple curbing ordinances. Other alternatives found in literature searched included dog toilets, or grassed areas near apartment buildings (probably would become offensive); punitive license fees, including a WCBS editorial suggestion of $1.00 per pound of body weight; waste areas at parks, authority for dog wardens to shoot free roaming dogs on sight; authority to require neutering of captured dogs before being returned to a claiming owner; etc. It was concluded that none of the above had sufficient merit and/or appeal to receive popular support.

Residents of Eastern Suffolk County are concerned about summer vacationers who often acquire dogs and then leave them behind upon their return "to the city". It was frequently suggested that dogs belonging to temporary residents be required to have an ear tattoo and be registered.

Dog controls are a highly emotional subject, as evidenced at numerous public hearings on dog laws. Strong leadership at the county and regional level may be necessary to bring about significant improvements in dog waste management.

6.4.2 Duck Controls

Duck farm animal waste disposal is regulated by Federal and State laws. Under those laws, duck farms are required to achieve zero discharge of wastewater to any receiving surface waters by 1983. A majority of the present Long Island duck farmers now plan to meet this requirement.

Wild duck population numbers are affected to a degree by Federal and State regulation of hunting. The Federal law sets hunting seasons, bag limits and areas where lead shot may not be used. State and local laws may further specify areas where hunting is prohibited or limit hunting in other ways. The overall effect is to protect and stabilize migratory waterfowl populations. Long Island tidal wetlands have been classified as "The most important coastal waterfowl area in the North Atlantic States" (Natural Resources Defense Council, Inc., 1975).

Semi-wild ducks are not specifically controlled or protected by law. The State law, authorizing towns and municipalities to establish dog catchers as peace officers with certain police powers, is not clear as to whether such persons can enter properties to capture and remove semi-wild ducks. Property owners can, under this law, have the town or municipality receive and impound the ducks which an owner removes from his property.

The Soil Conservation Service has found no law or section of a law that can be construed to support the contention that semi-wild ducks are a public nuisance. However, Article 26, Section 354 and Article 25B, Section 35 of the Agriculture and Markets Law do address aspects of the problem. The first, which attempts to discourage the sale of baby ducks for pets, states that, "No person shall sell, offer for sale, barter or give away live baby chicks, ducklings or other fowl under two (2) months of age in any quantity less than six" (Berman, 1970). In attempting to solve the problem of domestic ducks polluting local ponds, these laws may have complicated the issue by encouraging larger purchases. The second, which applies to dogs and other animals as well as ducks, states that: "The owner . . . of an animal, who abandons such animal . . . is guilty of a misdemeanor, punishable by imprisonment of not more than one year or by a fine of not more than $500 or both."

6.4.3 Horse Controls

The present primary document for statewide control of horse waste is the New York State Public Health Law, which cites animal wastes as sewage when they are water borne, whether carried by storm runoff or baseflow seepage, and as a public nuisance when the waste is offensive to neighboring property owners. Upon complaint, a health department representative may investigate, cause a hearing to be held relative to the nuisance, and require the abatement of the problem.

Zoning ordinances are often used to control the keeping of horses and, indirectly, the related problems. In the more densely populated areas in western Nassau County, such ordinances frequently prohibit the stabling of horses or limit such activities to a few selected locations.

Babylon Village and others require a special permit. In Smithtown,

where larger lots are more common, one horse may be kept on half an acre and up to three horses on one acre of land. Southold and Brookhaven allow no more than two horses on one acre of land. The Islip Town Board recently passed an ordinance prohibiting keeping a horse on less than half an acre of ground or more than two horses on each additional half an acre. Horse owners must provide stables with no less than 50 square feet of space, covered containers for manure, rodent-proof feed storage places and at least 400 square feet of outside corral space "enclosed by a suitable fence" ten feet from the property line. A $5.00 two-year license for each horse is required.

Methods for handling waste disposal are specified in Smithtown, Brookhaven and Islip ordinances. Closed waterproof containers away from property lines are required for manure storage. Huntington requires tertiary treatment of wastewater at dairies and commercial stables, unless served by the municipal sewage system; but has no regulation for horse manure disposal from private residences.

Outside the New York area, the Ogden, Utah and Greenwich, Connecticut codes prohibit the housing of horses or other large farm type animals or their waste, within 75 feet of a public street, drain or body of water.

6.4.4 General Recommendations

Recommendation I: Require that each landowner having concentrations of animals that exceed those stated in the table below, have a soil and water conservation plan.

Table 6–9

MAXIMUM ANIMALS PER ACRE OF OPEN LAND WITHOUT A CONSERVATION PLAN

Equine Livestock	2	Hogs	14
Beef Cattle	3	Ducks	400
Dairy Cows	2	Sheep	24
Turkeys	160	Dogs	20
Chickens	500		

or any combination of animals exceeding 2,000 lbs. of body weight.

Source: Federation of New York State Bird Clubs, New York State Waterfowl Count; rough work sheets; January 1976.

Under present State law, almost every agricultural producer must obtain a soil and water conservation plan by January 1, 1980. An amendment to the Soil and Water Conservation Districts Law, Chapter 441, of the Laws of New York 1975, directed the New York State Soil and Water Conservation Committee to define the lower limits of animal concentrations for concentrated agricultural operations. Table 6–9 above, quotes the figures that were adopted for all animals except dogs. This item has been added in response to local needs. The above recommendation will extend coverage to non-agricultural animals whose owners maintain high concentrations of animals per acre.

Chapter 441 describes a soil and water conservation plan as a "document containing proposals for the conservation of soil and water resources, and which provides an orderly method for landowners and occupiers to follow in limiting soil erosion and reducing the amount of pollutants entering into the waters or on the lands of the State of New York".

Soil and Water Conservation Plans are prepared for any requesting landowner or operator, by the local Soil and Water Conservation District. There is no charge for the services, which are subject to the limits of staff availability. Districts will determine priorities. Plans must meet USDA, SCS Conservation Planning Standards. Plans may be prepared by others as long as they are reviewed and approved by the District.

Conservation Districts historically give high priority to plan requests that result from animal waste problems. Health officers investigating an animal waste problem can refer property owners directly to the local Conservation District for such a plan. Implementation and installation of planned pollution control practices are the responsibility of the landowner or operator.

The amendment to the Soil and Water Conservation Districts Law cited above makes no provision for plan implementation and enforcement. Enforcement of provisions of the Conservation Plan should be by those local agencies now charged with regulating animal waste nuisance abatement. These agencies include the State DEC, the county health departments, environmental control agencies and town conservation agencies.

Recommendation II: Request the USDA Agricultural Research Service and/or others to conduct research to establish safe and effective methods and rates for land application of duck waste water on Long Island soils.

Research needs to include the following:

1. Investigation of the efficiency of marsh-pond duck waste water treatment in obtaining a high quality effluent for land application.
2. Monitoring of nitrogen movement and denitrification near duck pens.
3. Investigation of methods to enhance the economic feasibility of continuous housing of breeder-ducks.

6.4.5 Dog Recommendations

Recommendation I: Repeal ordinances that require the curbing of dogs in order to reduce dog waste pollution.

Curb your dog ordinances, specifying that the curb area of a street is the proper place for dogs to defecate, have a negative effect on the environment in most watersheds. These laws encourage dog defecation and urination on or near impervious street surfaces. Part or all or such curbed dog animal waste is usually flushed into the storm water collection system to pollute nearby receiving surface waters.

Albert C. Jensen, of the Division of Marine and Coastal Resources, New York State Department of Environmental Conservation, writes: "We believe that a major source of the coliform bacteria in street runoff is the feces of dogs and other animals. An informal survey of the Great South Bay watershed indicated a population of 80,000 to 100,000 dogs . . . approximately ten tons of dog feces per day impacting the ecosystem of the bay." (Jensen, 1973).

Dog curbing laws may not withstand court appeal. For example, an Essex County, New Jersey court decided that a local dog curb law is "unreasonable, arbitrary, and dangerous" (Knapp, 1972). The Essex (N. J.) County Court held, in October 1971, that,

> "a New Jersey ordinance requiring a dog owner to remove excrement and dispose of it in a sanitary manner constitutes proper exercise of police power, but portion of the ordinance requiring the dog owner to curb the dog in the street is invalid, since it exposes the owner and dogs unnecessarily to the dangers of vehicular traffic."

The decision reads, in part:

> "There was a time when dog owners loved their animals as pets, but today we find that such large dogs are being employed extensively for security purposes as well, because of the alarming increase in crimes of violence. The tons of solid waste and urine that are daily deposited by dogs have undeniably fouled our streets, our walks and parks to the extent that it has become well-nigh intolerable, threatening the health and safety of our citizens."
>
> "Persons stepping into dog feces on sidewalks or in street while crossing, or when entering or alighting from automobiles, can easily carry it on their shoes, and thence into their homes. Infants crawling about a rug or floor upon which such animal feces have been deposited may ingest them, since young children, especially babies, are known to be constantly placing their fingers into their mouths. Following a heavy rainfall, dog feces are known to find their way into sewers, along with other litter and debris."

The laws governing municipalities for N. J. hold that,

> "The right to the possession of dogs in a municipal corporation is subject to the limitation that such possession must not interfere with the health, security, and comfort of the other inhabitants of the corporation."

The use of the street-curb area for the deposit of dog waste can be further evaluated by comparing the rainfall runoff coefficients for lawns with those for pavement. Solid wastes are not easily flushed from sod areas by storm flows. During a three and one-half inch rainfall (two-year frequency, 24 hours storm) typical Long Island lawns shed only one-seventh (1/7) the runoff water as paved areas of equal size.

Recommendation II: Prepare a dog cleanup model ordinance *for inclusion in the 208 Plan recommendations and urge the adoption of this ordinance by municipalities having an average density in excess of 100 residences per square mile (or other appropriate ratio).*

Such a model ordinance should contain clauses that would accomplish the following:

1. Prohibit owners from permitting dogs to defecate on roads, sidewalks, parking lots, play areas, parks or other places where people congregate, unless there is prompt cleanup and removal of feces.
2. Prohibit the free roaming of dogs, with or without license and collar, except as expressly permitted by the landowner involved.
3. Call for the sanitary disposal of feces collected during cleanup.

The model ordinance should provide penalties for failure to comply, but make it clear that the dog owner's property is exempt from the cleanup requirement. It must provide some guidance for disposal of the cleaned material, such as public or commercial trash collection or shallow pit composting. However, the emphasis of the ordinance should be on dog control and the cleanup of solid waste from impervious surfaces that shed storm runoff to a public storm drainage system.

The primary objective of such an ordinance is the development of constructive public attitudes toward the control of dog waste in public places. If serious attempts at enforcement are to be considered, then such an ordinance will benefit from a "presumptive evidence" clause, wherein the person walking a dog shall be presumed to have no intention of cleaning up after the dog if he or she fails to carry appropriate clean up equipment.

The Soil Conservation Service feels that the clauses outlined above can adequately meet the needs of a community for managing dog waste in public places. However, local residents may desire additional clauses in the law to control dog damage to residential lawns and other property.

Several villages on Long Island have passed dog waste clean up laws. Malverne was the first, followed by Freeport, Great Neck, Hempstead, Valley Stream, Westbury, the Town of Smithtown, Rockville Centre, Great Neck Estates and Ocean Beach. Stewart Manor also has a cat ordinance. In Malverne in the last five years, between 175 and 200 summonses have been

issued, bringing fines as high as $25. The ordinance permits fines up to $250. Valley Stream passed its dog waste pickup ordinance a year ago, hired a part-time person to enforce it, and has issued summonses. Complaints have diminished since enforcement began.

Probably two-thirds of dog owners "put the dog out" to defecate at least part of the time. Data gathered in the five study areas for this report showed that only 40 percent of the owners said they leashed and walked their dogs.

Recommendation III: Revise dog licensing procedures under the NYS Agriculture and Markets Law, as follows:

1. Provide that first and second dog-related offenses may be handled administratively, without court proceedings.

2. Provide that local units of government be allowed to increase dog licensing fees: (a) to cover their dog-related expense and (b) to discourage fertile dog ownership.

3. Provide a record of dog-related offenses.

Administrative rather than judicial proceedings are needed to handle summonses related to dog control. Court calendars are crowded, especially in larger jurisdictions. Dog defecation cases are usually given low priority. Some law enforcement officers interviewed reasoned that dog-related offenses were not of much importance, since they were seldom given court hearing time. If an unlicensed dog is picked up, but returned upon purchase of the standard dog license, there may be no incentive to relicense the dog the following year. Under an administrative procedure, a set fine for failure to license dogs could be imposed. Automated, computerized dog licensing is needed to keep track of dog owner offenses effectively, thereby making it possible to increase penalties for repeat offenders. Such a record is a key element in dog control law enforcement and a major factor in dog waste management.

In 1971 the Town of Islip licensed 22,135 dogs and obtained $42,276 in license fees. Townwide dog control expense that year came to $296,000. For Babylon, the figures were 20,185 dogs licensed, $39,186 in fee income, and $75,000 in dog control costs.

An increase in fee differentials between sterilized and fertile dogs of either sex can help to reduce the number of unwanted dogs. Present fees, set in 1929, are $2.35 for a male or spayed female and $5.35 for an unspayed female. In 1929, spaying a bitch cost little more than the license fee differential, and that difference was sufficient to provide a large incentive for spaying. Today, dog neutering costs range from $30 to $80.

Recommendation IV: Fund a continuing public information program through the appropriate county environmental control agency to make dog owners more aware of their responsibilities.

Dog owners need frequent reminders that dog waste in streets pollutes; pet abandonment is a crime; their dog's waste in public places is their responsibility; failure to license a dog is wrong; and clean up is the law in some communities. The proposed public information program should extend to schools and other organizations.

Interviews of dog owners, conducted in the five study watersheds generally indicated that few if any dog owners had any idea that dog waste is a substantial source of storm runoff water pollution. More than 50 percent of the owners interviewed admitted they routinely released their pets; that they were not aware that a released dog was technically a stray dog; and that their action was, therefore, illegal in municipalities with leash laws.

Recommendation V: Provide partial funding for dog neutering programs in critical watershed areas; use increased license fees for fertile dogs to help defray costs. (The latter part of this recommendation would depend on the adoption of Recommendation III).

Anvik (Anvik, Hyne and Rahaman, 1974) reports dog and cat populations are expanding more rapidly than the human population, due largely to the numbers of stray animals. The Town of Brookhaven has already proposed the funding of a neutering program in their capital budget. The Town of Islip is preparing to set up a subsidized program of pet sterilization. Nassau County is also considering proposals for pet sterilization. "Critical Watershed Areas" are those municipalities with high density land areas (*e.g.,* more than 100 homes per square mile) shedding storm runoff to shellfish or recreation-use waters.

The probable dog population of the bi-county area is 425,000 animals. A sizable percentage of these dogs are not sterilized. It is probably too costly to subsidize an area-wide dog sterilization service. Therefore, a base map should be developed showing major land areas that contain critical watersheds. Dog owner residents of these critical watersheds should have first priority on available funding.

Whether or not to fund the sterilization of male dogs can be debated. It is doubtful that reducing by one-half the number of fertile males in an area would actually reduce dog pregnancies. The probability would always exist that a small but effective number of fertile males would be attracted to the female in heat. However, the public educational value of both male and female dog sterilization is recognized. Public support for controlling dog numbers is thought to be needed for any effective dog waste management program. Islip Town representatives, knowledgeable about their own neutering program, and leaders from other communities with dog neutering programs strongly support sterilization of both sexes, primarily for the educational value.

During our interviews with local officials, we learned that veterinarians have objected to continuous employment at dog sterilization clinics, preferring to work at more mixed activities. The cost of establishing these clinics was also considered objectionable.

Suggestions were received from interviewees urging the financing of dog neutering clinics through a local tax on pet food. It was also proposed

that animal shelters be required to offer only sterilized pets for adoption and that a limit be set on the number of unsterilized dogs per household. This section neither supports nor opposes these ideas.

6.4.6 Duck Recommendations

Recommendation I: Eliminate White Pekin ducks and their derivatives from inland ponds that are not part of a farm operation.

Alternatives for implementing this recommendation are as follows:

1. Generate legislation at the county and/or municipality level authorizing and directing dog wardens, park employees and law enforcement officers to remove White Pekin ducks and their derivatives from publicly controlled reaches of inland bodies of water.

2. Provide a bounty for the delivery to local animal pounds of White Pekin ducks and their derivatives that have been removed from non-farm inland freshwaters.

In support of this recommendation, it should be recognized that the introduced White Pekin duck stimulates artificial feeding, attracts wild ducks, is non-migratory, is a heavy coliform and nitrogen polluter, spreads avian diseases, and may destroy shoreline vegetation, causing shore erosion.

The Soil Conservation Service concludes that if the White Pekin duck and its descendants are effectively eliminated from public inland water bodies, the feeding of wild ducks, while not desirable, is not sufficiently harmful to surface water quality to warrant prohibition of such feeding.

Recommendation II: Prohibit the sale of White Pekin ducks as pets within the bi-county area.

Generate a penalty law against retail sales of ducks for pet keeping purposes.

In view of the nature of the proposed measures, it may be necessary to conduct a public information program to avoid adverse public attitudes toward White Pekin duck elimination.

6.4.7 Horse Recommendations

Recommendation I: Prepare a model ordinance for local use providing a limitation on the number of horses per acre on residential land and specifying the management of and disposal of certain horse wastes.

The following clauses should be included in order to insure adequate waste management:

1. Not less than one-half acre of open unpaved land shall be provided for a single horse or other equine livestock; not less than one-fourth acre of open unpaved land shall be provided for each additional horse.

2. Each premises having less than one-half acre of open, unpaved land per horse shall have and meet the provisions of an animal waste management plan, approved by (agency to be specified) or be in violation.

3. Animal waste, including manure and soiled bedding shall be kept in weatherproof containers at least 50 feet from adjoining property lines.

4. Paved or otherwise unvegetated or bare soil areas used as horse yards, paddocks, pastures, or similar shall be graded or controlled so that no storm runoff water from one-year frequency rainstorms falling on such areas, shall flow from the horse owner's property to other public or private lands.

Recommendation II: Where Horse Recommendation I is not implemented, authorize the county health departments to require the preparation and implementation of a conservation plan covering animal waste management whenever necessary to abate a horse waste related nuisance.

The plan should be prepared by a professional conservationist or the equal and reviewed by the SWCD for each horse waste related complaint involving (1) animal waste sewage flowing off the property, or (2) failure to properly store horse waste.

6.5 CONCLUSION

Nassau and Suffolk Counties are suburban residential counties having a 1977 population of approximately 2.8 million persons. The densest population centers are generally located in watersheds that discharge directly onto the marine edge and to inland lakes and ponds. Highways and local roads are usually depressed below the natural ground level and serve as principal drainage channels for runoff water. Recharge basins provide storage for storm water discharges for most new subdivisions in Suffolk County and many in Nassau.

Dogs and semi-wild White Pekin ducks were found to be unregulated sources of non-point animal waste pollution. Urban runoff containing dog waste and other animal waste is responsible for most of the recent closures of shellfish growing areas. An information program and new laws are recommended to control dog waste disposal. Semi-wild White Pekin ducks and their descendants are also serious sources of pollution in many ponds and lakes. Diseases are communicated to animals and man via waters contaminated by duck wastes. New laws and public awareness concerning the problem are needed to control these wastes.

Market duck waste has been a pollution hazard in the past and is now regulated by Federal and State laws. Under these laws duck farmers are required to achieve very limited discharges of wastewater by July 1, 1977, and zero discharge to any receiving surface waters by 1983.

Zoning ordinances in some municipalities are used to control horses and, indirectly, the waste related problems. However, there are many small non-point horse waste pollution sources affecting surface waters. These may require control.

Under present state law agriculture producers must develop a plan to reduce sediment and related animal waste pollution by January 1, 1980. This plan is developed with the assistance of the Nassau and Suffolk County Soil and Water Conservation Districts. It is recommended that the present law be amended to require non-agricultural animal owners, who have high concentrations of animals per acre, to develop a plan, with Soil Conservation District assistance, for the control of animal waste.

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Section 7 Modeling Studies

7.0 INTRODUCTION

The waste treatment planning process requires a knowledge of: the quantity and quality of the ground and surface fresh waters; the quality of the marine surface waters; the movements of ground and surface waters; the inter-relationships of ground and surface fresh waters with the marine waters—in terms of movement and quality; the contaminants that enter and impact each and all of these waters; and the structural and non-structural abatement alternatives most suited to cope with each set of problems in order to achieve the protection and/or rehabilitation of drinking and swimming waters to safe levels of water quality.

This requires an in-depth knowledge of existing conditions and an ability to predict future conditions under a variety of impacts. The study of existing conditions can be made by direct investigation. Water samples can be taken and analyzed, and controlled experiments can be conducted. This in fact has been done. However, in a region of more than 1200 square miles and as complex and dynamic as the Nassau-Suffolk Region it is prohibitive in terms of time and cost to totally rely on field studies. Furthermore, the only way that field studies can be used for predictive answers is to actually build a facility or to add contaminants and then measure the results. Fortunately a more effective and efficient set of tools is available to complement the field examinations; namely, the use of models.

One of the significant components of the Long Island 208 study centers on the development and use of appropriate mathematical models. The wastewater management plan for this area ultimately depends on the ability to quantify a preference for one set of structural and non-structural alternatives over another. In the process of doing so it is necessary to understand what the impact of these alternatives may be on ground and surface waters in terms of changes in movement and quality which result from the options used. The modeling efforts provide flexible tools to evaluate and predict such impacts without engaging in prohibitive tests on the actual water bodies themselves. That is, modeling is a surrogate for reality in which certain basic inter-relationships in the real world are expressed by mathematical statements. By manipulating these proxy statements one simulates, as it were, the events which actually take place. The models are therefore a method for organizing the complex interactions which occur between the water bodies and the stresses placed on them. This is a simplification of nature in that all interactions are excluded other than those which are of relevance to the study.

The use of mathematical statements to imitate reality has a long tradition in water management and other planning studies. Models enable researchers to carry out "what if" experiments on nature. For example, one can replace the actual waste loads which enter Long Island bays with esti-

mated loads which result from potential abatement options and then see what effect this has on subsequent bay conditions. Thus these changes can be simulated without having to physically build treatment facilities. That is, one can look into the future by tracking present conditions to determine what eventual effects they produce on water movement and quality. Finally one can play out enough such alterations in initial and boundary conditions to find the 'best' future scenario.

Section 7.1 of the report provides a straightforward but intuitive discussion of hydrodynamics. Fortunately, just a few basic facts concerning the relation between water elevation (or 'head') and flow velocity suffice to derive all the fundamental equations used in the modeling of movement of ground and surface waters. As a result there is an essential conceptual unity between the apparently different modeling efforts used in the 208 study. The various models also use a common and simple idea, that of mass balance, in calculations of water quality and "water budget" considerations.

Section 7.2 contains a review of the surface water (including river) models, with some discussion of their limitations and uses. These models characterize the changes which occur over time (in a water body) to constituents such as salinity, nitrogen and dissolved oxygen. There is also a discussion of the models developed for achieving ecological balances under various conditions of constituent loadings.

Groundwater models are reviewed in Section 7.3. Two were developed; an analog and a digital one. In addition, water budget studies are explained.

Section 7.4 attempts to tie together the entire 208 modeling effort with a discussion of the results actually obtained and how they will be used in the development of a wastewater management plan.

The reader who does not wish to linger over some of the technical arguments can simply read the last section to get a perspective of how the models relate to the 208 study. We caution the reader, however, that this report cannot be a substitute for the detailed documentation provided by the respective consultants. The aim of this report is to explain the ideas which are necessary to an understanding of the structure of the models, their limitations, and integration into the overall 208 study. Explicit details concerning computational schemes, data sources, and eventual model validation are only hinted at, and the technically interested reader must consult the original sources on these questions. (See Bibliography.) Also excluded is a description of model outputs for different sites on the Island since these are also fully documented in reports issued by the consultants.

Every attempt was made to explain these models in understandable prose form. Differential equations—the language of models—were eliminated from the discussion. In those instances where technical jargon was deemed inescapable it was followed by a common language definition. A glossary listing is included at the end of the report.

7.1 HYDRODYNAMIC BACKGROUND

7.1.1 Introduction

The groundwater and surface water models used in the 208 study are based on the same hydrodynamic principles. It will be convenient, therefore, to review these basic ideas before they are applied to the models themselves. The discussion is somewhat simplified in order to provide a broad understanding of this material.

The derivations therefore will generally be intuitive to avoid technical complications or the overuse of mathematical formulae that add little or nothing to an overall appreciation of the essential ideas. Those readers not familiar with mathematical notation can safely omit the occasional allusion to equations. These are given as footnotes and hopefully do not intrude in too distracting a way.

7.1.2 Fluid Flow

Imagine a water body as being represented by a rectangular tank of elevation H and a fixed surface area A_S connected to the outside by an inlet pipe or channel (see Figure 7–1). The tank volume is therefore $A_S H$. Water flows into or out of the tank through the channel with a velocity u. If the tube has a cross sectional area A_C then the net flow of water is designated by Q. Using meters as a unit of length, u can be expressed as meters per second. Therefore flow is given as cubic meters per second and the relation between the two is

$$Q = A_C u \tag{7.1}$$

It is apparent that if there is no mass flow into or out of the tank then the rate of change over time of the volume of water which it stores must be zero. This is simply a statement of *conservation of mass.* However if the net mass flow Q is non-zero then the volumetric change per second must equal Q itself. This is one of the two fundamental facts used in the models. Note that H (also known as the 'head') varies up and down as Q increases or decreases.[1]

Suppose now that the channel is connected to another water column and that the storage tanks are labeled as 1, 2. If the elevation of water in

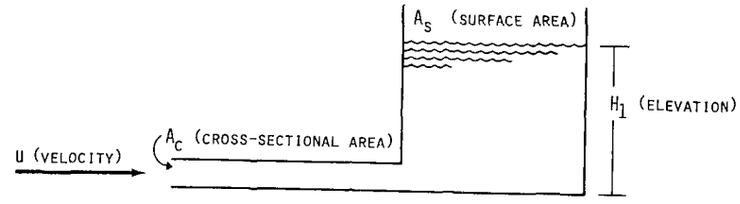


FIGURE 7–1 *Flow Into a Water Tank.*

each of these is different then the resulting pressure differences at the two ends of the channel cause water to flow (See Figure 7–2). The rate at which this flow changes is in fact proportional to the difference in head. In particular if $H_1 = H_2$ then there is no flow. In actuality there is another force which acts to impede flow in the conduit. This is frictional resistance, a quantity which we denote by R, caused by roughness of the channel walls. If we ignore this resistance, what we have is essentially a statement that water flows from a higher to a lower level and that the rate of flow is proportional to the difference in level. This is our second fundamental fact. In effect, it expresses Newton's contention that every body has inertia and that the only way it moves is in response to some external force. When that force is zero, there is no motion.[2]

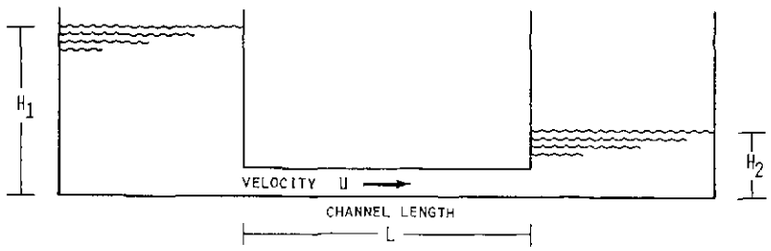


FIGURE 7–2 *Flow Between Water Tanks of Different Elevations.*

To adequately describe flow in the aquifers in the groundwater system it is necessary only to introduce a minor addition to the discussion above. In essence, the soil occupies some of the space which would normally contain water. It is as if we examined the tank in Figure 7–1 and, to represent soils, threw into the tank a number of balls to represent a porous medium. In such a case, the flow of water into the tank causes greater increases in the head since some of the space is already taken up. Similarly, in Figure 7–2 we should fill both tanks and, more importantly, the channel with balls. It is then evident that these will considerably restrict the flow of water from one tank to another (see Figure 7–3). In surface waters, where the flow is relatively free, water movement from one place to another in the system takes place over periods of hours which corresponds to a tidal cycle. However, in the groundwater system the flow is so restricted that it requires a much longer time. It should be kept in mind in reading later sections that this discrepancy in the time required for differences in head to be equalized is one of the most significant differences between surface and groundwater models.

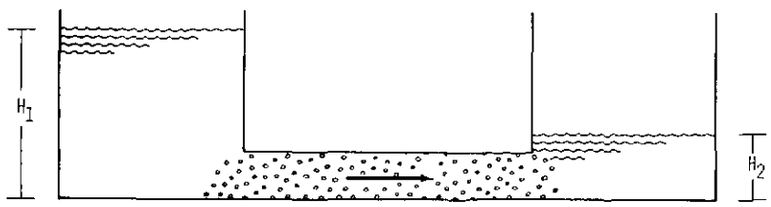


FIGURE 7–3 *Flow in a Porous Medium. For a Given Volume of Water, Both H_1 and H_2 Are Greater Than in Open Water Since the Medium Occupies Some of the Bulk of the Tanks.*

Let us try to make the discussion more precise. The flow of fluid in a porous saturated medium is dominated by two features not present in the open surface case. First, there is *porosity*. This represents the fraction of bulk volume in a tank which consists of open pores accessible to fluid storage. Porosity can be defined by the number ϵ, where

$$\epsilon = \frac{\text{volume of pores}}{\text{bulk volume}} \tag{7.2}$$

It is apparent that ϵ is less than one. Although in open waters H is volume divided by surface area A_s, in porous medium H equals the volume divided by ϵA_s and therefore is larger. Second, the interconnected pores act as thin capillary tubes. This creates a condition known as viscosity. *Viscosity*, which we denote by μ, describes the fluid resistance toward flow past a boundary. *Permeability*, indicated by k, describes the restriction upon flow imposed by the porous medium itself. These fluid and medium properties can be combined to describe the overall *hydraulic conductivity*, or ability of water to flow in the groundwater system.[3]

Two very similar pairs of relations are now derived; one for open water flow and the other for flow in a porous medium. The first set will be used in surface modeling and the other in groundwater modeling. Each pair of relations expresses the temporal change in hydraulic head of a water body in terms of velocity of flow into that body, as well as the temporal change in velocity between two parts of a water body in terms of the differences in head and the resistance of the medium. Thus the essential output of the hydrodynamic equations are a knowledge of how H and u vary over time in relation to each other.

The only major difference between the arguments used in the derivations above and those which would be used in a more exact mathematical approach is that the macroscopic view of tanks and conduits is replaced by a study of the instantaneous changes of infinitesmal slices of volume. This leads to what is known as partial differential equations of motion for H and u which are valid at any point of the water body rather than to an entire water column as above. Such equations are not used in this report.

Let the symbol Δ refer to an incremental increase or decrease of some quantity. In the discussion of rates of change of H and u over some time let ΔT denote the interval of time in which things happen and let ΔH and Δu refer to the corresponding jump in the value of H and u. If ΔT is the increment from some previous time to the present, then our two basic relations relate ΔH to the previous value of u and Δu to the previous value of

the head difference $H_1 - H_2$. This is an important observation because it says that one can compute present values of H and u from previous values since ΔH and Δu, the incremental change, is now known. Following this argument back to some initial time we see that if head H and velocity u are both specified initially, all future values are predictable. Note also that in the process of obtaining these future values, H and u are both dependent on each other. Taken together they tell us about the movement of a water body over successive intervals of time. In essence this is the core of what is called *hydrodynamics.*

In order to illustrate what can happen over successive intervals of time (where ΔT represents a few hours, for example) let us consider the exchange of water between two tanks as shown in Figure 7–4. This could represent "snapshots" of water elevation in two parts of a bay due to oscillations which result from tidal flow. Once set in motion, the water's momentum causes it to move back and forth. If the external influences of the open sea were suddenly to cease then the oscillations would eventually damp down (due to frictional resistance) and the system would come to rest. The second fundamental

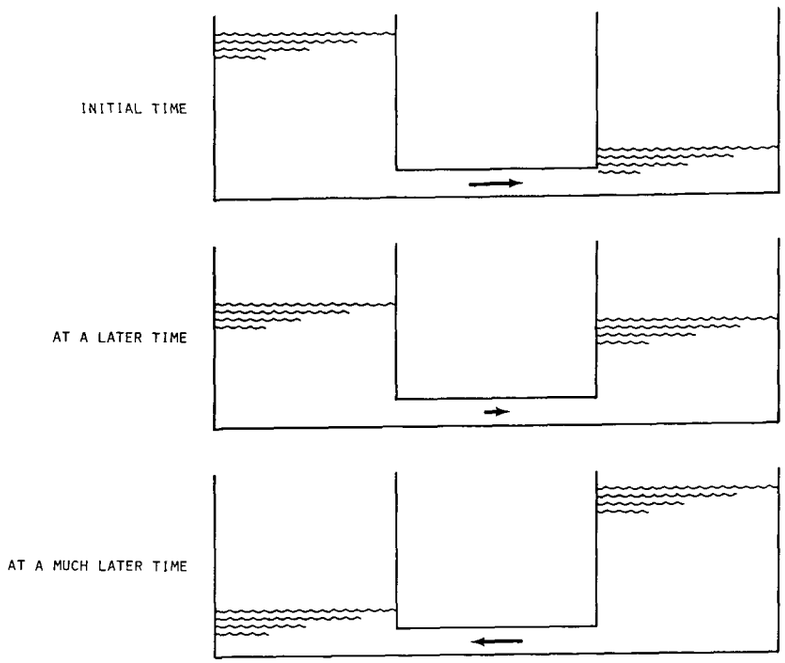


FIGURE 7–4 *Flow Between Water Tanks in Successive Instants of Time.*

relation is but a restatement of this fact. Except for the external forces which intrude, this is exactly what would happen in practice.

In the discussion of surface and groundwater models later in this report the simple ideas expressed above will prove to be the key ingredients to understanding how the models work. There is also another idea which we need to treat here since it forms the basis for water quality modeling and for the *water budget* model. This is an extension of conservation of mass, as used above for water, to include all substances which enter into the water due to natural and man-made discharges. If these substances, such as nitrogen and phosphorus, do not decay over time then in the absence of any external influences which may add or subtract from the total amount, the total mass remains unchanged over time. This statement is completely analagous to the observation made earlier about the water in a bathtub and the way it is used is to remark that the only changes which can take place in a water body, other than external "sources" or "sinks," is that the water constituent shifts in concentration from one place to another with the total amount remaining constant. Therefore if one adds up all decreases in the concentrations in different parts of a bay, these must equal the sum of increases in the remaining parts of the bay. This fact forms the basis of an accounting procedure known as "mass balances." The concept of "water budget" is also very similar, as will be shown.

There is one last remark to be made in this connection. If a substance is inserted into a water body it will move about due to two forces. The first, called *advection,* is the displacement of the constituent from one place to another because the water in which it finds itself happens to be moving. If a dye is put into a bathtub and a wave is generated, then the dye will tend to migrate in the direction of the wave movement. The other force, called *diffusion,* is the propensity for a substance to move from a region of high concentration to a lower one at a rate proportional to the difference in concentration between two points (this is similar to water itself wanting to move from a high point to a lower one at a rate proportional to the difference in head[4]). This results in a spreading out in all directions of the original mass until it reaches a state of total dispersion. Again, if you place a dye in a tub, even in a perfectly motionless tub, it will move away and thin out from where it was put in. One of the main goals of the surface and groundwater models is to capture the effects of advection and diffusion to describe water quality in a water body. To do this, hydrodynamic considerations are important since water movement determines advection.

To summarize: essentially two basic facts were reviewed which dominate the structure of all the models in the 208 project. Each states the premise that in the absence of any external forces a water body (or of a conservative substance within it) reaches a state of equilibrium in which total mass remains unchanged and in which velocity of flow is zero. When this is not true, the lack of equilibrium is proportional to the sum of the forces which act on the body or on the substances within it.

7.2 SURFACE WATER MODELS

7.2.1 Water Quality

7.2.1.1 Hydrodynamics in an Estuary. The Long Island waters are contoured by a number of bays and estuaries. Pollutants which enter these waters are largely dispersed through the flushing action of the tides. The purpose of the Tetra Tech modeling effort is to determine the concentrations of the various constituents which enter the waters both spatially, and over time, as a result of this tidal action. In order to understand how this can be done, it will be convenient to first describe the unsteady flows of the coastal waters and then to relate this to the procedures used in computing water quality. The first part therefore is based on the discussion of hydrodynamic relations which were developed in 7.1.

A number of plausible assumptions are made in the formulation of the model in order to make the analysis more tractable. To begin with there is the problem of spatial dimensionality. If one assumes the water body being studied is completely mixed in the vertical direction (no differences in salinity, for example) then it is possible to consider the body as a two dimensional expanse of water in which all changes take place in the planar directions. For bays and estuaries in which water depth is shallow compared to the planar width this assumption is reasonable. However, even the two dimensional description is generally too complicated. Therefore we further reduce this problem into a set of much simpler one-dimensional descriptions. How this is done will be shown in a moment. It is worth noting immediately that what makes this reduction from a single hard problem into many simpler ones useful is that it is typically more efficient to code a computer to carry out a large number of straightforward computations than to have it perform a single complex problem.

The model divides the water body in question into a set of "nodes" which are joined together in a network by a series of interconnecting "links." Each node represents a completely mixed "tank" of water having a specified surface area A_S, an elevation H (relative to some arbitrarily chosen datum) and a volume $A_S H$. The nodes are where water is stored in the bay (from now on "bay" refers to any coastal water body and may in fact be an estuary) and the links represent channels through which water is conveyed from node to adjacent node. Each channel preserves information about flow Q and velocity u of water movement as well as the coefficients of resistance to that flow; it also has a specified length L and a cross sectional area A_C which varies along its longitudinal dimension, as well as a specified width. Figure 7–5 exhibits a grid network of nodes and links overlayed on a typical bay while Figure 7–6 displays one possible representation of a node and of a channel. When there are N nodes in the network then it is useful to label them in some order.

Since flow is along the longitudinal direction of each channel the characteristics of motion in a channel are one-dimensional. The price paid for this reduction in dimensions is that there are now a large number of channels to

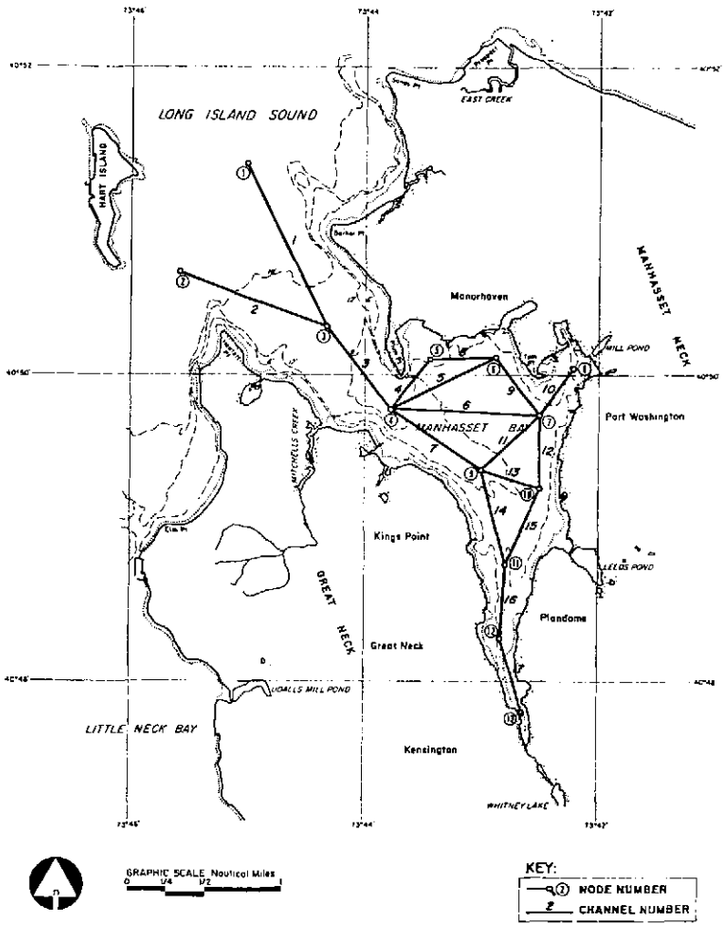


FIGURE 7–5 *Node and Channel Layout for the Manhasset Bay System.*

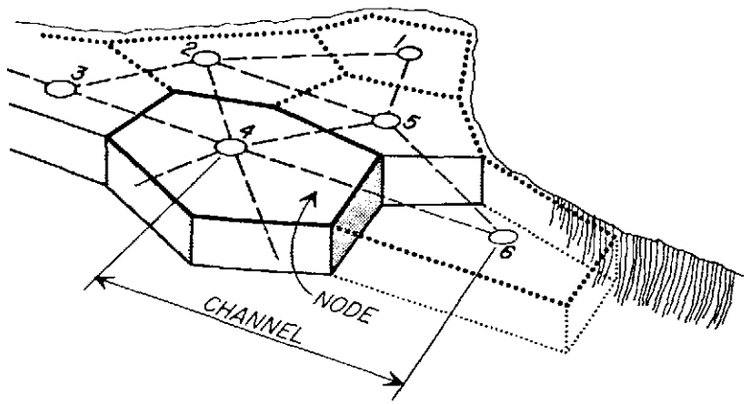


FIGURE 7–6 *Typical Section of an Estuarial Node-Link Network.*

consider simultaneously but, as said earlier, this is preferable from a computational point of view. Collectively, this network of one-dimensional flows constitutes a proxy for the original problem. It is apparent that in bays of irregular shoreline geometry, some care must be taken to account for changes in flow patterns caused by these irregularities by choosing a suitable placement of junctures for the links. If there are natural channels of flow then links of appropriate length and width are inserted to represent this. The grid is not uniform, being densely laid out where water quality or hydrodynamic conditions change rapidly and being more sparse in those portions of the bay where it is likely that there will be less action. The nodes themselves will vary in size (that is, in surface area) depending on the accuracy desired. Since a node represents a completely mixed water column, the extent to which the constituents of the water are actually homogeneously distributed is a determining factor in how big or small such nodes should be. Therefore careful judgement must be made in the preparation of a grid configuration prior to any computations. This is one of the places where the skill of the model maker is revealed.

Before continuing it must be noted that the channels are considered to extend from the center of one node to the center of the adjacent one. The nodes or water tanks are all contiguous and together cover the bay. Hence all exchanges of constituents within a node resulting from the flows into and out of the tank are assumed to occur at its center.

Let us now consider a typical node, having some fixed surface area. Over time the only thing that varies within it is the elevation or head of the water. Then as known from section 1 the rate of change of H, denoted by ΔH during the interval ΔT is proportional to the velocity u.

Suppose there are m channels connected to the given node which is labeled as node s as shown in Figure 7–7. The channels link to other nodes which we can arbitrarily index by j where j runs between 1 and the number m. At any given time the average flow in each channel is written as Q_j (away from or towards node s). In addition at node s there may be some *additional sources or sinks* (that is, additions or losses) of flow which we write as Q_s^{in} and Q_s^{out}. For example if node s is near the shoreline then Q_s^{in} could represent tributary inflows or sources of waste discharges from a treatment plant or some measure of runoff along the embankment while Q_s^{out} could denote water diversions and evaporation. Groundwater inflows and even rainfall can also be accounted for at each node. This allows us to extend our basic relation about head to say that at each node s, ΔH is proportional to the velocity in addition to the net flow $Q_s^{in} - Q_s^{out}$.[5] The second fundamental relation of section 1 does not require modification except to make the dependence on the node arrangement more explicit (see Figure 7–7).[6]

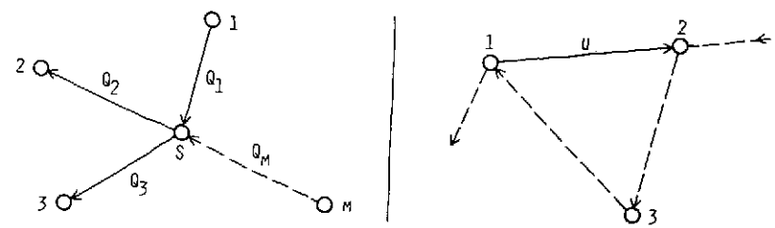


FIGURE 7–7 *Typical Flows as Seen in Part of an Estuary Node-Channel Layout.*

7.2.1.2 Solution Procedure. The detailed numerical procedure employed to obtain solutions to the basic hydrodynamic equations is described in "Documentation Report for the Estuary Water Quality Models" (*Tetra Tech,* May, 1977). Herein, it is only important to summarize the elements required in order to carry out these computations. To begin with the grid network must first be specified. This means that the geometic layout must be given, and also the values of surface area A_S for each node and the length L and widths of each channel.

In addition boundary and initial conditions must be specified. The solution of the equations begins at some initial time and proceeds over a set of incremental steps whose duration ΔT is usually of the order of an hour or more. All those nodes having a known inflow Q^{in} and outflow Q^{out} must have these values given at each time step for the entire computational horizon which is being considered for running of the model (the question of time span will be reconsidered in more detail later). These values may of course be constant in some problems. Generally speaking, the nodes so specified are located along the boundary of the bay. Also those nodes which interface with the

open sea (Long Island Sound and the Ocean) will need to have the elevations H given corresponding to the actual tidal oscillations which prevail there. These are similarly given at discrete time intervals over an entire tidal cycle.

The knowledge of head H_j at the boundary nodes is used to derive the elevations at all other nodes. In order to carry out the numerical procedure it is necessary to also specify in addition to the boundary conditions described above, a set of initial values for the velocities in each channel and a tidal elevation of other than seaward nodes (these may be taken initally to be zero). As the computations proceed these values repeatedly adjust and after running through several tidal cycles one begins to notice that successive values of velocity u and head H over two consecutive cycles no longer differ significantly. At this point equilibrium has been achieved in the model and the numerical procedure terminates. A typical plot of elevations at two nodes in an estuary would be as shown in Figure 7–8 where a shift in phase and a difference in amplitude can be seen. This is largely due to the drag induced by the channel resistance R, especially during ebb tide when the estuary is shallow.

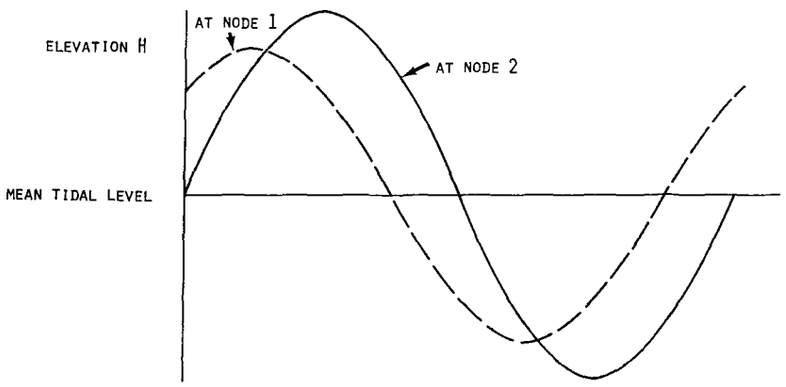


FIGURE 7–8 *Phase Shift of Tidal Oscillation in an Estuary.*

After equilibrium has been achieved in the computations one may wish to compare model results with actual field data obtained at monitoring stations in the bay. Tide gauges, for example, will give elevations which occur at various locations and these can be used for comparison. If the model results differ substantially from this data then the modeler engages in *model calibration.* The values of the resistance R along each channel are used for this purpose. By adjusting these values for each channel and re-running the model computations a greater or lesser degree of compliance to field results can be achieved although there is a reasonable limit to the amount of adjustments which are possible. Experienced modelers can usually do this without too many trials. If, however, compliance is still not satisfactory it may mean that the original grid of nodes and links does not supply enough detail. By enlarging the grid geometry by the inclusion of more nodes, it is possible to improve overall accuracy. However, there is a purely technical snag here which should be pointed out. For the computations to remain stable it is necessary to require that the time step ΔT be smaller than some factor of the smallest channel length in the network. Therefore as grid size is made more dense in portions of the bay the computation work is increased because of the extra nodes and links, and the number of time steps of size ΔT also decreases. There is therefore a practical limit to the amount of detail that can be expected from the network configuration itself.

After calibration it is usual to further check the model against a new set of field data (assuming these are available). This process is known as model *verification,* although in practice it is often difficult to distinguish the exercise of verification from that of calibration. If the model results fit the new data set reasonably well then this lends confidence in the use of the model as a predictive tool.

At this point one can use the hydrodynamic information so far obtained to derive an understanding of water quality. This is discussed in the next section.

7.2.1.3 Water Quality in An Estuary. When pollutants enter a bay, they are dispersed, largely as a result of the action of the tides. Some fraction is carried out to sea and the remainder is spread throughout the water body through mixing. In addition some of the constituents of the bay will decay over time. The relationship between the concentration of a constituent and the forces of tidal flushing and decay follows.

The model formulation assumes the same node/channel configuration of the bay as in the hydrodynamic equations. Several assumptions are made in addition to that of complete vertical mixing in each node. These will be described as we proceed. Vertical mixing is somewhat problematic for those nodes in the vicinity of an outfall or at the head of a fresh water tributary. Here the concentration of an effluent or, in the case of a tributary stream, of the salinity is non-uniformly dispersed and forms a plume. As a result there is some stratification of constituents in the water column. However these will be considered to be negligible effects in the model.

As a result of tidal oscillations, the concentrations which spread out from the boundaries of the bay are folded back and forth on each other. This dispersion is caused by two separate forces as seen in 7.1. The first, called *advection,* is the result of material being transported through the displacement of the water itself. The second, called *diffusion,* is the natural process by which any concentrated material tends to distribute itself uniformly throughout the water body.

Two kinds of constituents are handled by the Tetra Tech model—

conservative and *nonconservative.* The first group are the conservative components of salinity, total nitrogen, and total phosphorous. 'Conservative' refers to the fact that they do not decay in the water over time. The nonconservative components (that is, those which decay due to bacterial decomposition or which are otherwise removed due to chemical reaction and sedimentation) are total and fecal coliforms, nitrogenous and carbonaceous biochemical oxygen demanding materials (or simply *BOD* for short), and dissolved oxygen (or *DO*). Temperature in the water can also be modeled as a decaying substance but is not considered here. The nonconservative substances are assumed to decay at a rate which at any instant is proportional to their concentration at that time.

Let a constituent be measured by concentration c (kg. per cubic meter). Then its total mass in a node of volume V is simply V times c. Since the principle of conservation of mass says that the rate of change of a nondecaying substance c in the bay is zero (total mass is conserved), therefore, if one observes changes in mass from node to node it must be due either to advection or diffusion or decay or to other special sources or sinks. That is

$$\text{Rate of change of c in a node} = \text{Advection} + \text{Diffusion} - \text{Decay} + \text{Other Sources} - \text{Other Sinks} \quad (7.3)$$

Relation 7.3 is called a *mass balance relation* because it says that in order to know the total change of a constituent in a node during an interval of time ΔT one must add up all amounts coming in and subtract all amounts which leave. If these two amounts balance each other then the total mass of the constituent remains unchanged and, conversely, if no change in mass takes place then losses must balance the gains (principle of mass conservation). Of course there are N such relations to satisfy for each constituent if there are N nodes in the bay.

The advection terms in equation 7.3 reflect simply mass transport of the constituent from one node to another during tidal flushing. The concentration in the nodes shown in Figure 7–2 will depend upon volume of water in the tanks (here again a simplified view of the water body as a system of tanks with connecting conduits is adopted). The diffusion terms in equation 7.3 reflect the tendency of the difference in concentrations between the two tanks in Figure 7–9 to equalize. When c_2 is greater than c_1, there is a pollutant dispersion in the direction shown. This is similar to the spread of dye dropped into a bathtub as discussed in Section 7.1. The rate of diffusion is dependent on the level of concentrations between tanks. Where substantial differences in concentration are found, rapid diffusion is present. The overall rate of change of concentration is governed by an empirically determined diffusion constant which is labeled k_D. This constant is discussed further below.

For a nonconservative substance the decay rate is proportional to the quantity of the substance which may be present.[7] When the decay is zero it signals that the substance is conservative.

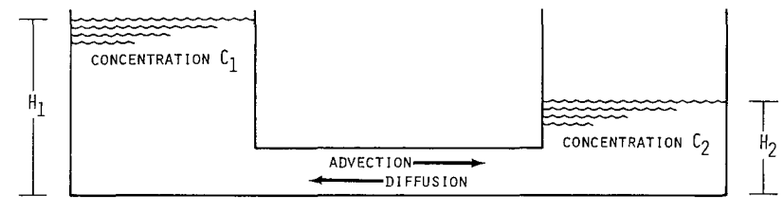


FIGURE 7–9 *Suppose C_2 is Greater Than C_1, but H_1 is Greater Than H_2. Then Advective and Diffusive Flows Are in the Directions Shown.*

Sources include waste discharge outfalls, storm runoff, groundwater inflow, rainfall, etc. Sinks refer to losses such as benthic uptake, water pumping, and so forth. Although it is not explicitly shown here equation 7.3 can be further extended to include other terms of constituent loss or accretion when these are applicable. In particular the equation for dissolved oxygen would include first order relations for *re-aeration* and *photosynthesis* (positive accretion terms) and for *respiration* (negative loss terms).[8] Both photosynthesis and respiration depend on the concentration of algae. One can also add terms for loss of constituent if there is benthic uptake since this acts as a sink.

It is important to note that since constituents such as nitrogen and phosphorous are nutrients for the various microorganisms and other marine life (especially phytoplankton) which inhabit the bay, one could usefully include in the balance equation an accounting of how nutrients are used up and later returned to the estuary by this marine life. In the process oxygen levels will vary considerably over a diurnal cycle (that is, over a 24 hour period) since photosynthesis depends on the amount of sunlight which penetrates the water body. The phytoplankton are prey for the various zooplankton and the populations of both fluctuate over time. Therefore the terms used above in which photosynthesis and algal concentrations are assumed constant must be considered as rough approximations. Benthic uptake is also assumed constant. *Benthic* uptake represents chemical and biological oxygen losses to the bay bottom. An extension of the water quality model to include these additional marine interactions constitutes what is known as an ecological model. This will be briefly discussed at the end of this chapter.

In order to solve equation 7.3 one must know, in addition to decay constants, diffusion constants, and the like (all empirically determined) the values of the volume of each node and the flows which determine advection. Moreover these must be known for each successive interval of time. But of course the flows and volumes (which are given in terms of head)

are already known from the solution of the hydrodynamic relations. One can therefore appreciate now why the Tetra Tech modeling process is necessarily a two step procedure: water quality mass balance equations require hydrodynamic inputs.

7.2.1.4 Calibration Procedure. When the model is to be calibrated one has available the various constants used in equation 7.3. Perhaps the most significant is that of k_D, the diffusion constant. It is worth taking a closer look at it. Mixing in a bay or estuary is subject to location. At or near the ocean outlet most mixing is due to velocity differences which advect the constituents in the water in varying directions and at varying rates. This induces a kind of turbulence which causes the constituents to disperse. At the same time the back and forth flow caused by tidal oscillations also results in mixing. However as one moves further into the bay these forces tend to lessen especially in estuaries where tidal flow from the ocean interfaces stream flow. At the interface we have a mix of salt and fresh waters and dispersion occurs mainly as a result of the increased salinity gradients, by which is meant that the stratification of the estuary into layers, due to differences in water density, causes mixing to occur between water at different depths. Finally as the fresh water zone is neared all of the above effects abate and non-advective dispersion will be minimal. Although density differences are supposedly ignored in the assumption of vertically mixed water columns, the constant k_D can capture this effect indirectly. Tetra Tech proposes therefore that k_D be computed as

$$k_D = k_{D1} + k_{D2}\,\Delta s$$

where Δs is the salinity differences between two nodes divided by channel length. k_{D1} and k_{D2} are chosen so that where tidally induced and advective mixing predominates k_{D1} is larger than k_{D2} but the contrary be true where salinity effects begin to predominate. This is illustrated in figure 7–10. By suitable adjustment of k_D one may adequately account for the actual dispersive effects in the water body. Again this is a question of judgement and skill on the part of the modeler.

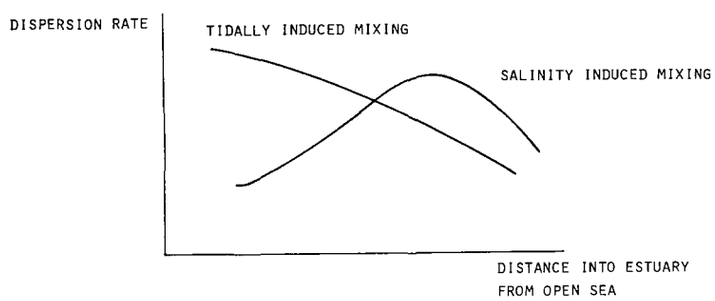


FIGURE 7–10 *Dispersion Rates Versus Distance.*

There is one more observation to make about the solution of the balance equation. It may happen that relations which apply to one constituent require information about another one. In this case one has a coupled system and it matters which set of equations is solved before the others. This is especially true in the case of BOD/DO interactions since the amount of DO depends on the amount of BOD there is. The solution to the equation for DO therefore requires that the solution to that for BOD be obtained first.

7.2.1.5 Dynamic Versus Steady State. The above model formulation can be run in a computer in several different modes, each of which has its own virtues and limitations. These are steady state, quasi-dynamic and dynamic. Tetra Tech refers to these as Aqual and Dyqual. The most complex and detailed is the *dynamic, or time varying, model* in which changes at each node are followed at each time step of duration ΔT over an entire tidal cycle or indeed longer. The time step can be as small as one wishes depending on the level of detail that is desired but of course computational expense usually limits ΔT to be of the order of one or several hours. If no essential changes take place in a bay over repeated tidal cycles then it suffices to run the model for one or two such periods. However the major utility of the model is to account for short term and rapidly changing boundary conditions which may induce variations in water quality over a longer period of time. For example, stormwater inputs or intermittent and unsteady effluent discharges will require source flows and concentrations to be altered over a sequence of time steps at the boundary nodes. The resulting concentrations of the several constituents in the water may fluctuate considerably for a long stretch of time and over a period of several days or weeks may never actually settle down to equilibrium values. In addition the values of temperature (which affects the decay constant k) and photosynthesis and respiration rates (which vary over a diurnal cycle) may also be varied over the time steps allowing for a better accounting of nutrient interactions with marine life. Of course this is still only a proxy for a more comprehensive ecological model but in many cases it may suffice for an adequate prediction of water quality changes.

However dynamic models are expensive to run, as we said, and so one may on occasion more usefully employ a simpler version known as the tidally-averaged, or *quasi-dynamic,* model. This consists of computing average water quality conditions over an entire tidal cycle and then monitoring subsequent changes from cycle to cycle. This approach is especially apt when one wishes to follow changes which may occur in the bay over a long term period, from several weeks to several months. The results of the hydrodynamic model are first calculated as in the dynamic version. Then instead of using the resulting flows and elevations at each time step, the computed values are averaged over all the increments used in the tidal cycle. At the same time any inflows and outflows of constituents, which vary over time are also averaged over each successive cycle, and the concentrations which result from the mass balance equations then represent average water quality conditions over consecutive time periods, where the duration of each

period is a cycle. If one wishes, in fact, the averaging can even be done on a daily basis. Although this would lead to less accurate portrayals it does permit one to more economically track the changes in pollutant levels over longer time horizons. This model is dynamic in the sense that it does allow for gross temporal changes although it does sacrifice the detail of the more truly dynamic version discussed above. An even simpler approach is the *steady state* model. This too is tidally-averaged but it further assumes that no significant changes occur from cycle to cycle. In essence this assumption implies that the bay has come to equilibrium with respect to the pollutants and other constituents which enter the water and that all transient effects due to past disturbances have died out. This kind of situation would prevail in the long run if ideally the initial influences on the bay (in terms of inflow, outflow, algae concentrations and the like) had dissipated and no further changes took place. Obviously this is a considerable simplification but it does allow one to make some rough comparisons between alternative wastewater abatement schemes or to estimate the approximate effect of the water body of different boundary conditions. Of course this approach would be inadmissible if one were to track a series of storm events.

Since time no longer plays a role in steady state modeling both the hydrodynamic and mass balance equations become considerably simpler to handle. This is because the left sides of the equations can now be made to vanish since the rates of change over time must be zero. Needless to say, if the water body is in fact subject only to slow changes in pollutant levels, and if it is relatively undisturbed as in some less populated coastal areas, the steady state modeling may be the appropriate and only sensible tool to use.

One should also note that after a sufficiently long time period has been simulated with dynamic or quasi-dynamic models, all changes that occur in successive time periods may become increasingly negligible. In this case the dynamic models eventually reach a condition of steady state. What the steady state model does is to regard the future as now.

A technical note should be interjected concerning steady state and quasi-dynamic models. Since both are tidally averaged, the dispersion of pollutants due to advective forces is less significant than in the dynamic model since only average values are used and the larger velocity changes at extremes of the tidal cycle remain underrepresented. In order to compensate for this, it is expedient to increase the value of the dispersion coefficient k_D in order to better approximate the actual mixing which occurs in a cycle. This procedure is followed by Tetra Tech.

One can summarize the discussion of the Tetra Tech modeling effort by noting that the water quality component is a set of equations which are simply adjoined to the equations for hydrodynamics. The latter describe how water flows into and out of the bay while the water quality model tells how something which is injected into that water will disperse because of the back and forth motion. The relation between the two is graphically illustrated by Figure 7–11 which is adopted from the Tetra Tech user's guide.

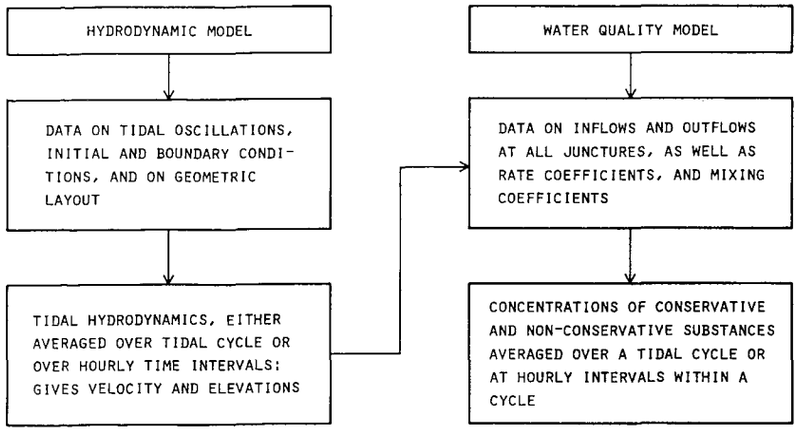


FIGURE 7–11 *Tetra Tech Modeling Efforts.*

7.2.2 Limitations and Uses of Estuary Model

The discussion has attempted to underscore the most significant assumptions made in model development. Each such assumption is a shortcut to reality, and it reflects an implicit belief that in spite of such simplifications all essential relationships which occur in nature will be preserved by the model. Depending on the context this may or may not be true. Credibility in a model rests on the extent to which the user is willing to accept such assumptions as plausible and the extent to which model calibration and verification demonstrates the ability of the model to portray actual conditions in the water body considered.

Some of the simplifications made are explicitly stated by modelers, but often there are others which appear only implicitly. For example, although complete vertical mixing is clearly part of model formulation for surface water quality, much less explicit is the fact that the equation ignores the effect of velocity differences over the length of the channel. Fortunately, this is not a very significant omission.

Many assumptions have been made beginning with the choice of a particular geometric configuration for the grid layout, the size of nodes, the choice of time step, the use of first order reaction terms for decay and photosynthesis of material (among others), the setting of dispersion k_D as a linear function of salinity differences and so on. Also, although some of the parameters used as constants in the models are better known than others, all are but approximations to actual values which may vary both spatially and over time. Similarly, boundary conditions on distributive inflow sources, dis-

charge rates of treatment plants, and tidal depths at the sea are only known approximately. Therefore the models cannot be expected to reproduce exactly the behavior of the water body. However, experience with the models has demonstrated that they can be usefully employed to obtain acceptable measures of actual water quality conditions and, therefore, to predict future conditions under a variety of changes.

Calibration and of course the eventual verification of a model does depend on having available a data source on actual water quality and hydrodynamic conditions over time at a variety of sampling stations. These are used to adjust or "tune" the model and then to compare model outputs to actuality. Such data is, however, hard to come by and is sometimes incomplete or of poor quality. For this reason adequate validation remains a difficult and time consuming task, although in the 208 project this does not appear to be a serious problem.

It may be argued that by increasing model detail, accuracy and confidence can both be improved. The most cogent reason for limiting such detail is however to achieve a level of complexity which is compatible with the available computational capabilities. Also, complexity for its own sake is illusory since the information needed to closely model certain interactions is often not known well enough. In the Long Island 208 the Tetra Tech modelers have avoided this pitfall.

In the context of the 208 project the Tetra Tech models are used to provide information on water quality as part of the general assessment of environmental conditions and structural alternatives. They play a crucial role in quantifying the impact of sewage and runoff on the coastal water. What is more, the models can compare alternative tactics for abating this impact through sewage treatment, recharge, and shifts in land use.

The basic input to the models is information generally provided on discharges into the rivers and bays in terms of flows from various sources (streams, point discharges, runoff, and so on) and in terms of the pollutant loads carried by these flows. As the reader now appreciates, this information constitutes much of the boundary data for the models.

The models can be run in three modes, as discussed earlier. The dynamic, or time varying mode, is especially useful in studying the short term transient effects of storm runoff and in computing the diurnal variations in dissolved oxygen which result from changes in algal activity. The information is provided over small time steps but this of course precludes model runs which exceed more than a few tidal cycles. For longer stretches of time, a more flexible mode is quasi-dynamic or tidally-averaged dynamic. Here one can follow slow changes in pollutant levels as boundary conditions gradually change over a period of weeks and months. Changes which occur over a tidal cycle are averaged out so that the fine detail of a more fully dynamic model is now lost. Finally, in the event that discharges to the water body are reasonably constant over a long period, or when one can assume that the water body has come to equilibrium with respect to the flows and loads which enter it, a steady state model is more appropriate. Here not only is information averaged over a tidal cycle, but it also no longer varies from cycle to cycle. Tetra Tech has found all the above modes useful in its work with some modes being more appropriate than others in certain bays. In all bays, however, steady state runs were provided in addition to some dynamic runs in select areas.

The actual use of a model depends not only on the time scale and level of detail required but also on whether it is to be used as a descriptive or predictive tool. As a descriptive tool, one uses the model to explain existing conditions in the water bodies. For example, to understand the extent to which tidal fluxes will account for larger concentrations of some constituent in one part of a bay over another. This kind of information is generally part of the process of model verification. Another use is as a predictive tool. Here one wishes to know what future changes will occur in the water body as a result of present conditions. For instance, what are the nitrogen concentrations in a bay tomorrow as a result of a storm surge today? Here one predicts future changes in a way that clearly is impossible by observation of the bay itself until after the storm surge has occurred. The value of a well designed model as an oracle largely accounts for the fascination such quantitative tools possess. Finally, the models can be used for purposes of optimization. Not only do we wish to predict future conditions but one would like to shape that future by manipulating the present. Thus, for example, by varying the outfall location, size, and level of treatment of a plant, one gets different eventual concentrations of BOD in portions of the bay. Of these many options on the treatment plant, one of them will clearly result in a lowest BOD level at some future time. If one disregards cost and other factors which may actually inhibit the selection of this option, one now has an optimal way of influencing the future of the bay. In the 208 study all the above model uses are present but in terms of developing a final waste management plan it is the predictive and optimization modes which will dominate as a tool.

7.2.3 River Models

Tetra Tech has developed appropriate hydrodynamic and water quality models for the Carlls and Peconic Rivers. This section is much shorter than preceding ones since the essential ideas are really special cases of what has gone before, and the equations used are very much simpler.

Once again one employs a node/channel schematization with the same assumption of complete vertical mixing. However, now each node is linked to only two adjacent nodes (as shown in Figure 7—12) in a simple linkage which follows the course of the river. Each channel links only two nodes which are labeled $j = 1, \ldots, N$ starting at the river source. The channels are similarly labeled. The model structure will allow two upstream channels to converge at one node. Likewise the downstream flow from one node can diverge into two channels. These features will allow one to model river tributaries, rivers with branching structures, and two flow channel systems.

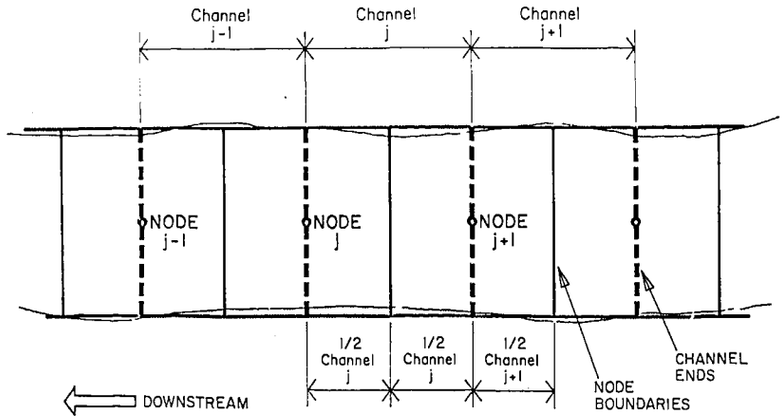


FIGURE 7–12 *Model Representation of a River.*

All flow is now unidirectional beginning at the river source and moving to the mouth. No tidal motion is involved. This means that elevation differences play a different role than before in that flow into node j + 1 is simply the flow out of node j plus inflows from tributaries which empty into the river at that node, as well as plant discharges and groundwater inflows along the river's boundary (Figure 7–13). Hence, if these boundary inflows are known, the total flow out of the node is determined from flow into the node. If we carry this argument back to the source, one need only know the upstream flow at the first node, plus boundary inflows, in order to determine the rest.

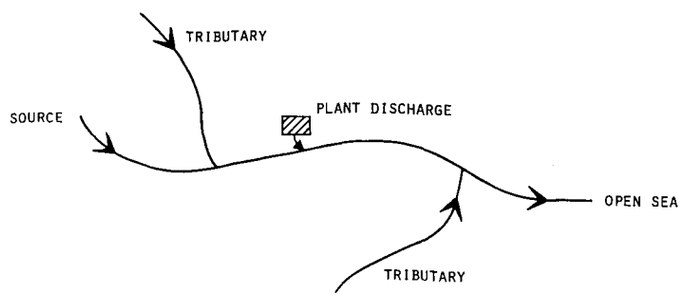


FIGURE 7–13 *Schematic of a River.*

Once flows are known at each node, one refers to empirically determined *stage-flow relationships* (that is, observed values of river depth at different river locations for varying flow rates) to obtain estimates of river depth in a channel. The depth in the node is the average of the channel depths at each end of the node. River width is determined from the channel cross section. Width of a river node is the average of the channel widths. The channel cross sectional area is calculated as a trapezoid. The velocity u in a channel is then simply flow divided by area A_c, as in the previously discussed estuary model.

The channel/node scheme should roughly correspond to changes along the river. Each stretch of river from one tributary juncture to the next should certainly include at least one node. Also, major changes in the river's configuration (such as bends) may suggest additional node detail.

Using this hydrodynamic information, the water quality component of the model computes concentrations of various constituents exactly as before except that now the question of dispersion by diffusion is far less significant than the result of the advective unidirectional flow. Of course, decay of nonconservative substances, benthic uptake and the like, all have their effect and are taken into account in balance equations which resemble those of the estuary models. It is not necessary to repeat this description here because it is but a slight variant of the previously derived equations. It does appear, however, that Tetra Tech does incorporate the effect of heat losses and gains in the river across the air/water interface in a more pronounced way than in the bay models. Temperature, together with re-aeration, photosynthesis and respiration of algae, and BOD loading, are all factors which contribute to the dissolved oxygen deficit of the river. Each of the balance computations involve the volume of a node, but these are easily computed from the depth, width, and channel length.

If inflows and outflows along the river vary with time then the hydrodynamic computations would be carried out over a set of successive time increments of duration appropriate to the rate at which significant changes occur (hourly, daily, or even longer time spans). When all flows and loads are constant over time and when there is no change in constituent concentrations, one obtains the steady state modeling situation referred to in the discussion of surface models. However, in the event that one wishes to track variations over a diurnal cycle, it is possible to do so by choosing suitable small time steps in the water quality mass balance equations. This is referred to as the dynamic water quality model by Tetra Tech.

7.2.4 Phytoplankton Model

Some consideration is being given to an ecological assessment of how structural and nonstructural abatement alternatives impact on the bays. This work essentially extends the water quality considerations which were treated earlier. In the estuary model it was noted that dissolved oxygen is dependent

on concentrations of algae in the water, since these microorganisms both produce and utilize oxygen through the process of photosynthesis and respiration. This concentration is assumed to be a known quantity which is given as one of the model inputs. What this explicitly ignores, however, is that the algae concentration is itself dependent on other factors which include not only the level of nutrients in the water, such as the various nitrogen and phosphorous compounds which form part of the waste loads discharged into the bays, but also on the level of oxygen itself. In effect, one has a coupled system of mutually interacting influences which are accounted for in the Tetra Tech models only in an implicit way.

An *ecological model* attempts to capture some of the interactions which take place over time between nutrients and organisms in the water in order to give a better grasp of the diurnal fluctuations which do occur, and in order to predict the conditions which can lead to *eutrophication.* The process of eutrophication is characterized by an excessive growth of algae ("blooms"), an accumulation of organic debris, as well as low oxygen levels.

The model uses a set of mathematical relations which describe how *phytoplankton* (a class of microorganisms which include algae) are consumed by herbivorous animals (the *zooplankton*) and how the detritus of dead matter and excreta is recycled through bacterial decomposition to provide a new supply of nutrients for the phytoplankton. These relations are conceptually similar to the ones used in the water quality model in that each of them give the rate of change of one constituent over a time interval ΔT in terms of the values of other constituents. For example, the rate of growth of zooplankton is proportional to the population level of phytoplankton, with a growth rate which measures the efficiency of feeding (zooplankton graze more than they actually consume). In this way one in effect writes down a set of equations which simply extends and complements the ones given in the earlier model. Figure 7–14 below displays a schematic of the various interrelations which are dealt with in an ecological model. Note that oxygen is used in the process of bacterial decay of waste loads generated either by man induced wastes or through the natural processes of organic decay in the waters. The nutrients on which the phytoplankton feed are provided either through these same man-induced loads which enter the bays as sewage and runoff or through the natural recycling process which transforms decomposed material into a new supply of nutrients. Therefore, one deals here with a nearly closed system except for such external factors as waste discharges or temperature and sunlight (each of the last two affect both the rates of photosynthesis which generates oxygen) and of respiration (which absorbs oxygen). Incidentally, large temperature increases can also occur from man-made heat discharged from power plants.

The complete loop is generally self limiting in the sense that under "normal" conditions all interactions balance each other and therefore no single constituent can grow in an unlimited fashion. An unbalanced situation, triggered perhaps by a large input of organic wastes during a storm surge, can

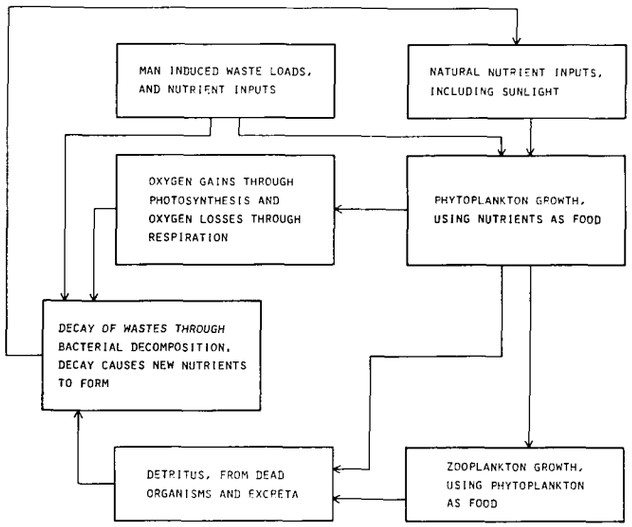


FIGURE 7–14 *The Ecological Cycle in Estuaries.*

cause excessive algae growth, and a mathematical model allows one to roughly predict what the extreme conditions must be to cause such behavior. In this way another tool is added to the arsenal which is available to manage water quality in surface waters. One should caution that, as with all modeling, it is clearly impossible to capture all of the interactions which actually take place and that the equations can at best approximate reality. Moreover, many of the parameters of the model (such as grazing rates, growth rates as a function of sunlight penetrations, and so on) are imperfectly known. Nonetheless, with proper interpretation of the results useful insights can be obtained. The environmental consultant intends to utilize these ideas as part of the overall environmental assessment in combination with other techniques and approaches. The model, in fact, is essentially a modification of the classical mathematical relations which describe interactions between predator and prey. In this case the predators are zooplankton, and prey are phytoplankton which feed on a nutrient source. In the absence of predators the growth of the prey is limited by the population carrying capacity, denoted by a value k_A, which varies with the level of nutrients in the water. The predators grow at a rate which is proportional to AB, where A is the concentration of prey and B is the concentration of the predators themselves. (The units of A, B are biomass per unit volume). However, these organisms also have a carrying capacity which limits their productivity and in the model an additional curtailment on growth is imposed which is based on the idea that predators reach a level of satiation in their feeding. The various feeding rates and the satiation constants are determined empirically.

7.3 GROUNDWATER MODELING

7.3.1 Introduction

The groundwater modeling studies carried out for the 208 project by Princeton University and the United State Geologic Survey are oriented toward an understanding of groundwater flows and pollutant dispersion in the aquifers which underlie Long Island, as shown in Figure 7–15. Model development is similar to that described in Section 7.2 for surface waters but with two important distinctions. The geometry and physical characteristics of the soils which constitute the aquifers act to impede and redirect the fluid flow. Consequently, it becomes necessary to accurately represent the interaction between the water and the medium through which it flows. In addition, whereas vertical mixing in surface waters permits reduction to planar flow, here three-dimensional water movement is considered. In reality, the vertical flows are considerably smaller than horizontal and a simplified picture may be constructed in which an aquifer is represented as a series of horizontal planes, or layers, which are then linked together in the vertical direction. As in the case of surface waters, the hydrodynamics of water flow is first modeled and pollutant dispersion, or water quality modeling, is then based upon the hydrodynamic solution. The general character of both hydrodynamics and pollutant dispersion follows the discussion in chapter 1 of this report, though the analogy of the use of tanks interconnected by pipes is replaced with a more specific description of how the groundwater system is represented for model development.

In this description of groundwater flow, it is assumed that the aquifer, or medium, is saturated with water. The medium gives rise to several important features of fluid flow not present in the earlier discussion of surface waters.

Since the material of the medium takes up some of the space in a given total volume, the remaining open pores available for the storage of water are characterized by a porosity ϵ. In addition, empirical studies show that water flows through the medium as if it were moving through long capillary tubes. This creates a condition in which the medium is partially restrictive of the water flow, and this is described by permeability k. Within the thin capillaries, viscosity μ of the fluid establishes resistive forces which dominate the flow. The porous structure of aquifers is also highly *anisotropic*. That is, under specified pressure differences the velocity of groundwater flow will vary widely with direction, often by more than an order of magnitude. Flow velocities are greatest along more or less horizontal planes in the aquifers and least in the vertical direction. Finally, these primary physical parameters which govern groundwater hydrodynamics—porosity, permeability, viscosity, anisotropy--are all dependent upon the specific aquifer (since these have different soil types) and upon spatial distribution within an aquifer both horizontally and vertically. Consequently, while the model equations will have the same form from place to place within an aquifer, the values of the governing parameters will need to be specified in great detail.

Two fundamental relationships are required to describe groundwater flow which are analogous to the hydrodynamic equations for surface waters. First, the velocity of flow is driven by differences in pressure, or head, from one point to another in the aquifers. Second, hydrostatic head changes with time as the flow velocity transports fluid from one place to another in the aquifers.

Therefore, two equations are required to determine the two variables of head (pressure) and velocity. The basic form of the equations was discussed in Section 7.1 and, here, they are made specific to groundwaters.

For convenience in model formulation and computation, consider an aquifer divided into layers of square nodes of finite volume interconnected by channels. For the present, the vertical coupling between layers is ignored, to be added as a source term later. In the simplified illustration of nodes coupled together in Figure 7–16, a change in head (water elevation or pressure) at node 1 results from the net flow of fluid into the node. Since the node surface area A_S remains constant, the volume change is due to change in head. Compared to surface waters, the porosity ϵ (which is less than or equal to one) implies larger head changes for the same net inflow into the node. In addition to flow of water from one node to another due to differences in head, there may be various natural and/or man-made mechanisms for flow into or out of the node. Consider for example the aquifer layer which represents the water table, or top of the groundwater system. This layer is subject to distributed recharge from natural sources as well as direct wastewater recharge at specific locations. Recharge flow Q^{in} (cubic meters per second) at each node must be specified and these contribute to increasing head. Similarly, there are natural and induced sinks or losses. Wells utilized for public water supply and other withdrawal purposes act to decrease head at each node they impact. In addition, there are groundwater seepages and discharge to streams and underflow to bays. The pumping wells and natural discharges are introduced at each node by terms Q^{out} (cubic meters per second).[9] Finally, there is the coupling from one layer in the model to another. Since such flows are driven by vertical pressure differences in the aquifers, they are characterized by terms analogous to the horizontal velocity. It should be emphasized that such terms reflect the anisotropic flow and the vertical velocity will tend to be small in relation to the horizontal flow velocity. It proves convenient to define a *specific storage* S as $\epsilon A_S/A_C L$, where L is the channel length between nodes, which is roughly the node horizontal surface area divided by node volume. Specific storage S is therefore approximately the height of the aquifer layer.[10] The change in velocity with time is limited by hydraulic conductivity K, a team which combines fluid viscosity with the permeability of the medium. This constant reflects the role of viscous forces upon fluid flow in porous soils.

This discussion of groundwater equations may be summarized by noting that the starting point for both Princeton and USGS models is in the

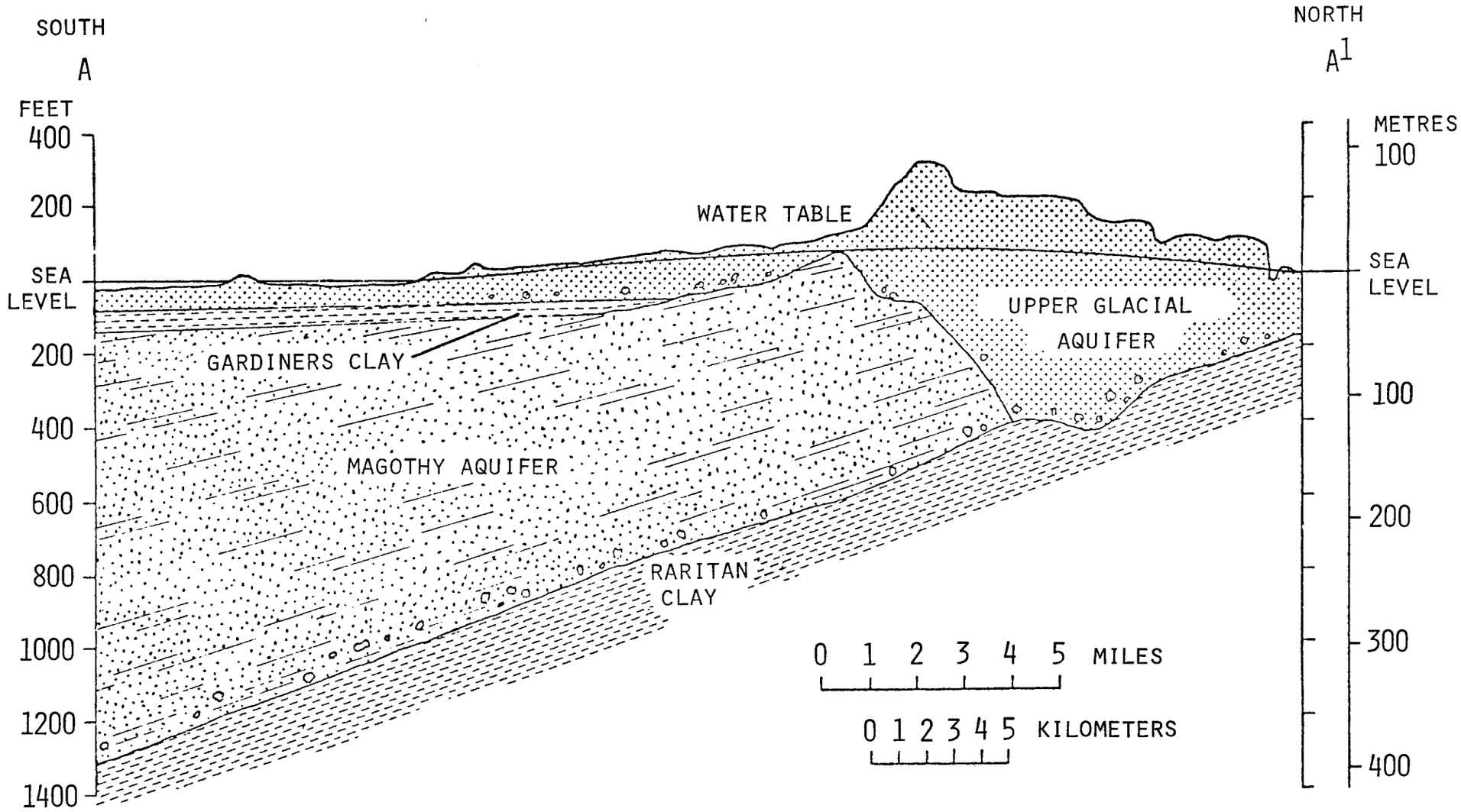


FIGURE 7–15 *Crossection of Long Island Groundwaters.*

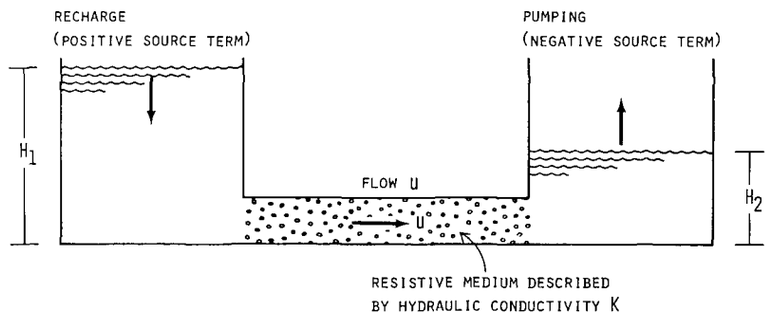


FIGURE 7–16 *Simple Schematic to Illustrate Flow in a Porous Medium.*

hydrodynamic equations of motion for head and velocity. There are then two basic choices in an approach to construction of a model of groundwater movement. One can adopt a strategy of taking the basic hydrodynamic equations and develop a direct computer solution. Such computer solutions have the advantage that information in the model may be adapted from one area to another so that the model is relatively transferable. This is how the Princeton group approached it. An alternative is to build some type of physical structure which behaves in the same way as the groundwater system. This is the approach taken by the USGS. It should also be emphasized that a computer oriented approach facilitates the inclusion of pollutant dispersion, which will be discussed in connection with the Princeton University modeling effort, whereas analog models generally do not.

Before we proceed to detailed discussion of the Pinder finite element method and USGS analog model structures, it will be helpful to get some idea of the magnitude and relation between head H and velocity u and the parameters of specific storage S and hydraulic conductivity K. It can be shown that the solution to the velocity equation has the form shown in Figure 7–17. In physical terms, the velocity responds to a pressure difference by increasing to a maximum steady state velocity u_o which is known as the *Darcy Velocity* (first measured in experiments by Darcy in the late 1800's).[11] Using hydraulic conductivity typical of Long Island Upper aquifers, and a hydrostatic head difference of 2 meters between nodes of spacing about 2000 meters apart (as in the USGS model), the steady state velocity u_o is about .01 meters per day and flow rate is therefore quite small. Note that the time t_o required for velocity to respond to pressure difference is about K/g from Figure 7–17. Using the hydraulic conductivity above and gravitational acceleration 9.8 m/sec$_2$, the equilibrium time becomes 9 microseconds. As we see below, this represents very rapid achievement of the steady state Darcy velocity compared to the time over which hydrostatic head differences are compensated.

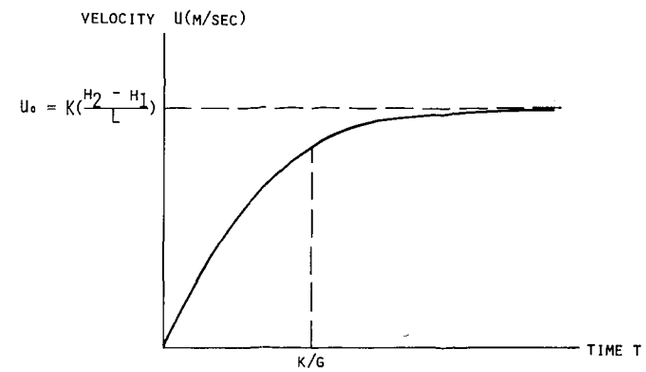


FIGURE 7–17 *The Darcy Velocity in a Porous Medium.*

Using the steady state velocity, the equation for hydrostatic head has a solution shown in Figure 7–18. The heads approach a steady state condition $H_2 = H_1$ in which there is no pressure difference and consequently no remaining flow. As noted earlier, the specific storage is approximately an aquifer thickness of about 50 meters. Then using hydraulic conductivity (10m/day) and node spacing (2000 m) from above, the time required for the pressure to go to equilibrium in Figure 7–18 is about 30 years. Hydrostatic head equilibrium is achieved slowly because viscous flow in the porous medium limits hydraulic conductivity, and hence limits velocity to .01 m/day. This brief description of the general character of groundwater flows is sufficient to proceed to specific model formulations.

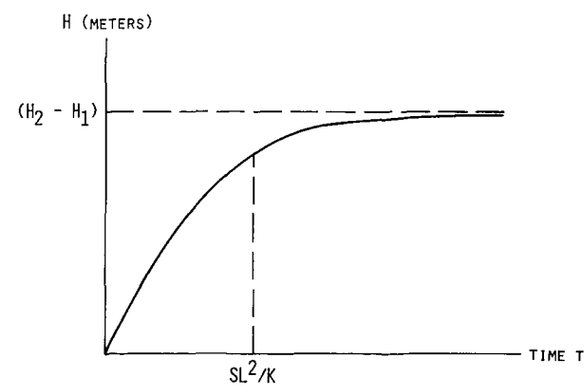


FIGURE 7–18 *Head Change in a Porous Medium.*

7.3.2 Analog Model

The USGS model of Long Island groundwater is formulated by using an analogy between the hydrodynamic equations for steady flow and the voltage-current relationships in electrical circuits. In Figure 7–19, it is seen that water flow into a node, or tank, in the groundwater system leads to an increase in head. Analagously the flow of current into a capacitor leads to increase in voltage across a capacitor. Indeed, the two equations for these physical phenomena have exactly the same form. Consequently, to construct a physical representation of the groundwater system requires that a capacitor be chosen of the right size to represent storage at each node of the model. It might be noted that capacitors are devices which are each about the size of a U.S. twenty-five cent coin. Continuing with the development of the analogy, Figure 7–20 shows that the flow of water from one point to another in the groundwater system is driven by a difference in head. Analagously, the current through a resistor is driven by the difference in voltage between the two ends of the resistor. Consequently, for each channel which connects nodes together, one resistor which is a device about the size of a small piece of chalk is introduced. Overall, the model may be constructed as a set of capacitors which represent specific storage within each node and a set of resistors which represent hydraulic conductivity associated with a flow between the nodes, as shown in Figure 7–21.[12]

The model includes a description of recharge and discharge at each node in the system. Recharge to the aquifers is represented by current generators which pump current directly into the capacitor which represents a node, much as is shown in Figure 7–19. Similarly, discharge or seepage to streams and bay waters, pumping and other sources of loss from a node, are presented by a current drain away from the node.

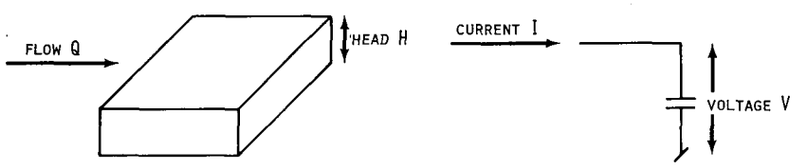


FIGURE 7–19 *Analogy Between Water Flow and Electrical Current in USGS Model.*

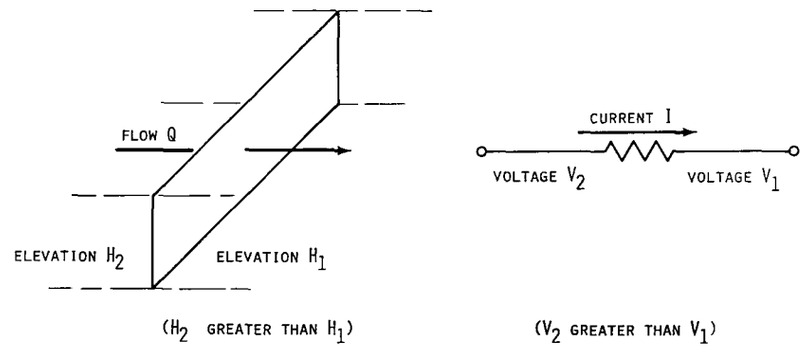


FIGURE 7–20 *Analogy Between Water Flow and Electrical Current in USGS Model.*

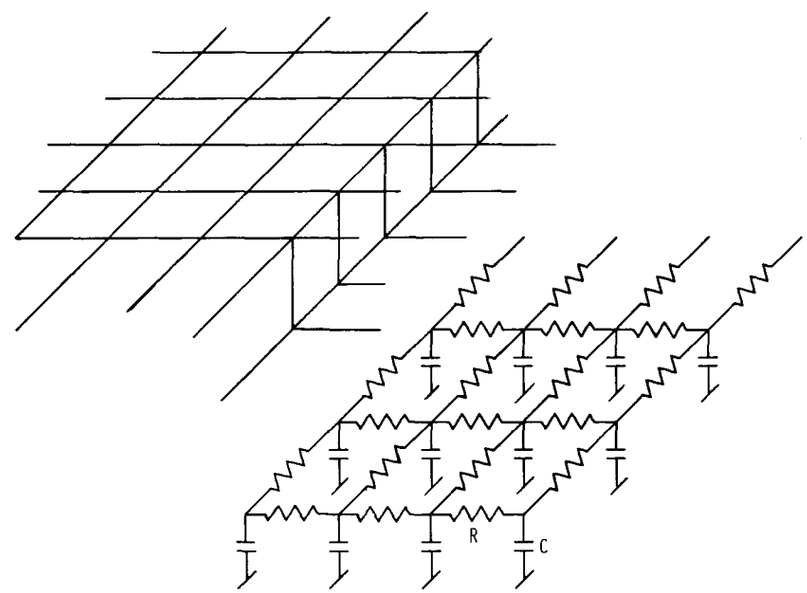
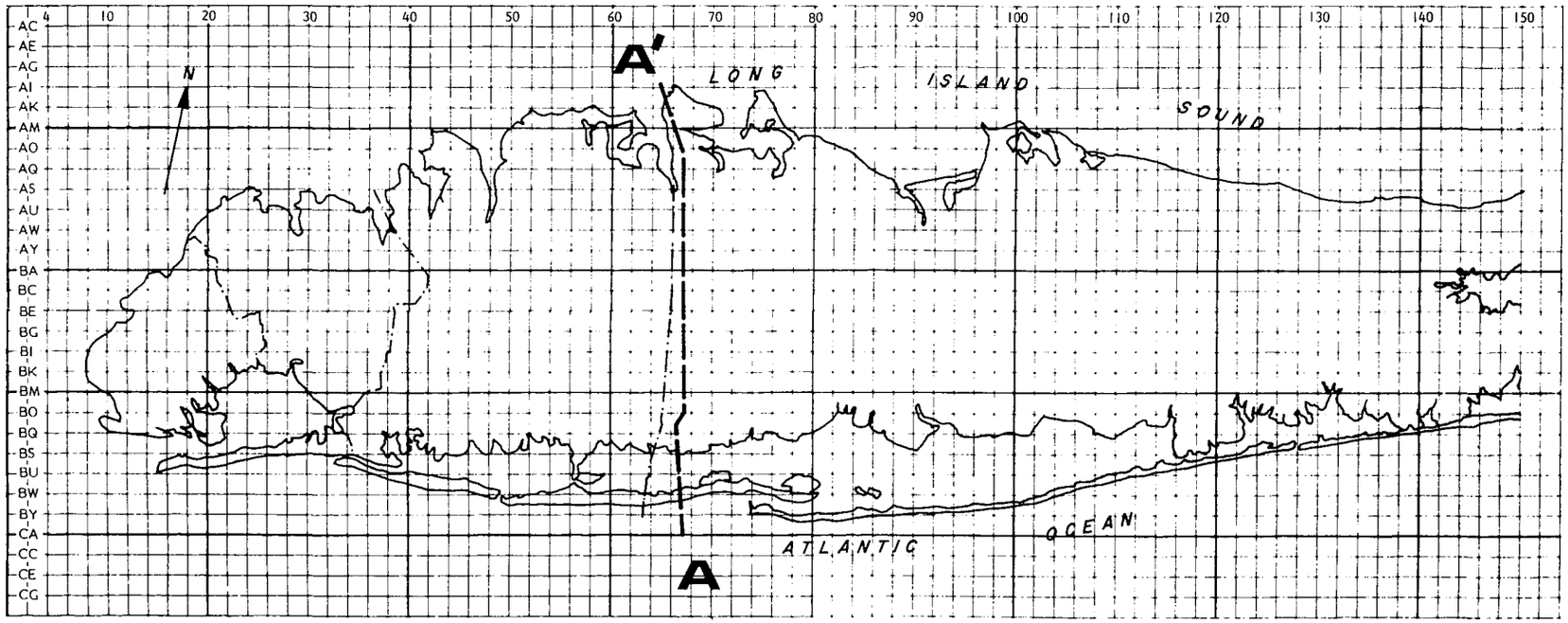


FIGURE 7–21 *Analogy Between Water Flow and Electrical Current in USGS Model.*

The USGS analog model represents the upper glacial, Jameco and Magothy aquifers in a five layer structure. As seen in Figure 7–22, the grid system specifying the nodes extends into the New York City portions of the Long Island groundwater system. Groundwater conditions in the North Fork and South Fork are not included in the model. The horizontal node spacing is 1829 m, while the vertical depth of nodes ranges from zero to about 120 m. The five layer structure is required to accurately represent vertical change in hydraulic conductivity K and specific storage S which are the governing parameters in the hydrodynamic equations. More importantly, these two parameters vary widely in the horizontal plane. Therefore, it is necessary to specify K and S for each grid element in Figure 7–22 and to calculate a value for the resistor R and capacitor C which represent these parameters in the analog model. In practice, the specific storage is poorly known but appears relatively constant over reasonable areas, and this simplifies determination of capacitors. Conversely, hydraulic conductivity varies widely.

There are some 2000 horizontal grid elements in Figure 7–22 which are represented in the model, and there are five such layers. Consequently, there are about 10,000 nodes or capacitors. At each node, there may be a connection to as many as six other nodes using resistors. In addition, recharge, pumping wells, discharge to streams, and the like are all entered at specific nodes primarily in the upper layers, from which we see that the construction of a physical analog model can be quite laborious.

Given the types of data available on specific storage and hydraulic conductivity throughout the aquifers, the USGS model makes several plausible assumptions. Specific storage is taken as constant within a particular model layer; capacitors are uniform. The primary variation in hydraulic conductivity is its anisotropy. They assume a roughly 10:1 ratio between horizontal and vertical conductivity. Therefore, at each point in the system an average horizontal conductivity is established from field data and the vertical values are then scaled accordingly.



BASE FROM U.S. GEOLOGICAL SURVEY, 1:250,000 SERIES: HARTFORD, 1962; NEW YORK, 1957; NEWARK, 1947

5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

FIGURE 7–22 *Grid Layout For USGS Model.*

The effects of recharge and discharge are thought of as "stresses" upon the groundwater system. The model is assumed calibrated and verified if it replicates past variations in head when the historical pattern of stresses is used to drive the model. Where discrepancies arise between predicted and observed head, the vertical hydraulic conductivity is a primary calibration parameter because it is the least certain of the data inputs (remember this requires physical change in the values of resistors). Following such calibration, the model is assumed valid for future prediction of response to new stresses upon the system.

7.3.3 Finite Element Model

The Princeton University group (Pinder for hydrology models, Cleary for the groundwater quality model) has prepared groundwater models which have been utilized in hydrology studies on the South Fork and main portions of the Island and in examination of water quality surrounding the Babylon landfill site. It should be noted immediately that the hydrodynamic equations for the USGS analog model and the Pinder computer-based models are the same; only the solution technique differs.[13] However, within the analog model it is virtually impossible to introduce pollutant dispersion, whereas the computer formulation lends itself to an extension into groundwater quality modeling.

The use of the hydrodynamic models, and pollutant dispersion models within the overall framework of the 208 project will be quite different. For area-wide studies of the impact of pumping and recharge upon water table, the USGS analog and Pinder computer-based models provide comparable information. On the other hand, it was noted earlier that groundwater flows are quite slow and it requires decades for water to move over distances of a mile or so. As a result, the dispersion of pollutants within the groundwater system is quite localized. The Cleary groundwater quality model best serves to define the details of contamination around localized sources, such as the Babylon landfill.

The Princeton University group has prepared four specific models for analysis of groundwater conditions on Long Island, as noted in Table 7–1. The two South Fork models are of course specific to this particular area of the Island where water availability and quality have become major concerns. The regional South Fork model describes head, or water table, throughout the area and includes explicit representation of the saltwater-freshwater interface as it shifts due to withdrawals for water supply and irrigation needs. The local well South Fork model specifically considers saltwater intrusion into a major pumping well where the regional model results indicate that such problems might arise. The Long Island groundwater model is identical to the USGS analog model (with the exception of mathematical solution technique as noted earlier). Both models essentially describe change in head or water table for various stresses such as pumping, recharge, changing stream flow, and the like upon the groundwater system. Because these Long Island models

Table 7–1

Computer Based Groundwater Models

Title	Purpose
South Fork-Regional (Pinder)	Spatial distribution of height of water table. Movement of saltwater-freshwater interface.
South Fork-Local Well (Pinder)	Saltwater intrusion into a pumping well.
Long Island-Regional (Pinder)	Spatial distribution of height of water table (equivalent to USGS but different mathematical formulation).
Groundwater Quality (Cleary)	Contaminant plume (pollutant concentration from a landfill or other source).

are designed for large-scale analyses, they do not include any detailed characterization of saltwater/freshwater interface for the main island and, as a result, are not appropriate for saltwater intrusion studies. Finally, the Cleary groundwater model is a very localized hydrodynamic model somewhat similar to the South Fork local well model, augmented by pollutant dispersion which will be described briefly below. Cleary takes an approach which involves direct solution of the coupled hydrodynamic-pollutant concentration equations so that certain non-linear interactions between groundwater flow velocities and contaminant diffusion are fully represented in the model and permits study of a very wide range of contamination problems.

In the description of pollutant dispersion, there is one important distinction between the surface water system and groundwater. Nonconservation pollutants are those which tend to decay or change over time. This includes, for example, fecal coliforms, biological oxygen demanding substances (BOD), and the like. Such contaminants have rates of decay which are typically hours or days. In consideration of tidal flows, the movement of water takes place over periods of hours as does pollutant decay, and it is important to track both the movement and the decay of such pollutants. However, in the groundwater system, the residence time before there is any substantial movement of water is decades. Consequently, nonconservative pollutants introduced into the groundwater system undergo effective decay at the point of entry, and they will not be found at any substantial distance from the source. As a result, the pollutant dispersion mechanism need be considered only for conservative pollutants. With this distinction, the description of pollutant dispersion is otherwise quite similar to that in surface waters.[14]

The general character of pollutant dispersion in the groundwater system is shown in Figure 7–23. The change in concentration of a contaminant introduced into the groundwater at, say, a recharge well, occurs because of two general forces. First, advection describes the overall flow of water from one point to another in the aquifers. If the motion were entirely uniform, a "slug" of contaminant would remain intact. In reality, we have noted earlier that flow is anisotropic. The small downward components of flow lead to some vertical spreading of the pollutant and, hence, reduction in level of concentration. Superimposed upon this advection is diffusion, the tendency of any concentrated pollutant to spread out and fill the entire volume in which it is situated, as illustrated in Figure 7–23. In the absence of any groundwater flow (no advection) diffusion itself will lead to lower concentration of pollutant. For example, a drop of dye placed in a bathtub gradually diffuses to fill the entire tub with a low uniform level of dye, as pointed out earlier. As noted in Figure 7–23, the superposition of advection and diffusion leads to development of a containment *plume* in the aquifer. Such a plume extends several miles south of the Babylon landfill site on Long Island. Remember that groundwater flow is quite slow and that it takes decades for such plumes to form.

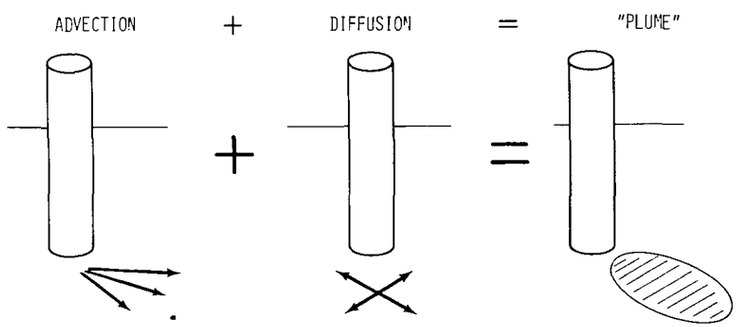


FIGURE 7–23 *Physical Analog of the Formation of "Plumes."*

7.3.4 Uses and Limitations of the Groundwater Models

Five distinct models have been described: USGS and the four Princeton ones. Each of these has been utilized in the study of selected problems. Some have been mentioned earlier and need only brief mention here. In some ways, the models have much in common. They are all dynamic models and depend upon the same basic aquifer parameters. They tend to differ in their detailed descriptions of specific phenomena such as saltwater intrusion which are primarily localized phenomena.

All of the models assume that an adequate data base exists for specific storage (porosity of the soils in the aquifer) and hydraulic conductivity (permeability of the soil in conjunction with viscosity) which govern the hydrodynamics. However, these parameters vary widely depending upon spatial location in the Long Island region and upon depth and type of aquifer. These may be adjusted during calibration to achieve an adequate match between head predicted by the model and actual field data, but other factors such as stream flows might also be factors. Thus, one cannot always be certain that the right parameters have been set during calibration. Once again this largely depends on the experience of the modeler and in the Long Island 208 this is not a real concern.

The USGS analog model and Princeton Long Island models serve the same purpose. They each compute the height of the water table or head at roughly 1 mile spatial increments everywhere between the New York City line and Riverhead in the Bi-County region. In addition to specific storage and hydraulic conductivity parameters, the models require groundwater seepage to streams, natural recharge and other stresses including pumping well locations and volumes, injection wells for recharge and the like. The information needs for such regional models, involving up to 10,000 nodes, are extensive. Fortunately, such a set of data has been prepared for the Long Island region. The models may be run in a dynamic mode using time steps of a year since decades are required for large differences in head to appear. The analog model requires considerable effort to establish electrical circuit arrangements for stresses and/or physical parameters and this places some limits on its ability to compute a wide range of alternatives for wastewater management. The Princeton model provides a computational advantage over the analog model simply because it is computer based. In the Princeton version it is easier to change the values used in the model and even the geometry of the grid system itself. The model is therefore more flexible in that the time required for modifications is short. This means that it is more readily transferable from one place to another since it does not entail the re-wiring of a physical analog.

The South Fork model is a parallel to the Long Island hydrology models. Because of the geology of the South Fork and the potential of saltwater intrusion problems, the model is structured as a two-layer aquifer system (rather than five for the Island) and includes a detailed description of the saltwater-freshwater interface. It is utilized to assess overall impacts of pumping in much the same way as the models above and is subject to the same limitations. Again, the model provides a dynamic history and/or future of head changes and how the saltwater/freshwater interface shifts in response to pumping stresses.

The Local Well model is essentially a small piece of the regional model in which a fine grid configuration may be used to follow saltwater intrusion into a well. In this case, it relies upon an accurate knowledge of the physical constants of the aquifers as well as some detailed history of saltwater and freshwater movement in the local area of the well considered. Such measurements are often difficult to assemble. Consequently, these highly localized models are often calibrated and verified for the specific well under study, for which an extensive data base may exist, but the model and its results may not be easily transferable to other situations.

The Cleary groundwater quality model is another highly localized

model which is an adaptation of a small section of the hydrology models with additional relations to describe dispersion of pollutants within an aquifer. As such it is a water quality model. In addition to data limitations associated with the groundwater hydrology, the model requires sufficient local data to establish a pollutant diffusion coefficient in order to track the spread of the contaminants.

Overall, the groundwater models fall into two categories. The hydrology models are designed to supply information of the spatial distribution of the water table and its change in the future. The localized well and water quality models are useful in the specific sites for which they are prepared and are not directly applicable on a more extensive basis.

7.3.5 Water Budget Model

The water budget model prepared by the Cooperative Extension Service (CES) for the 208 project has two primary purposes: first, to estimate recharge of precipitation and/or irrigation to the groundwater and, second, to provide a transport model for nitrogen loadings to both ground and surface water, in the Long Island area. In this section, the transport mechanisms contributing to the overall water cycle and the extension of this transport model to consider nitrogen loads is described.

We wish to draw attention immediately to the fact that this work does not constitute a groundwater model in the sense of the USGS and Princeton efforts. Recharge here is to the upper aquifers where the soil is relatively unsaturated and does not deal with movements of water in the deeper aquifer layers. The basic premise of the water budget model is that most of the predominant processes involving uptake of water and/or nitrogen occur within the root zone for vegetation on the Island. One consequence of this observation is the fact that whereas lateral movement of groundwater is more significant than vertical flow in the models of sections 7–1 and 7–2, in the present discussion it is the vertical infiltration of the unsaturated subsurface medium which is important. Lateral flows are, as we will see, considered insignificant.

A schematic of water flows is shown in Figure 7–24. The root zone itself is some one to three feet deep depending upon vegetation type. The whole of the Long Island Bi-County region is divided into such cells with surface areas of 2.25 miles, coincident with the planning maps for demographic and land use development. Twelve types of land use development may be introduced on the surface of any cell. The model states simply that recharge is the net of precipitation and/or irrigation inflow over runoff, evapotranspiration uptake by plants, and other outflows from the cell.

In each cell a *mass balance* relation is employed which asserts that total water into a cell must equal total amount leaving it. This assertion is conceptually no different from the mass balance relations utilized in the water quality models discussed earlier. For a given cell one has the following relation which defines 'water budget':

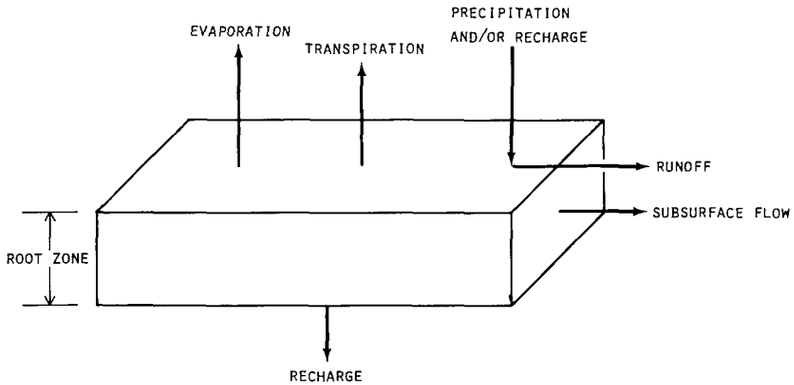


FIGURE 7–24 *Representation of the Recharge Model of CES. Subsurface Flow is Generally Assumed to be Zero in this Model.*

$$\text{Recharge} = \text{Precipitation} + \text{Irrigation} - \text{Runoff} - \text{Evapotranspiration} \qquad (7.4)$$

One should also add to this equation a term for net horizontal flow of water into or out of neighboring cells, but this is considered negligible in relation to vertical flow since the soils are generally considered to be loose, sandy and unsaturated. The term *evapotranspiration* in relation (7.4) refers to evaporation plus transpiration of water through the root zone of plants.

The generation of recharge to the groundwater system may be viewed as a two step process. First, precipitation and/or irrigation cause the entry of water into the system, as illustrated in Figure 7–25. Secondly, vegetation takes up some water for respiration. These evapotranspiration losses are also shown in Figure 7–25.

At the surface, water either infiltrates the ground or creates runoff. The split between these two is characterized by a runoff coefficient determined for various types of soils and surfaces. Impervious surfaces associated with land use development are assumed to block all infiltration. There is an effective "active storage capacity," which describes its overall ability of the soil to capture and retain water. This storage capacity is the product of depth of the root zone and an available moisture capacity.

In general, the moisture content of the soil varies from a "field capacity" in which all available pore space in the soil has been occupied by water down to a minimum in which the little remaining water is locked into the soil structure (see Figure 3.12). When soil moisture drops, evapotranspiration by plants becomes limited by available moisture. At the minimum level, called the "wilting point," the little remaining water is unavailable to plants. Conversely, near the field capacity, soils are near saturation and excess water is generally present over and above that required to support plant respiration at its maximum. As the moisture content drops below the satu-

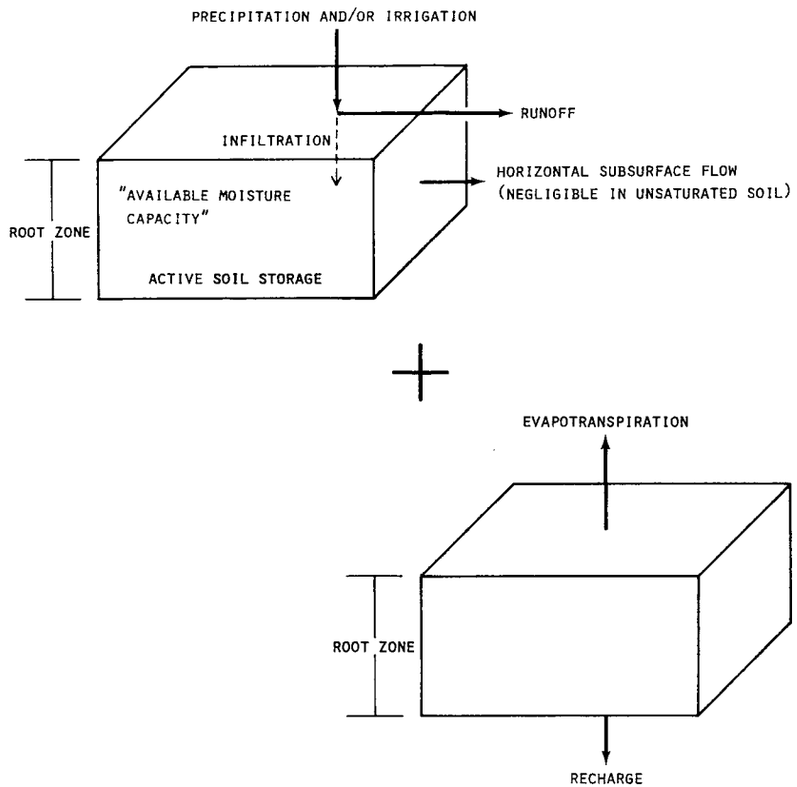


FIGURE 7–25 *Recharge as a Two-Step Process.*

rated condition, plants still have a plentiful supply. However, at a level denoted as critical moisture, plant respiration requires larger amounts of water than available from the soil. Moisture content of the soils becomes the limiting factor in plant respiration. The wilting point is that where no free moisture remains and plant life ceases.

Within the model it is necessary to characterize four major parameters noted above:

precipitation/irrigation—these are the primary water inputs to the system.

runoff coefficient/impervious area—the coefficient describes runoff in areas of vegetation, whereas impervious area gives 100% runoff. However, because of the wide distribution of recharge basins, both natural and man-made, runoff is assumed to occur only in those grid cells adjacent to a water body, e.g. only within about 2 miles of shorelines or streams.

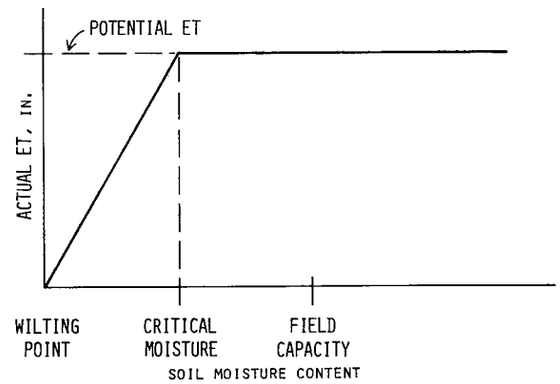


FIGURE 7–26 *Relation Between Evapotranspiration (ET) and Soil Moisture Levels.*

active soil storage (root zone depth multiplied by the available moisture capacity)—this parameter describes the ability of the root zone area to store water.

critical moisture—this parameter characterizes the limiting moisture content for evapotranspiration.

To establish values for these parameters, the CES group relied upon an extensive review of existing data and literature supplemented by field testing, particularly in the area of evapotranspiration effects. The model is calibrated for iteration over steps of one month to obtain annual water cycles. Since precipitation rates, and hence soil moisture content, vary widely within any month, it is important to test the accuracy with which one month averages describe actual recharge. In general, errors in using monthly rather than daily water balances are less than five to ten percent. In addition, following calibration of the parameters above, estimates of recharge and runoff from the model are in good agreement with past direct measurements in selected areas on the Long Island region.

The model is oriented toward the immediate impact of land use development upon recharge to the groundwater system. In its present form it provides a picture of the way in which continuing and alternative land use development limit eventual recharge.

The model above may be supplemented by the addition of nitrogen loadings. Primarily, nitrogen loads reflect the use of fertilizers in residential and commercial areas for lawn maintenance as well as in agricultural areas. It becomes necessary in this case to augment the evapotranspiration relationships with a description of nitrogen uptake in the plant life. With this addition, the model tracks the infiltration and/or runoff of nitrogen, its uptake in the root zone, and the balance which flows on through the system as recharge.

7.4 INTEGRATED USE OF MODELS

The Long Island area is one of wide variety in terms of marine and hydrogeologic water systems. The study area shown in Figure 7–27 has some 1000 miles of shoreline, wetland areas, barrier beaches, shallow bays, and a number of other important elements of the coastal environment. The groundwater system is equally complex, consisting of shallow and deep aquifers, intervening clay layers, underflow to bays, seepage to lakes and streams, and is subject to the problem of salt water intrusion near shorelines. Surface features which contribute recharge to groundwater and runoff to estuaries range from built up urban environments to natural meadowlands. Within this kind of framework the use of models plays an important role in addressing the difficult question of regional strategy for wastewater management, particularly in our ability to quantify the impacts of different land use schemes and wastewater alternatives. Data gathering and assessment for model development, as well as the models themselves, also prove valuable in clarifying the present condition of surface and groundwaters in the area and thus serve to provide a backdrop against which the future may be judged.

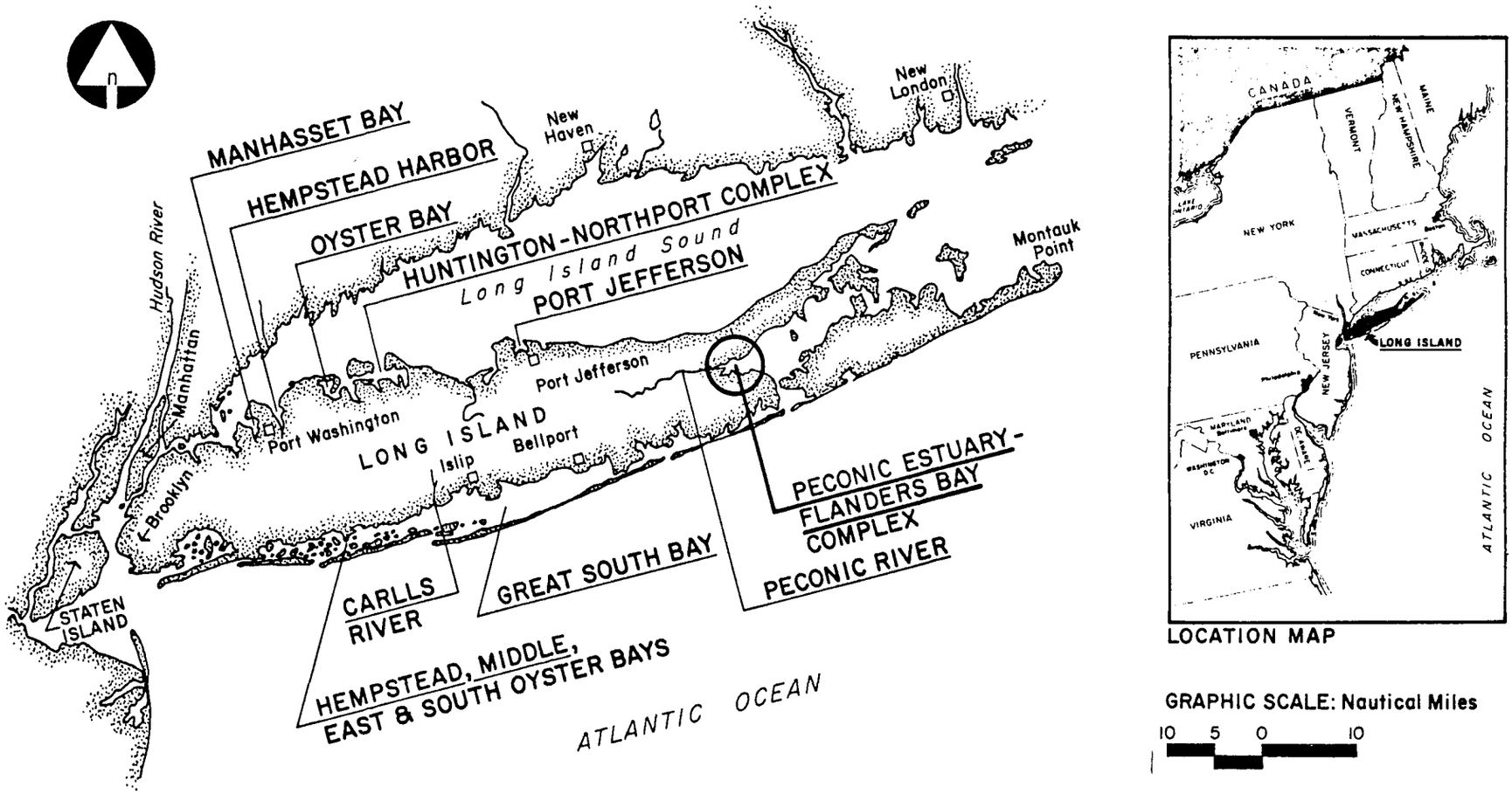


FIGURE 7–27 *Location of Study Areas.*

The way in which results from the different modeling efforts are used in the evaluation of various alternatives for the wastewater management is a complex process. Moreover, it is important to distinguish the use of the models in their role as evaluators of alternatives from that of guiding the selection of alternatives which are appropriate to specific areas. As observed above, much of the data used in model development and calibration serves as a backdrop for the selection of alternatives. In addition, some of the estimates of future wastewater loads may be used in conjunction with the models to define the general character of the region's wastewater future. The model computations, in this case, serve as a backdrop of future conditions, within which to choose viable management strategies. While it is appropriate to discuss such overall regional strategies, specific alternatives will most often concern selected study areas. Consequently, we provide here a short discussion of the models and the ways in which information from these is integrated. It should be pointed out that this integration generally takes place in the context of meetings of groups of individuals, rather than through any type of formal or computer link between the models themselves. The illustrative case study is the Riverhead/Peconic Bay (Figure 7–28). Similar considerations of course apply elsewhere.

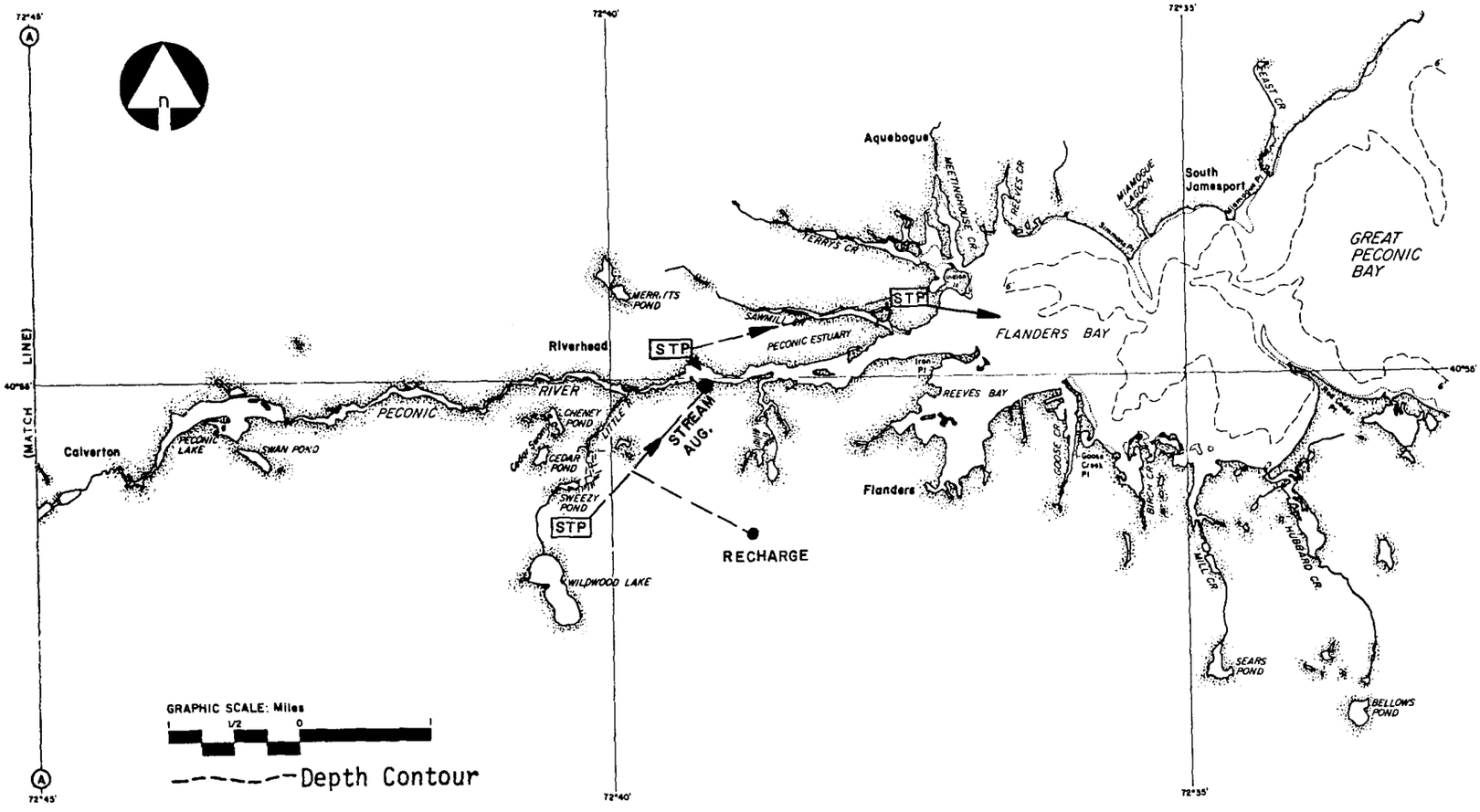


FIGURE 7–28 *Peconic River, Peconic Estuary, Flanders Bay with Waste-Water Management Structural Alternatives.*

The engineering consultants have recommended a number of alternatives which include the use of regional, sub-regional, and local sewage treatment plants or diversions to the Riverhead sewage treatment plant, which may require-expansion of that plant. There have also been expressed concerns with Peconic River stream flow conditions so that it might be appropriate to consider stream augmentation and/or recharge options which assist in maintaining stream flows, the water table, or water quality, respectively. To test the various alternatives, including location of outfall pipes, stream augmentation, recharge, and the like, requires the use of different models for different water bodies. The impacts of discharge to rivers can have secondary effects upon the bay systems, for example through increased effluent loading to the bays. Likewise, in the Riverhead/Peconic area, recharge options may reduce nutrient and organic loading to streams which could have adverse effects upon flora, fauna, and stream water quality. In the face of these complex interactions, it often becomes necessary to combine the information from the several models to properly evaluate these types of wastewater management alternatives.

Figure 7–28 illustrates some of the possible structural options in the Riverhead/Peconic region.[15] The water budget model (Cornell Extension Service) is utilized to establish an accounting of precipitation, evapotranspiration recharge, and runoff components in the total water cycle as shown in Figure 7–29 for the Riverhead area. Of course, paved surface, recharge basins, and other characteristics of the future land use lead to changes in runoff, while removal of vegetation decreases evapotranspiration water loss. The model is so constructed that it can describe the impact of land use development upon runoff, which is a component which enters into estuary and stream models, and recharge, the flow of water which enters the groundwater system. Since it has been estimated that runoff nutrient levels can be a substantial part of the total load to surface waters in areas such as Riverhead, the water budget model can be used to estimate runoff itself as a contaminant to bays, and for recharge to the water table. It should be noted, however, that this model describes only aggregate water flow over large areas and is able to only include conservative contaminants as part of the water cycle, primarily nitrogen and phosphorous. Some of the information which the model does not address is made available through estimates provided by the engineering consultants.

With regard to sewage treatment plants, some method of disposal of effluent is required either to surface waters or groundwater. In the event of discharge to estuarine waters, the Tetra Tech models prove useful in the assessment of the impact upon water quality in such bays. Outfall discharges may add to the water flow and contaminant load. For example, if one considers a specific outfall site in the bay, the Tetra Tech model provides profiles of constituent loading at various locations (as shown by the nodes along the bay channel in Figure 7–30, such as for total nitrogen N and phosphorous P. This is shown in Figure 7–31. The curves correspond to total concentrations

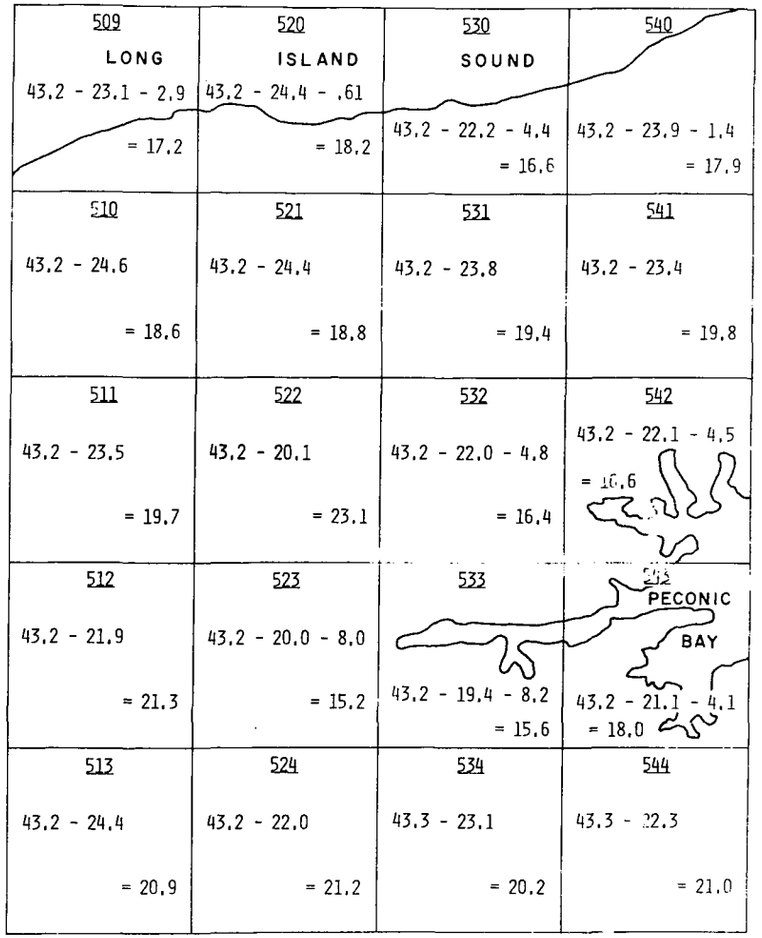


FIGURE 7–29 *Example of CES Computations in Peconic Bay: Precipitation–Evapotranspiration–Runoff=Recharge.*

in milligrams per liter for a typical model run. An alternative strategy might be to consider the diversion of wastewater flows to existing or new plants as suggested in Figure 7–28. The options for wastewater discharge from such plants may include stream augmentation. In this case, the Tetra Tech river models are utilized to describe water quality along the length of a river as well as the impact of the discharge upon the water flow itself.

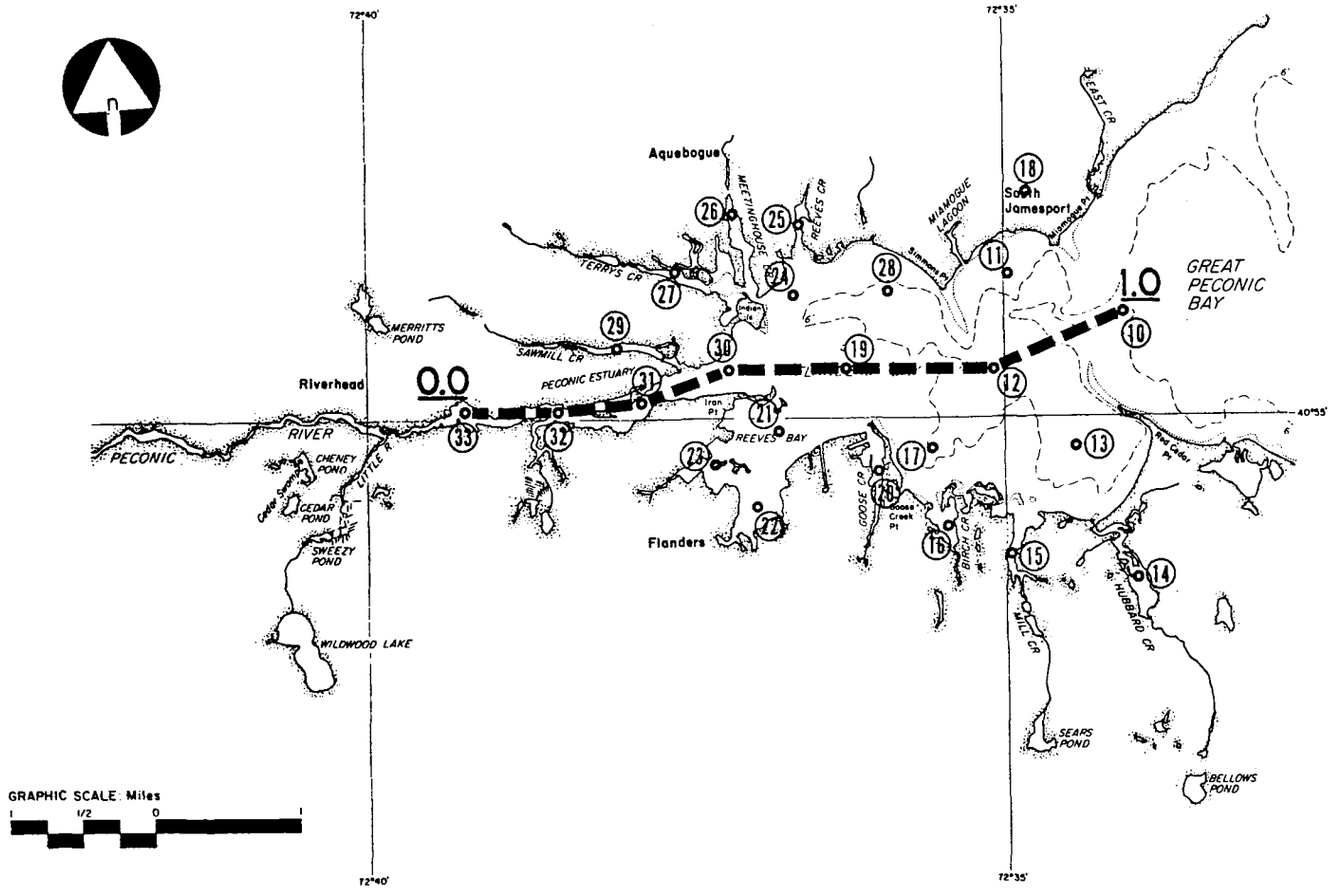


FIGURE 7–30 *Transect Specified for Calibration, Verification and Sensitivity Profile Plots.*

Discharge to the groundwater system has two effects. First, there are local increases in the water table elevation and in addition, the local groundwater quality may be either improved or degraded depending upon prior water quality. Where only a description of impact upon water table and water flow from one point to another in the aquifers is necessay, the USGS and Princeton University models may be applied. For example the Pinder model for North Haven would typify groundwater "hills" such as those shown in Figure 7–32 which would surround an injection well at the point of recharge. In the evaluation of alternatives involving recharge, it might also prove useful to utilize the Cleary groundwater quality model for assessing the flow of contaminants away from the injection well though data sufficient to effectively utilize the model is not readily available for all areas of the Island.

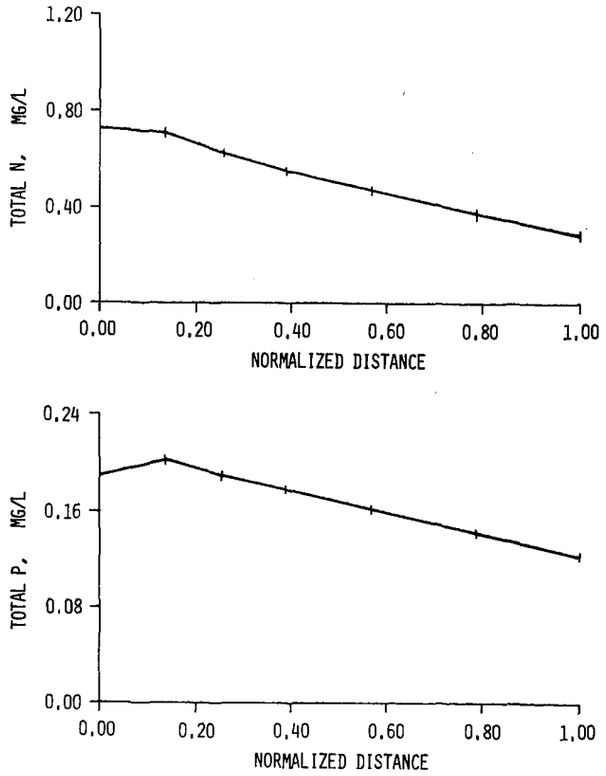


FIGURE 7–31 *Typical Plots of Total Nitrogen and Total Phosphorous Along Transect of Peconic Bay, for Seven Locations Shown in Figure 7–30.*

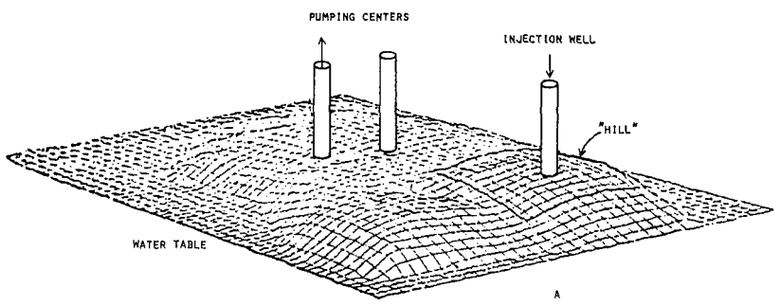


FIGURE 7–32 *Illustration of Water Table "Hill" Due to Recharge.*

The flow of data and information for the evaluation of wastewater management alternatives is exhibited in a different form in Figure 7–33. Here we indicate the possible role of land use development as a basic driving force for the region.

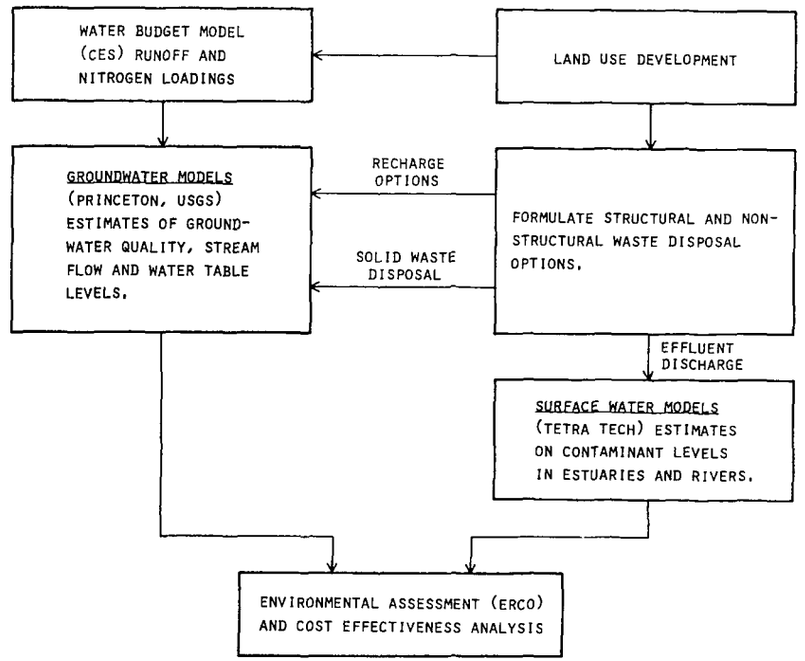


FIGURE 7–33 *Evaluation of Management Alternatives.*

It should be noted that the solid lines indicated in Figure 7–33 denote flow of information within the 208 project itself and not formal links between the various computer models. Ideally, one would like to tie together the models into an overall comprehensive assessment. However, there would be a number of difficulties in carrying this out. The models were all developed by separate organizations using different programmers, programs, computer languages and computer systems. Consequently, it would be a formidable task to pull these together into a comprehensive whole. In a practical sense, however, it is not really necessary to pull all the models into one package. In the assessment of various alternatives, such as a sewage

treatment plant option, its impact upon the water system in the area is assessed using only the specific models which apply. For example, if only a bay outfall is to be considered as the discharge option, the Tetra Tech estuary model alone would be used to assess this. There are, in addition, a wide range of qualitative and quantitative considerations which are drawn into the evaluation of wastewater management alternatives at this point, but which lie outside the scope or abilities of the models. Outfalls to open surface waters could have impacts on stream flows. The groundwater models are not constructed to deal effectively with such effects in individual streams. Moreover, the river model itself does not accurately describe the impact of outfalls on upstream water levels. Environmental impacts upon shorelines, drainage structures, flooding, and ecology of bay and river systems also fall outside the range of the models. However, the models do provide the quantitative background of water quantity and quality required to address these questions. Where impacts of alternatives are considered undesirable, one may cycle back by reconsidering the option, introduce some changes in the character of the alternative, and then run the new option back through the models to assess whether its impacts might now be considered more favorable.

After having surveyed in this report the several modeling components of the 208 it is useful to give a brief summary of what each model does in terms of output, where that output is directed in terms of Long Island waste management, and the inputs required to make the model operational. This is shown in a series of flow diagrams, given in Figures 7–34, 7–35 and 7–36. This introductory view of the 208 models may hopefully encourage the serious reader to consult some of the more technical documents provided by the consultants.

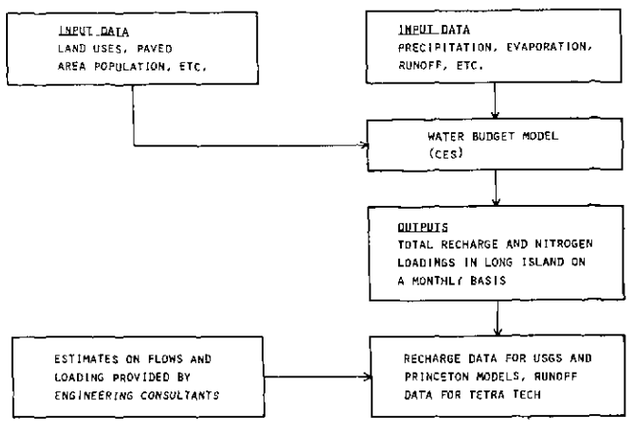


FIGURE 7–34 *Water Budget Modeling.*

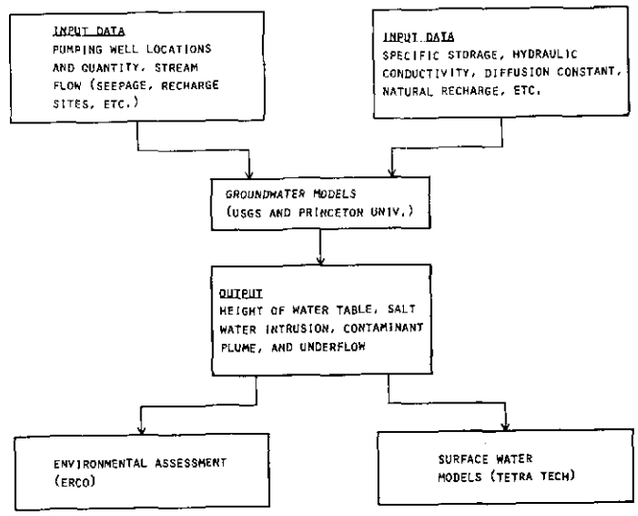


FIGURE 7–35 *Groundwater Modeling.*

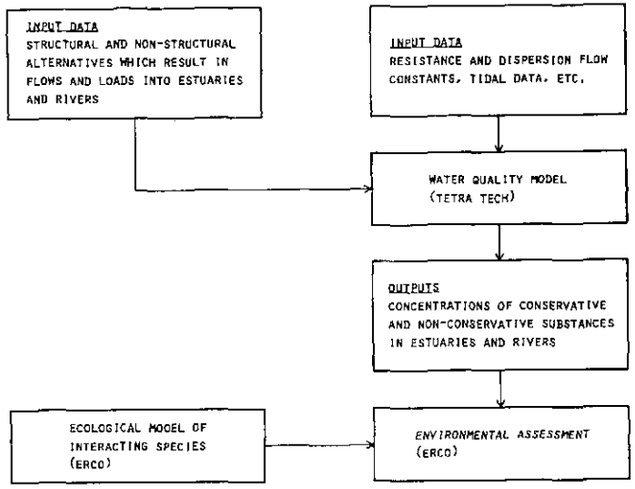


FIGURE 7–36 *Surface Water Modeling.*

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NOTES

1 Let ΔH denote the incremental change of H during a time interval of duration ΔT seconds. Then the volumetric change during ΔT is given by $\Delta H A_s$ and the principle of mass conservation then says that

$$\Delta H A_s = Q\Delta T \tag{1}$$

where $Q\Delta T$ is the net flow during ΔT. Using (1) equation (2) is often written as

$$\frac{\Delta H}{\Delta T} = \frac{A_c}{A_s} u \tag{2}$$

As we will see later a simple variant of (2) also holds for groundwater flows.

2 Let ρ denote the water density (kg per cubic meter) so that $\rho A_c L$ is the total mass in kilograms of the water in the tube. The momentum of the moving fluid is the product of mass and velocity and is given by $\rho A_c L u$. Newton's second law of motion says that the rate of change of momentum over time must equal the sum of the forces which act on the moving body. In the absence of any external forces on the fluid, the rate of change of momentum is zero, which is the principle of *conservation of momentum*. One such force, as we already noted, must be due to the pressure difference exerted at the two ends of the channel. If we add to this the resistive force due to friction caused by the roughness of the channel then, since u is the only quantity which can vary in the expression for momentum, the rate of change may be stated as

$$\rho A_c L \frac{\Delta u}{\Delta T} = \text{Pressure Force} + \text{Resistive Force} \tag{3}$$

in which Δu is the incremental change in velocity during an interval of duration ΔT.

It can be shown that the *pressure force* is given by

$$\rho g A_c (H_1 - H_2)$$

where g is a number known as the gravitational constant (9.8 meters per second squared). Note that if H_1 is greater than H_2 then the force is positive and it acts so as to give a flow from tank 1 toward tank 2. When H_2 is greater than H_1 the opposite is true and the flow is reversed. When $H_1 = H_2$ the the net force is zero and there is no exchange of water between tanks.

Resistive force is found from an empirically derived relationship which states that resistance is proportional to the square of the velocity. That is

$$\text{Resistive Force} = -\rho A_c R L u|u|$$

where R is a constant which measures the roughness of the channel walls. As the ratio of the area A_c to the perimeter of the cross section of the channel increases the resistance R decreases. The particular form of the above expression was chosen so that the force will always operate in a direction opposite to the direction of flow (if we had written u^2 instead of $u|u|$ this would no longer be true.)

By combining the above remarks together into relation (3) and by eliminating ρA_c from both sides of the equation one obtains

$$\frac{\Delta u}{\Delta T} = g\left(\frac{H_1 - H_2}{L}\right) - Ru|u| \tag{4}$$

3 Hydraulic conductivity is defined by a number K which equals $\mu\rho g/k$. Once again g is the gravitational constant. As K increases, resistance decreases.

In view of the above discussion the basic relations 2 and 4 need to be modified slightly. Consider 2 first. Since ϵ is now the fraction of volume which may store water, then $\Delta\epsilon A_s H$ is the effective change in volume of the water in the tank due to a change H in head. Otherwise the same conservation of mass principle still applies as before and so equation 2 becomes

$$\frac{\Delta H}{\Delta T} = \frac{A_c}{\epsilon A_s} u \tag{5}$$

When $\epsilon = 1$ (as in open water) this relation of course reduces to the previous one. Note also that when ϵ is smaller than 1 then, since there is now less volume in which to store water, the change ΔH is larger than for open waters. Relation 4 for open water is similarly modified in the case of a porous medium. Once again A_c is replaced by ϵA_c as the effective cross-sectional area which is acted on by the pressure force. Also the resistive force is now due to the viscosity of the water in the permeable medium as we discussed above and is empirically found to be proportional to the velocity u. Specifically one can show that

$$\text{Resistive Force} = -\rho g \epsilon A_c L \frac{u}{k}$$

This allows us to write an analog of relation (4) as

$$\frac{\Delta u}{\Delta T} = g\left(\frac{H_1 - H_2}{L}\right) - g\frac{u}{k} \tag{6}$$

Note that although in open water resistance to flow is proportional to the square of the velocity, in the porous medium it is simply proportional to the velocity itself.

4 The analogy can be carried further. Heat flows from a point of high temperature to a lower, also at a rate proportional to the temperature difference. Finally, in an analogy that will be referred to again in the section on groundwater models, current flows in a circuit at a rate proportional to voltage difference between two points. The difference in concentrations relative to the distance between two points of water levels, or temperature, or voltage, describe what are called "gradients." When these gradients or differences are zero there is no further exchange between the two points in the body and the system is said to be in *equilibrium*. One more point: all the flows described here are also subject to the level of conductivity (or permeability, or what have you) in the channel which connects the points. The smaller the "conductivity," the greater is the resistance to flow.

[5] Referring to equation 2 this can be stated mathematically for each node s,

$$\frac{\Delta H_s}{\Delta T} = \sum_{j=1}^{m} \frac{A_c}{A_s} u_j + Q_s^{in} - Q_s^{out} \qquad (7)$$

where all flow conditions on the right side of (7) are determined at some previous time and ΔH_s is the net incremental change in H during a time step ΔT which takes us to the present moment. The symbol Σ is of course the usual shorthand for taking a sum of terms from j = 1 through j = m.

[6] Equation 4 must now be interpreted in terms of a head difference between two specified nodes labeled as j_1 and j_2 and u then flows between these two nodes.

[7] Consider BOD, for example. Suppose k_B is a constant which denotes the rate at which BOD decays over time. If c is the quantity of BOD in a given volume V, at some earlier instant, then $k_B c \Delta T$ is the amount of BOD lost to decay during the next time interval of duration ΔT. If we subtract this from the previous value of c we obtain the current value of BOD. That is

$$V \Delta c = - k_B c \Delta T$$

The reason for subtracting is that the new value of BOD will always be less than its previous value. Of course this argument assumes that all other factors which may affect BOD are absent during the time interval. That is, no sources or sinks and no advection or diffusion. The relation for BOD is simply a special case of equation 7.3. In general the full relation for BOD will include all these other terms in addition to the one given here for decay.

[8] *Re-aeration* refers to oxygen gains which occur at the surface of the water due to contact with air, while *photosynthesis* is the process whereby microorganisms in the water release oxygen as a result of the manufacture of carbohydrates from water and carbon dioxide. Finally *respiration* is the opposite of photosynthesis and refers to the biological activity in which organic carbon is oxidized. As a result oxygen is consumed.

[9] This leads to the equation

$$\epsilon A_s \frac{\Delta H}{\Delta T} = u A_c + Q^{in} - Q^{out} \qquad (8)$$

where u is velocity in the channel of the area A_c. This extends the equation to include source and sink terms and is analagous to equation (7) for surface models.

[10] Consequently, using the expression (8) above we see that

$$S \frac{\Delta H}{\Delta T} = \frac{u}{L} + \frac{Q^{in}}{\epsilon A_s L} - \frac{Q^{out}}{\epsilon A_s L}$$

where the left side is approximately the percentage change in head which is driven by the velocity and the various recharge, pumping and seepage flows for the node. Note that since $\epsilon A_s L$ is the node volume for water storage, $Q/\epsilon A_s L$ is a percentage volumetric flow. The overall change in head is a result of all incoming flows from other nodes within the layer considered, or to the layers above and below, and contributions from recharge or discharge at the node.

The expression for change in velocity (or momentum) with time requires no modification. As shown in Figure 7–15, the velocity is driven by the difference in head, or water elevation between two adjacent nodes. However, the soil acts to restrict flow of groundwater and the rate of change of velocity is

$$\frac{\Delta u}{\Delta T} = g\left(\frac{H_2 - H_1}{L}\right) - g\frac{1}{k} u \qquad (9)$$

for the two coupled nodes. If we generalize to a multi-layer aquifer system, three separate equations of type (9) must be written for velocities u_x, u_y, and u_z along x, y, and z axis, respectively. However, this will not be critical to our discussion of the model below.

[11] given by $u_o = K(H_2 - H_1)/L$

[12] The choice of resistor and capacitor values is important. For convenience, capacitors should be small enough that the currents required to drive the physical model are appropriate for small operational amplifiers and small signal equipment. Similar conditions hold for resistors in order that impedance match to external sources not be a problem. Also, the time required to resolve pressure differences in the real groundwater system is something like thirty years, as we know, and in the model this is characterized by the time constant for resistor/capacitor circuits. However, we prefer this not be the thirty year equilibrium for the aquifer, but some convenient laboratory time. The USGS model is formulated so that two years real time is about 1/1000 sec. in model time.

[13] The Princeton models are finite element models as opposed to finite differences represented in the USGS model. Finite difference refers to sectioning the aquifer layer into nodes (points) and channels (lines) so that one has a set of difference equations involving head at each node. Finite element refers, roughly, to sectioning the aquifer layer into finite-sized cells (of any shape). The head is described by a mathematical function having spatial dependence and the particular value for water elevation at each finite element is found simply by numerical evaluation of the function.

[14] The above numbers, although generally true, overlook the fact that the distribution of pollutants observed in groundwater systems is due to several mechanisms, of which physical dispersion is only one. A pollutant which may behave conservatively (not decay with time or react with the permeable media) in one aquifer may behave non-conservatively in another. For example a pollutant which absorbs strongly in silt and clays would be attenuated in shorter distances than in a system which is mainly sand and gravel. Moreover, the ability of groundwater systems to assimilate certain pollutants may be limited upon the rate at which pollutants are introduced (e.g., simple wastewater soil treatment systems clog with excessively high organic loads.)

[15] Those shown in the figure are somewhat hypothetical and do not conform with the options being prepared by the engineering consultants.

GLOSSARY

Because this report is largely intended for the general reader certain unfamiliar technical terms have been defined in the text at the place at which they first occur. These are listed below together with the page location where the definition can be found. Certain more commonly used expressions are not included.

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