U.S. Department of the Interior
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# SIMULATION OF THE EFFECTS OF DEVELOPMENT OF THE GROUND-WATER FLOW SYSTEM OF LONG ISLAND, NEW YORK

Water-Resources Investigations Report 98-4069

Prepared in cooperation with the
NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS,
SUFFOLK COUNTY DEPARTMENT OF HEALTH SERVICES,
SUFFOLK COUNTY WATER AUTHORITY, and the
NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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The distribution of ground-water pumping as represented in the model is shown by county and model layer (aquifer) in table 12. The greatest increase in pumping is expected to be from the basal zone of the Magothy aquifer (layer 3) in Suffolk County, and the highest rate of pumping will remain in Nassau County from the basal zone of the Magothy aquifer. Projected changes from the distribution of pumping in 1983 to 2020 can be evaluated through comparison of table 10 and table 12.

**Table 12.** Distribution of ground-water pumping for public-supply, industrial-commercial, and agricultural uses for the year 2020, as represented in model

| County | Model layer | | | | Total |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| | (water table) | (Magothy and Jameco) | | Lloyd | |
| Kings and Queens | 24 | 2 | 17 | 3 | 46 |
| Nassau | 10 | 10 | 181 | 13 | 214 |
| Western Suffolk | 26 | 2 | 79 | 0 | 107 |
| Eastern Suffolk | 37 | 15 | 39 | 0 | 91 |
| Total | 97 | 29 | 316 | 16 | 458 |

## Ground-Water System Response

The predicted hydrologic response to the water-supply development strategy for the year 2020 is presented in terms of (1) base flow; (2) movement of the saltwater-freshwater interface, (3) ground-water levels and flow patterns; and (4) the ground-water budget. These results provide a guide to water-resource managers who must define acceptable levels for the adverse effects of development and modify development strategies to meet these levels. The predicted response also is compared with simulated results for the predevelopment and recent hydrologic conditions to demonstrate the evolution of the development of the Long Island ground-water system.

### Base Flow

Model predictions of base flow of major streams for the 2020 water-supply strategy are presented in table 13. Streams are represented in the model as drains, similar to simulations of the 1960's drought, however, recent stressed conditions were used as a baseline. Recovery of ground-water levels in Queens and western Nassau County is expected to increase base flow and restore flow in some dry stream channels (table 13 and fig. 31); the base flow of Flushing Creek, Springfield Stream, Simonsons Stream, Valley Stream, Motts Creek and Pines Brook will increase. From South Pond in western Nassau County eastward, however, base flow in all streams will decrease.

Base flow in East Meadow Brook, Bellmore Creek, and Massapequa Creek in Nassau County are estimated to decrease the most—their combined flows will decrease 92 percent, from 22.3 $ft^3/s$ during 1968-83 to 1.8 $ft^3/s$ by the year 2020. East Meadow Brook is projected to be dry from its headwaters to the gage. Base flow of Santapogue Creek, Carlls River, and Sampawams Creek in western Suffolk County together will decrease to about 60 percent of their flow during 1968-83. As indicated in the analysis of the 1960's drought, long streams that extend far inland are affected most severely; this is evident from comparing the estimated base flow in Massapequa Creek, Bellmore Creek, and East Meadow Brook with Milburn Creek, Cedar Swamp Creek, and Carman Creek in table 13. Streams east of Nissequogue and Connetquot Rivers will be less severely affected than those to the west because the increase in stress will be smaller and because the effects of stress in the west do not propagate past these large streams.

### Saltwater-Freshwater Interface

The movement of the saltwater-freshwater interface between 1983 and 2020 cannot be determined by the islandwide model. Movement of the interface was assumed to be

**Table 13.** Average base flow of major streams on Long Island, estimated for predevelopment and during 1968-83 and predicted for the year 2020

| Map number (fig. 3) | Stream name | Period: Predevelopment | Period: 1968-83 | Period: 2020 | Map number (fig. 3) | Stream name | Period: Predevelopment | Period: 1968-83 | Period: 2020 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Jamaica Creek | 17.9 | 0.0 | 0.0 | 17 | Sampawams Creek | 9.9 | 6.7 | 3.6 |
| 2 | Springfield Stream | 7.9 | 0.0 | 0.1 | 18 | Penataquit Creek | 6.8 | 6.5 | 5.0 |
| 3 | Simonsons (Brookfield) Stream | 9.6 | 0.3 | 2.9 | 19 | Pardees and Orowoc Creeks | 10.3 | 8.9 | 6.9 |
| 4 | Valley Stream | 14.3 | 0.3 | 1.7 | 20 | Rattlesnake Brook | 9.2 | 8.8 | 8.5 |
| 5 | Motts Creek | 6.4 | 2.1 | 4.3 | 21 | Connetquot River | 36.0 | 34.6 | 31.0 |
| 6 | Pines Brook | 13.0 | 0.5 | 1.0 | 22 | Green Creek | 6.5 | 6.5* | 6.5 |
| 7 | South Pond | 20.0 | 0.4 | 0.1 | 23 | Patchogue River | 18.9 | 18.9* | 18.4 |
| 8 | Parsonage Creek | 8.1 | 4.5 | 3.9 | 24 | Swan River | 13.3 | 13.3* | 13.0 |
| 9 | Milburn Creek | 13.0 | 6.9 | 4.3 | 25 | Carmans River | 24.9 | 24.9* | 24.1 |
| 10 | East Meadow Brook | 15.3 | 6.3 | 0.0 | 26 | Forge River | 9.6 | 9.6* | 9.1 |
| 11 | Cedar Swamp Creek | 9.5 | 6.8 | 2.8 | 27 | Little River | 7.4 | 7.4* | 7.4 |
| 12 | Bellmore Creek | 14.6 | 9.4 | 1.5 | 28 | Peconic River | 37.4 | 37.4* | 35.7 |
| 13 | Massapequa Creek | 12.0 | 6.6 | 0.3 | 29 | Nissequogue River | 41.7 | 40.2 | 37.1 |
| 14 | Carman Creek | 6.8 | 6.7 | 2.6 | 30 | Mill Neck Creek | 7.0 | 5.6 | 3.1 |
| 15 | Santapogue Creek | 10.0 | 8.0 | 4.9 | 31 | Glen Cove Creek | 8.7 | 3.7 | 1.8 |
| 16 | Carlls River | 27.3 | 20.5 | 11.9 | 32 | Flushing Creek | 21.5 | 7.8 | 15.5 |

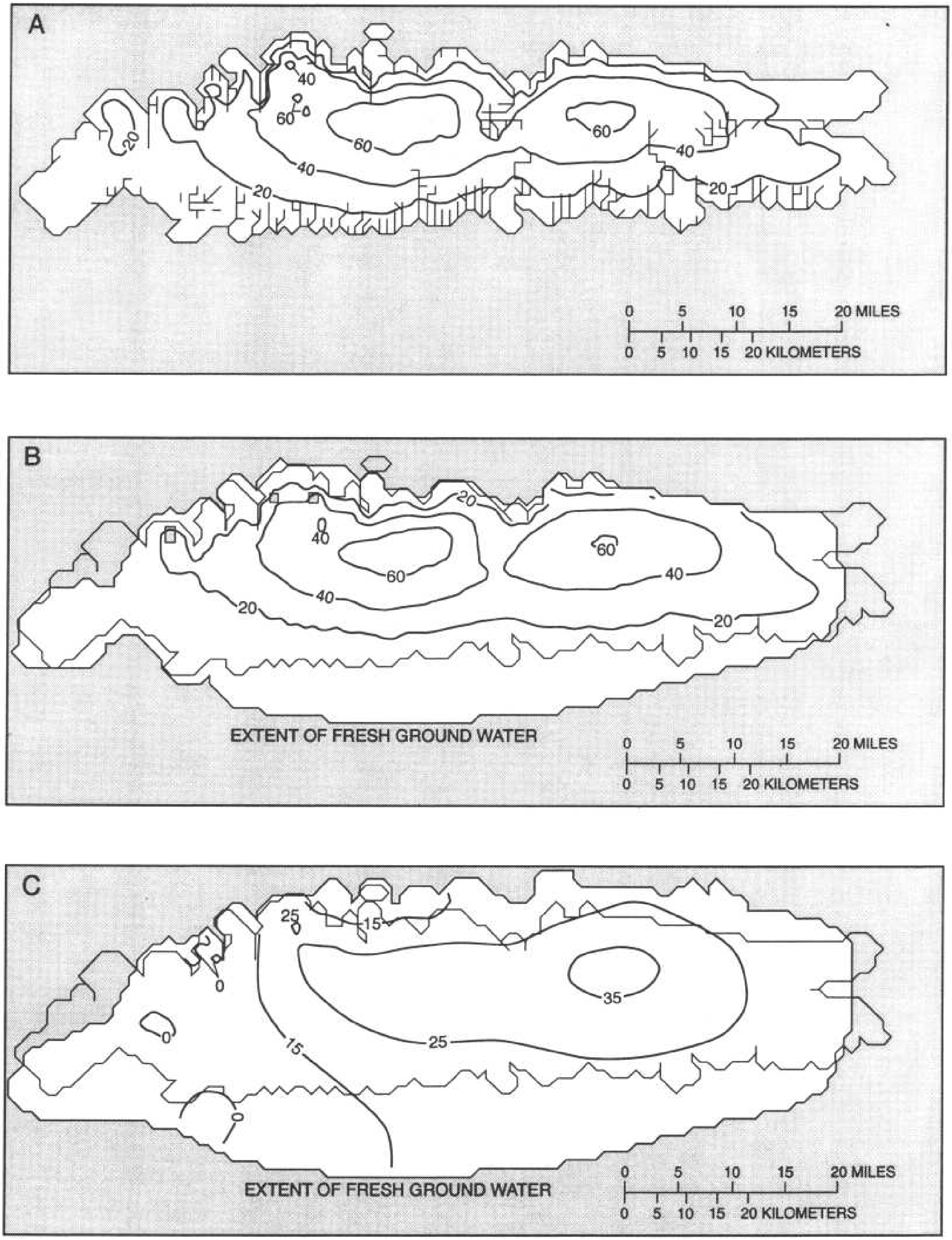
* Assumed to be the same as under predevelopment conditions because development is minimal, and records indicate no decrease in base flow from predevelopment conditions.

negligible however, because the average velocities would not cause movement of more than one model cell (4,000 ft). Although this assumption is acceptable at the regional scale and for estimating the ground-water flow budget and water levels, it does not address the possibility that saline ground water could be moving landward in local strata and in dilute concentrations sufficient to affect water supplies, particularly in southern Queens and Nassau Counties. Despite some water-level recovery in this area, water levels near the saltwater-freshwater interface in the Magothy and Lloyd aquifers have the greatest deficit in relation to the head needed to balance static sea water in these aquifers (fig. 31), indicating that this is the most likely place for saltwater intrusion and, therefore, the best location for monitoring.

The interface generally is closer to shore on the northern shore than the southern shore. Small-scale pumping close to the northern shore could induce rapid local saltwater intrusion, particularly near the bays where erosion of confining units could have created a hydraulic pathway to confined aquifers.

### Ground-Water Levels and Flow Patterns

The predicted distribution of hydraulic head in the three major aquifers in 2020 is shown in figure 31. (Corresponding maps for recent and predevelopment conditions are in figures 24 and 17, respectively.) The maps show that water levels in Kings, Queens, and




EXPLANATION

—— 20 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would rise in a piezometer. Contour interval, in feet, is variable. Datum is sea level

**Figure 31.** Predicted ground-water levels for the year 2020. A., Water-table aquifer (model layer 1). B., Magothy aquifer (model layer 3). C., Lloyd aquifer (model layer 4).

most of western Nassau Counties in all three aquifers will recover from conditions during 1968-83 because pumping in Queens County will be decreased from 61 to 30 Mgal/d, and pumping in southwestern Nassau County will be replaced by pumping at the Muttontown Preserve pumping center. Stream lengths in this area also will increase (compare figures 31A and 24A.

The most severe water-level declines will be in central Nassau County, where the water table and potentiometric surface of the Magothy aquifer will decline 20 ft below levels during 1968-83 and 40 ft below predevelopment levels, on average. The potentiometric surface of the Lloyd aquifer in central Nassau will decline more than 10 ft below recent levels and 25 ft below predevelopment levels (fig. 31), and increased pumping from the Lloyd aquifer on the barrier island in southwestern Nassau County will result in increased drawdown very near the saltwater interface. Water-level declines in western Suffolk County will be smaller than in Nassau and will dissipate rapidly eastward; declines east of the Nissequogue and Connetquot Rivers will be only a few feet.

Although the total stress on the ground-water system in 2020 will be greater than that during recent conditions, the general redistribution of pumping away from severely affected areas of western Long Island will mitigate the severe drawdown below sea level in Queens and western Nassau Counties.

### Ground-Water Budget

The ground-water budget for the year 2020 is shown in table 14; the values are derived solely from model-generated flow rates. The net stress on the ground-water system is 57 Mgal/d (24 percent) greater than during 1968-83 and represents an increase in pumping of 51 Mgal/d and a decrease in ground-water recharge from returned water of 6 Mgal/d. Under equilibrium conditions, the increase in net stress is balanced by a corresponding decrease in discharge from the system. Comparison with the water budget for recent conditions (tables 9 and 14) indicates that 77 percent of the increased stress will be balanced by a net decrease in discharge to streams, and 12 and 11 percent by a net decrease in discharge to the shore and subsea boundaries, respectively. Comparison with the water budget for predevelopment conditions (tables 4 and 14) indicates that the total stress on the ground-water system in 2020 (297 Mgal/d) results in a decrease in base flow of 179 Mgal/d (39 percent), a decrease in discharge to shore boundaries of 89 Mgal/d (15 percent), and a decrease to subsea boundaries of 29 Mgal/d (36 percent). Islandwide, base flow is predicted to decrease to 86 percent of recent levels, or 61 percent of predevelopment levels.

**Table 14.** Ground-water budget for the year 2020 on Long Island

| County | Recharge | Discharge | | | |
|---|---|---|---|---|---|
| | Precipitation and returned water use[1] | Pumpage[2] | Stream | Shore | Subsea |
| Kings and Queens | 136 | 46 | 22 | 66 | 3 |
| Nassau | 317 | 214 | 26 | 71 | 11 |
| Western Suffolk | 333 | 107 | 100 | 119 | 21 |
| Eastern Suffolk | 501 | 91 | 133 | 240 | 17 |
| Total | 1,287 | 458 | 281 | 496 | 52 |

[1]Total recharge at the water table; includes water returned to the ground-water system after use and decreases due to increased runoff in Kings and Queens. (See table 11.)

[2]Includes total public-supply, industrial-commercial, and agricultural pumping.

The projected decrease in pumping in Kings and Queens Counties will cause increases in all components of natural discharge, including a 10-Mgal/d (83 percent) increase in base flow, a 10-Mgal/d (18 percent) increase in shore discharge, and a 1-Mgal/d (50 percent) increase in subsea discharge. Concern for increased flooding of underground structures or structures built near filled historic stream channels is warranted.

In Nassau County, a 58-Mgal/d increase in stress will decrease base flow to less than half of the amount under recent conditions and to about 20 percent of the predevelopment amounts (tables 4, 9 and 14). Shore and subsea discharge will decrease by 13 and 21 percent, respectively. Although the total decrease in subsea discharge warrants concern for salt-water intrusion, the increase occurs mostly in eastern Nassau, where the interface is far off-shore and recent rates of intrusion are very slow.

In western Suffolk County, a 26-Mgal/d increase in stress will have considerably less effect. Base flow will decrease 19 percent from recent amounts, and shore and subsea discharge will decrease by 6 percent and 16 percent, respectively. In eastern Suffolk County, the increased stress will be only 4 Mgal/d, and the effects will be minor.

The increased pumping and sewering in the 2020 water-supply strategy also will disturb the distribution of flow within the ground-water system (table 15). Recharge will decrease in Nassau and western Suffolk Counties because new sewering will decrease the amount of returned water. Recharge will increase in eastern Suffolk, where pumpage will increase and cause a corresponding increase in returned water because most of the area is projected to be unsewered. Although the amount of water that flows deeper than the water-table aquifer will decrease in Kings and Queens Counties, significantly more water will flow to the deep aquifers on an islandwide basis. Ground water that flows to model layers deeper than layer 1 (generally below the water-table aquifer) increased from 462 Mgal/d under predevelopment conditions (table 5) to 648 Mgal/d during 1968-83 (table 10), and will increase to 681 Mgal/d by 2020 (table 15). Similarly, the amount of water that flows deeper than model layer 2 (generally the basal zone of the Magothy aquifer) increased from 235 Mgal/d under predevelopment conditions to 446 Mgal/d during 1968-83, and will increase to 474 Mgal/d by 2020. This information indicates that ground-water flow patterns, velocities, and residence times will be further altered by continual development. The most significant implication of which is that increased downward velocities to the deeper aquifers will increase the risk of contamination of those aquifers from land surface sources.

**Table 15.** Distribution of ground-water flow with depth for the year 2020 as represented in model

| County | Model layer[1] | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| | (water table) | (Magothy and Jameco) | | (Lloyd aquifer) |
| Kings and Queens | 136 | 42 | 31 | 5 |
| Nassau | 317 | 238 | 203 | 14 |
| Western Suffolk | 333 | 194 | 134 | 8 |
| Eastern Suffolk | 501 | 207 | 106 | 8 |
| Total | 1,287 | 681 | 474 | 35 |

[1]Flow into layer 1 is recharge from precipitation and returned water use; flow into layers 2, 3, and 4 is leakage from the overlying layer.

## SUMMARY

Land use in Long Island ranges from highly urbanized and industrialized in the west to open land and agriculture in the east. In 1990-92, the population was nearly 6.9 million. Ground water is the sole source of water supply for Nassau, Suffolk and southeastern Queens Counties. In 1981, 385 Mgal/d was pumped for public supply, and an additional 115 Mgal/d was pumped for industrial-commercial and agricultural uses.

The Long Island ground-water system consists of a sequence of seven major hydro-geologic units. In order of deposition they are: the Lloyd aquifer, the Raritan confining unit, the Magothy aquifer, the Jameco aquifer, the Gardiners Clay (a confining unit), and the upper glacial aquifer. These units form a complex hydrogeologic framework that generally has three major aquifer units whose degree of hydraulic connection varies locally, depending on the extent of intervening confining units.

This report describes the results of the simulation of the response of the Long Island ground-water system to water-supply and land development. Ground-water levels, base flow, and water budgets are provided for (1) predevelopment conditions (before-1900), (2) a severe drought in the 1960's, (3) conditions during 1968-83, and (4) the conditions that would likely result from a proposed water-supply development strategy for the year 2020. A three-dimensional ground-water flow model of the main Long Island ground-water system was used to provide quantitative estimates of these hydrologic conditions and of the relations between the hydrologic stress and the response of the ground-water system.

Before development, recharge from precipitation entered the Long Island ground-water system at an estimated rate of 1,126 Mgal/d; nearly 60 percent of which remained in the water-table aquifer; 37 percent moved to deeper units; and only about 3 percent entered the Lloyd aquifer. Recharge was balanced by discharge to streams (460 Mgal/d), the shore (585 Mgal/d), and subsea boundaries (81 Mgal/d). The water table attained a maximum altitude of more than 90 ft above sea level at the center of the island (near the Nassau-Suffolk County border) and contained prominent depressions near more than 100 ground-water-fed streams. The potentiometric surface of the Magothy aquifer was a subdued replica of the water table, and that of the Lloyd was considerably more subdued. The extensive Raritan confining unit severely retards ground-water flow to the Lloyd aquifer, but flow through local holes in this confining unit in Queens and northern Nassau Counties affects the source of water to and the shape of the potentiometric surface in the Lloyd aquifer.

Long Island's ground-water system is bounded laterally by saline ground water; the saltwater-freshwater interface in the confined aquifers is offshore throughout most of southern Long Island, but lies close to the shore throughout northern Long Island. Ground-water levels in the confined aquifers indicate that the interface off the southern shore probably was moving landward, albeit slowly, even during the predevelopment period, in response to the sea-level rise since the last glacial period.

Development during the past 3 centuries has continuously affected the ground-water system of Long Island. Recharge from precipitation has been reduced by the paving of land surface, and large public-supply wells withdraw ground water from deep aquifers. Sewers discharge wastewater and in some places stormwater to the ocean, and stormwater infiltration basins augment recharge in Nassau and Suffolk Counties. Many streams in Kings and Queens have disappeared and subways and deep basements in parts of Kings now function as ground-water drains and require continuous dewatering.

By the early 1980's, more than 400 Mgal/d was pumped islandwide for public, industrial-commercial, and agricultural supplies, but some is returned as leakage from water-supply and sewer lines and as infiltration from domestic septic systems. Kings and Queens Counties import 700 Mgal/d from upstate reservoirs, and more than 50 Mgal/d of this probably reaches the ground-water system through leakage as an unintended form of artificial recharge.

The net stress on the ground-water system (reduced recharge and increased discharge as a consequence of development) during 1968-83 is estimated to be 240 Mgal/d. In response, base flow has decreased by 28 percent (135 Mgal/d). These effects are greatest in Kings, Queens, and western Nassau Counties, where water levels in all aquifers show considerable declines, and some cones of depression extend well below sea level. In these areas, the saltwater-freshwater interface has moved landward, and low ground-water levels indicate that continued movement is likely. Monitoring between the interface and pumping centers would allow early detection of saltwater intrusion.

Simulation of the response of the ground-water system to the 1960's drought indicates that base flow of streams is sensitive to small water-table fluctuations, and that long streams are more sensitive than short ones. This is consistent with the observation that, during recent conditions, the reduction in base flow represents 56 percent of the net stress on the ground-water system.

A projected ground-water-supply strategy for the year 2020 was evaluated using the islandwide model. The net stress on the ground-water system was estimated to be 297 Mgal/d, an increase of 57 Mgal/d over 1968-83. The distribution of stress is expected to be dispersed over the island more uniformly than under recent conditions, however, and thus stress would decrease in Kings, Queens, and western Nassau Counties. As a result, ground-water levels would recover in western Long Island, mitigating the severe cones of depression and the landward gradients that threaten to induce saltwater intrusion in southwestern Long Island, and increasing the base flow in some streams. Most (77 percent) of the increased stress on the ground-water system would be balanced by decreased base flow, mainly in eastern Nassau and western Suffolk Counties; base flow would be reduced to about 20 percent of predevelopment levels in Nassau County and to about 70 percent in western Suffolk County.

The predicted ground-water system response to the proposed water-supply strategy for 2020 could best be used by comparison with the predicted effects of alternative strategies to identify the most effective methods to minimize the adverse hydrologic effects of development.

## REFERENCES CITED


Aronson, D.A., Reilly, T.E., and Harbaugh, A.W., 1979, Use of storm-water basins for artificial recharge with reclaimed water, Nassau County, Long Island, New York—A feasibility study: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water Resources Bulletin LIWR-11, 57 p.

Bailey, B.H., Webster, Kenneth, and Stewart, Ronald, 1985, Long Island precipitation patterns and drought probability: State University of New York at Albany, Atmospheric Sciences Research Center, publication no. 1000, 71 p.

Burr, W.H., Hering, Rudolph, and Freeman, J.R., 1904, Report of the Commission on Additional Water Supply for the City of New York: New York, Martin B. Brown Co., 980 p.

Buxton, H.T., 1985, Estimating average annual base flow at low-flow partial-record stations, Long Island, New York: U.S. Geological Survey Water Resources Investigations Report 84-4240, 32 p.

Buxton, H.T., and Modica, Edward, 1992, Patterns and rates of ground-water flow on Long Island, New York: Groundwater, v. 30, no. 6, p. 857-866.

Buxton, H.T., and Reilly, T.E., 1985, Effects of sanitary sewers on ground-water levels and streams in Nassau and Suffolk Counties, New York, part 2—development and application of southwest Suffolk County model: U.S. Geological Survey Water-Resources Investigations Report 83-4209, 39 p.

_____ 1987, A technique for analysis of ground-water systems at regional and subregional scales applied on Long Island, New York, *in* Subitzky, Seymour (ed.), Selected papers in the hydrologic sciences 1986: U.S. Geological Survey Water-Supply Paper 2310, p. 129-142.

## REFERENCES CITED--Continued


Buxton, H.T., and Shernoff, P.K., 1995, Ground water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 92-76, 111 p.

Buxton, H.T., Smolensky, D.A., and Shernoff, P.K., 1999, Feasibility of using ground water as a supplemental supply for Brooklyn and Queens, New York City: U.S. Geological Survey Water-Resources Investigations Report 98-4970, 33 p.

_____ 1989, Hydrogeologic correlations for selected wells in Long Island, New York—A data base with retrieval program: U.S. Geological Survey Water-Resources Investigations Report 86-4318, 107 p.

Cohen, Philip, Franke, O.L., and Foxworthy, B.L., 1968, An atlas of Long Island's water resources: New York State Water Resources Commission Bulletin 62, 117 p.

Cohen, Philip, Franke, O.L., and McClymonds, N.E., 1969, Hydrologic effects of the 1962-66 drought on Long Island, New York: U.S. Geological Survey Water-Supply Paper 1879-F, 18 p.

Doriski, T.P. and Wilde-Katz, Franceska, 1983, Geology of the "20-foot" clay in southern Nassau and southwestern Suffolk Counties, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 82-4056, 17 p.

Dvirka and Bartilucci Consulting Engineers, 1987, Suffolk County comprehensive water resources plan: Hauppauge, N.Y., Suffolk County Department of Health Services, Division of Environmental Health, 2 v.

Franke, O.L., and Cohen, Philip, 1972, Regional rates of ground-water movement on Long Island, New York, *in* Geological Survey Research 1972: U.S. Geological Survey Professional Paper 800-C, p. C271-277.

Franke, O.L., and Getzen, R.T., 1976, Evaluation of hydrologic properties of the Long Island ground-water reservoir using cross-sectional analog models: U.S. Geological Survey Open-File Report 75-679, 80 p.

Franke, O.L., and McClymonds, N.E., 1972, Survey of the hydrologic situation on Long Island, N.Y., as a guide to water-management alternatives: U.S. Geological Survey Professional Paper 627F, 59 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Getzen, R.T., 1974, The Long Island ground-water reservoir—a case study in anisotropic flow: Urbana-Champaign, Illinois, University of Illinois, Ph.D. thesis, 130 p.

_____ 1977, Analog-model analysis of regional three-dimensional flow in the ground-water reservoir of Long Island, New York: U.S. Geological Survey Professional Paper 982, 49 p.

Gupta, S.K., and Pinder, G.E., 1978, Three-dimensional finite-element model for multilayered ground-water reservoir of Long Island, New York: Princeton University, Department of Civil Engineering, Research Report 78-WR-14.

Harbaugh, A.W., and Getzen, R.T., 1977, Stream simulation in an analog model of the ground-water system on Long Island, New York: U.S. Geological Survey Water-Resources Investigations 77-58, 15 p.

Harbaugh, A.W., and Reilly, T.E., 1976, Analog-model analysis of effects of wastewater management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report II—Recharge with waste water: U.S. Geological Survey Open-File Report 76-847, 34 p.

## REFERENCES CITED--Continued


_____ 1977, Analog model analysis of the effects of wastewater management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report III—Reduction and redistribution of ground-water pumpage: U.S. Geological Survey Open-File Report 77-148, 24 p.

Holzmacher, McLendon, and Murrell, P.C., 1980, Master water plan, Nassau County, state of New York: Mineola, N.Y., Nassau County Department of Public Works, 2 v.

Jacob, C.E., 1941, Notes on the elasticity of the Lloyd sand on Long Island, New York: American Geophysical Union Transactions, v. 22, pt. 3, p. 783-787.

Jensen, H.M., and Soren, Julian, 1974, Hydrogeology of Suffolk County, Long Island, New York: U.S. Geological Survey Hydrologic Investigation Atlas HA-501, 2 sheets, scale 1:250,000.

Johnson, A.H., and Waterman, W.G., 1952, Withdrawal of ground water on Long Island, New York: New York State Water Power and Control Commission Bulletin GW-28, 13 p.

Kilburn, Chabot, 1979, Hydrogeology of the Town of North Hempstead, Nassau County, Long Island, New York: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water-Resources Bulletin LIWR-12, 87 p.

Kilburn, Chabot, and Krulikas, R.K., 1987, Hydrogeology and ground-water quality of the northern part of the Town of Oyster Bay, Nassau County, New York, in 1980: U.S. Geological Survey Water Resources Investigations Report 85-4051, 61 p.

Kimmel, G.E., 1973, Change in potentiometric head in the Lloyd aquifer, Long Island, New York: U.S. Geological Survey Journal of Research, v. 1, no. 3, p. 345-350.

Kimmel, G.E., and Harbaugh, A.W., 1975, Analog-model analysis of hydrologic effects of sewerage in southeast Nassau and southwest Suffolk Counties, Long Island, New York: U.S. Geological Survey Open-File Report 75-535, 22 p.

_____ 1976, Analog-model analysis of effects of waste-water management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report 1—Proposed and current sewerage: U.S. Geological Survey Open-File Report 76-441, 32 p.

Kimmel, G.E., Ku, H.F.H., Harbaugh, A.W., Sulam, D.J., and Getzen, R.T., 1977, Analog model prediction of the hydrologic effects of sanitary sewerage in southeast Nassau and southwest Suffolk Counties, New York: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water Resources Bulletin LIWR-6, 25 p.

Kirkwood, 1867, The Brooklyn water works and sewers—a descriptive memoir: New York, Van Nostrand.

Krulikas, R.K., and Koszalka, E.J., 1983, Geologic reconnaissance of an extensive clay unit in north-central Suffolk County, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 82-4075, 9 p.

Ku, H.F.H., Hagelin, N.W., and Buxton, H.T., 1992, Effects of urban storm-runoff control on ground-water recharge in Nassau County, New York: Groundwater, v. 30, no. 4, p. 507-514.

Lindner, J.B., and Reilly, T.E., 1983, Analysis of three tests of the unconfined aquifer in southern Nassau County, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 82-4021, 52 p.

## REFERENCES CITED--Continued


McAlpine, W.J., 1852, Supplying the city with water: Report made to the Water Committee of the Common Council of the City of Brooklyn, 11 p.

McClymonds, N.E., and Franke, O.L., 1972, Water-transmitting properties of aquifers on Long Island, N.Y.: U.S. Geological Survey Professional Paper 627-E, 24 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meisler, Harold, Leahy, P.P., and Knobel, L.L., 1984, The effect of eustatic sea-level changes on saltwater-freshwater relations in the northern Atlantic coastal plain: U.S. Geological Survey Water-Supply Paper 2255, 28 p.

Miller, J.F., and Frederick, R.H., 1969, The precipitation regime of Long Island, N.Y.: U.S. Geological Survey Professional Paper 627-A, 21 p.

Nemickas, Bronius, and Koszalka, E.J., 1982, Geohydrologic appraisal of water resources of the South Fork, Long Island, New York: U.S. Geological Survey Water-Supply Paper 2073, 55 p.

O'Brien and Gere, 1987, Brooklyn-Queens aquifer study: City of New York, Department of Environmental Protection, v. I, 69 p.

Perlmutter, N.M., and Geraghty, J.J., 1963, Geology and ground-water conditions in southern Nassau and southeastern Queens Counties, Long Island, N.Y.: U.S. Geological Survey Water-Supply Paper 1613-A, 205 p.

Peterson, D.S., 1987, Ground-water recharge rates in Nassau and Suffolk Counties, New York: U.S. Geological Survey Water-Resources Investigations Report 86-4181, 19 p.

Pluhowski, E.J., and Spinello, A.G., 1978, Impact of sewerage systems on stream base flow and ground-water recharge on Long Island, New York: U.S. Geological Survey Journal of Research, v. 6, no. 2, p. 263-271.

Prince, K.R., Reilly, T.E., and Franke, O.L., 1989, Analysis of the shallow groundwater flow system near Connetquot Brook, Long Island, New York: Journal of Hydrology, v. 107, p. 223-250.

Prince, K.R., and Schneider, B.J., 1989, Estimation of hydraulic characteristics of the upper glacial and Magothy aquifers at East Meadow, New York, by use of aquifer tests: U.S. Geological Survey Water-Resources Investigations Report 87-4211, 43 p.

Reilly, T.E., and Buxton, H.T., 1985, Effects of sanitary sewering on ground-water levels and streams in Nassau County, New York, Part 3—Development and application of southern Nassau County model: U.S. Geological Survey Water-Resources Investigations Report 83-4210, 41p.

Reilly, T.E., Buxton, H.T., Franke, O.L., and Wait, R.L., 1983, Effects of sanitary sewers on ground-water levels and streams in Nassau and Suffolk Counties, New York, Part 1—Geohydrology, modeling strategy, and regional evaluation: U.S. Geological Survey Water-Resources Investigations Report 82-4045, 45 p.

Reilly, T. E., Franke, O.L., Buxton, H.T., and Bennett, G.D., 1987, A conceptual framework for solute-transport studies with emphasis on physical mechanisms of solute movement: U.S. Geological Survey Water-Resources Investigations Report 87-4191, 44 p.

## REFERENCES CITED--Continued


Reilly, T.E., and Harbaugh, A.W., 1980, A comparison of analog and digital modeling techniques for simulating three-dimensional ground-water flow on Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 80-14, 40 p.

Reynolds, R.J., 1982, Base flow of streams on Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 81-48, 33 p.

Sawyer, R.M., 1958, Progress report on streamflow investigations in Nassau County, Long Island, New York, 1903, 1937-55: U.S. Geological Survey Open-File Report 58-88, 226 p.

Smolensky, D.A., 1984, Potentiometric surfaces on Long Island, New York—a bibliography of maps: U.S. Geological Survey Water-Resources Investigations Report 84-070, 31 p.

Smolensky, D.A., Buxton, H.T., and Shernoff, P.K., 1989, Hydrologic framework of Long Island, New York: U.S. Geological Survey Hydrologic Investigations Atlas HA-709, 3 sheets, scale 1:250,000.

Soren, Julian, 1971, Ground-water and geohydrologic conditions in Queens County, Long Island, N.Y.: U.S. Geological Survey Water-Supply Paper 2001-A, 39 p.

______ 1978, Subsurface geology and paleogeography of Queens County, Long Island, New York: U.S. Geological Survey Water-Resources Investigation Open-File Report 77-34, 17 p.

Spear, W.E., 1912, Long Island sources—an additional supply of water for the City of New York: New York City Board Water Supply, 708 p.

Stoddard, J.S., 1854, Supply Brooklyn with water by the well system: Document Nine, Documents and Plans, submitted by the Water Committee to the Common Council of the City of Brooklyn.

Suter, Russell, 1937, Engineering report on the water supplies of Long Island: New York State Water Power and Control Commission Bulletin GW-2, 64 p.

Thompson, D.G., and Leggette, R.M., 1936, Withdrawal of ground water on Long Island, New York: New York State Water Power and Control Commission Bulletin GW-1, 28 p.

Vaupel, D.E., Prince, K.R., Koehler, A.J., and Runco, Mario, 1977, Potentiometric surfaces of the upper glacial and Magothy aquifers and selected streamflow statistics, 1943-1972, on Long Island, New York: U.S. Geological Survey Open-File Report 77-528, 23 p.

Veatch, A.C., Slichter, C.S., Bowman, Isaiah, Crosby, W.O., and Horton, R.E., 1906, Underground water resources of Long Island, New York: U.S. Geological Survey Professional Paper 44, 394 p.

Warren, M.A., DeLaguna, Wallace, and Lusczynski, N.J., 1968, Hydrology of Brookhaven National Laboratory and vicinity, Suffolk County, New York: U.S. Geological Survey Bulletin 1156-C, 127 p.