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Simulation of subsea discharge to Jamaica Bay in New York City with a three-dimensional, variable-density, finite-element model

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Abstract A three-dimensional version of the U.S. Geological Survey's Saturated-Unsaturated Transport (Sutra) model was used to simulate groundwater flow and the movement of the freshwater/saltwater interface on western Long Island, the eastern part of New York City. Jamaica Bay, on the south shore of the island, is part of a national recreation area and is a major freshwater-discharge site of the local aquifer system. Analysis of simulated fresh- and saltwater flows at constant-pressure model boundaries indicated that subsea freshwater discharge to Jamaica Bay during 2000 was 114×10^6 L day^{-1}. Simulated subsea freshwater discharge to Jamaica Bay under predevelopment (1900) conditions was 178×10^6 L day^{-1}. Major hydrogeologic factors that affect subsea discharge to Jamaica Bay are the shoreline configuration, the extent and thickness of the Gardiner's Clay (a south-shore confining unit), variations in groundwater recharge, and gaining streams. The effects of these features were investigated through the USGS SutraGUI (graphical user interface) and an additional post-processor designed to analyze subsea discharge.

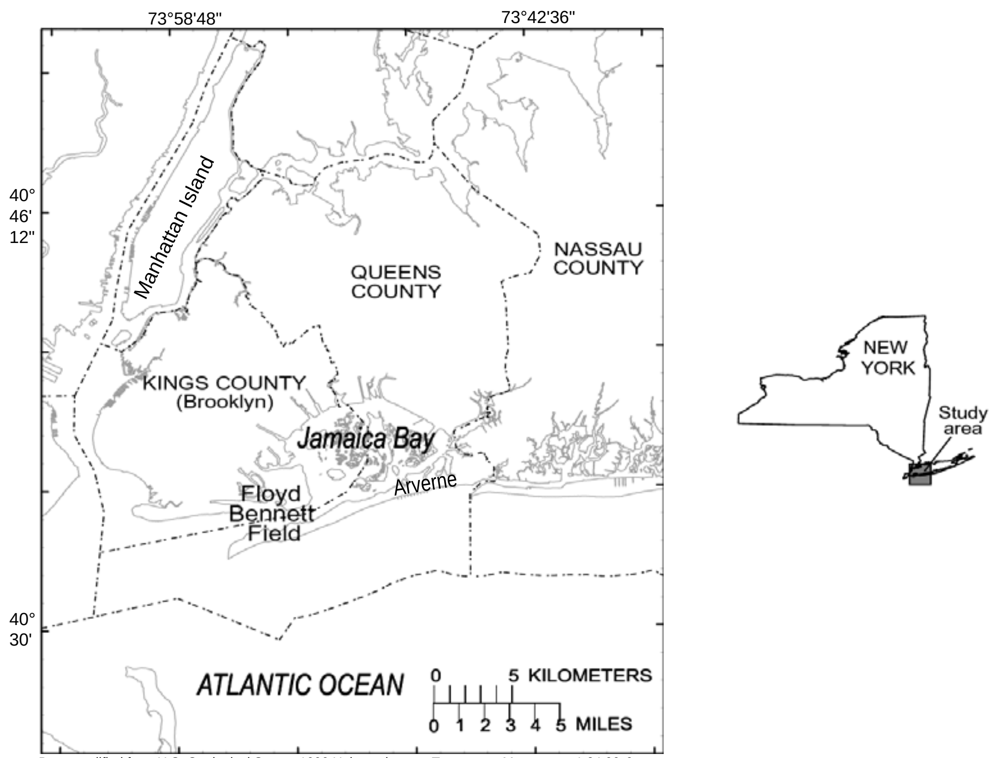
Key words SUTRA, New York City, groundwater, freshwater/saltwater interface

INTRODUCTION

Jamaica Bay, an estuary in the southern part of Kings (Brooklyn) and Queens Counties in New York City (fig. 1), is widely used for recreational purposes. Concern about nutrient loading to the bay prompted the application of a previously-developed groundwater model to estimate groundwater discharge through the seafloor. In 2001, the U.S. Geological Survey, in cooperation with New York City Department of Environmental Protection (NYCDEP), began a 3-year study to develop a three-dimensional, density-dependent, groundwater-flow model. Density-dependence was generally used to investigate saltwater intrusion resulting from groundwater withdrawals, but was found to also be useful in investigating the mechanisms of discharge through the floor of a bay.

Long Island is underlain by a sequence of unconsolidated deposits that lie unconformably on Precambrian bedrock. Total sediment thickness is zero where bedrock crops out in northwestern Queens near Manhattan, about 300 m at Arverne, southeastern Queens (fig. 1), and continues to thicken beyond this point. The bedrock surface forms the relatively impermeable bottom of the groundwater system.

Hydrogeologic units from land surface downward are: (1) the upper glacial aquifer; (2) the Gardiners Clay, which was deposited during an interglacial interval and has an irregular northern boundary and several erosional holes (at Arverne and Floyd Bennett Field, fig. 1) near south-shore barrier beaches; (3) the Jameco aquifer, which was



Base modified from U.S. Geological Survey 1990 Universal Transverse Mercato r, 1:24,00 0

deposited as an ancient river channel fill consisting primarily of gravel; (4) the Magothy aquifer; (5) the Raritan confining unit; and (6) the Lloyd aquifer. Model-calibrated hydraulic properties of the hydrogeologic units are given in Misut *et al*. (2002).

Freshwater enters the groundwater system as precipitation that infiltrates to the water table; it also enters the study area as westward underflow from Nassau County.

About half of the long-term average precipitation, 0.56 m yr^{-1}, was lost through evapotranspiration during the predevelopment period and left a potential recharge rate of about 1.6×10^6 L day^{-1} km^{-2}, which corresponds to a rate of 600×10^6 L day^{-1} to the land area of Kings and Queens Counties. Urbanization has decreased infiltration and increased runoff however; recharge in 2000 is estimated to have been only 50 percent of the predevelopment rate, or about 300×10^6 L day^{-1}. Additional discharge of about 570×10^6 L day^{-1} flows through city sewer lines; most of this water is surface water imported from upstate New York reservoirs; the rest consists of storm-water runoff and leakage of local groundwater into sewers.

The 2002 New York State Department of Environmental Conservation (NYSDEC) yearly inventory of groundwater withdrawals indicates that about 38×10^6 L day^{-1} was pumped for public supply and about 100×10^6 L day^{-1} for industrial and commercial purposes. Much of the pumpage represents dewatering of subway tunnels and deep basements that are flooded as a result of water-table recovery since the curtailment of more extensive public-supply pumping.

MODEL DESIGN AND SIMULATION

The Sutra model code (Voss and Provost, 2002) that was applied uses a modified Galerkin finite-element method with bilinear quadrilaterals. The USGS SutraGUI (Winston and Voss, 2004) provides a geographical information system (GIS) with automatic mesh generation, and was used to generate a list of Jamaica Bay discharge nodes. A FORTRAN program was then used to sum SUTRA nodal output on this list.

The model bottom (bedrock) was simulated as a no-flow boundary because the bedrock is relatively impermeable and forms a physical barrier to flow. A digital elevation model was used to delineate the shoreline. A specified-flux boundary at the land surface was used to represent groundwater recharge from precipitation.

Saltwater hydrostatic-pressure boundaries were applied in offshore zones, and freshwater hydrostatic-pressure boundaries were applied at streams, ponds, and to parts of the eastern boundary of the model to represent the continuation of aquifers beyond the model domain. Some hypothetical stresses may propagate to this boundary, and a more accurate representation may be obtained by eastward extension of the eastern model boundary.

The model domain covers all of Kings and Queens Counties, including the offshore areas, and the part of western Nassau County shown in fig. 1. The mesh contains about 100,000 elements. About 12,000 elements were used to represent each of the aquifers and confining units to allow convective circulation and curvature in simulated saltwater interfaces within hydrogeologic units. A distinction was made between outwash and moraine zones to represent the permeability differences within the upper glacial aquifer and the unsaturated zone; otherwise permeability is uniform throughout the hydrogeologic units. Dense fingers related to convective instabilities of saltwater entering at the sea floor may be possible (Kooi *et al*, 2000) but cannot be represented at the coarse level of model discretization that was used.

Dispersivity values are unknown; therefore, values that were sufficiently large to obtain numerical stability were used. These values probably are unrealistically large, however, and may be refined in the future. The uniformly-distributed parameters were as follows: porosity, 30 percent; longitudinal dispersivity, 800 m; and transverse dispersivity, 8 m. Other key scalar parameter values are freshwater density: 1,000 kg m^{-3}; saltwater concentration: 19,000 mg L^{-1}; fluid viscosity: 10^{-3} m^{-1} s^{-1}; coefficient of fluid density change: 700 kg m^{-3}; water compressibility: 4.47×10^{-10} Pa; molecular diffusivity: 1.0 × 10-9 $m^{-2}s^{-1}$.

Most of the flow system is thought to have approached present (2000) steady-state conditions except for the freshwater/saltwater interface in the Lloyd aquifer (Meisler *et al*, 1984). Simulation of an extended historical period was necessary to generate the present-day Lloyd configuration. About 20,000 years of simulation time resulted in a reasonable present initial condition for all hydrogeologic units, including the Lloyd aquifer. Saltwater entering the Lloyd aquifer was found to consist of both downflow through the Raritan confining unit and lateral flow from specified pressure boundaries offshore at the model domain. Precise timing of the downflow component of saltwater input is infeasible within the context of the time-invariant boundary conditions that were applied, in which sea level was fixed throughout the simulation. Breaches in the Gardiners Clay at Floyd Bennett Field and Arverne (fig. 1) are slightly below the present (2000) sea level and become exposed to saltwater at some unidentified time leading up to the present as sea level rises. The arrival of the rising sea at a breach in the Gardiners Clay opens a new path for density-driven downward flow of saltwater, but the long-term history of sea-level rise is uncertain.

Inspection of the simulated vector fields demonstrates that present conditions flow through the floor of Jamaica Bay consists of both freshwater and saltwater components. Brackish discharge occurs where freshwater flows upward and mixes with overlying saltwater just below the seafloor, or where freshwater mixes with saltwater at the transition zone near a freshwater/saltwater interface. Freshwater flows upward at the north part of the Gardiners Clay holes and discharges directly through the seafloor without mixing; denser saltwater flows downward at the south part. Estimation of the total fresh groundwater discharge was based on the assumption that equal amounts of saltwater recharge and discharge at the Jamaica Bay seafloor; thus subtracting the total inflow (all salty) from the total outflow yields the freshwater component. About 10 percent of the total flow of water through specified pressure boundaries at Jamaica Bay is the saltwater inflow necessary to set up the saltwater-circulation patterns of the upper glacial aquifer. Simulation of 2000 conditions indicated freshwater discharge to be 114×10^6 L day^{-1}, or about 21 L day^{-1} km^{-2} as a total aerial rate for the bay. Simulation of predevelopment conditions indicated freshwater discharge of 178×10^6 L day^{-1}, or about 33 L day^{-1} km^{-2}.

Groundwater flow through the floor of a south-shore embayment similar to Jamaica Bay, about 50 miles east of New York City, was measured by Bokuniewicz and Zeitlin (1980). Measurements were made through a series of devices that enclose a small area in a cylinder that is vented to a plastic collection bag; a rate of 50 L day^{-1} km^{-2} near the shore, decreasing to about 30 L day^{-1} km^{-2} at distance of 100 m offshore was obtained. Assuming exponential decrease in outflow rate with distance from the shore yielded a total aerial rate of 14 L day^{-1} km^{-2} from this embayment. This approach yielded a somewhat smaller number than what is simulated for Jamaica Bay, possibly because it excludes the density dynamics of upward leakage across the Gardiners Clay and was applied to an area that may not be affected by large holes in the Gardiners Clay.

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