UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

ADMINISTRATIVE REPORT

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CONVERSION FACTORS AND ABBREVIATIONS

Factors for converting the units used in this report to International System of Units (SI) are shown below.

Multiply	By	To obtain SI units
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	43.81	liter per second (L/s)
	Hydraulic Units	
transmissivity, square feet per day (ft^2/d)	0.0929	square meter per day (m^2/d)
hydraulic conductivity foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
inch per year (in/yr)	25.4	millimeter per year (mm/y)

ANALYSIS OF THREE-DIMENSIONAL GROUND-WATER FLOW IN VICINITY OF HYDE PARK LANDFILL, NIAGARA FALLS, NEW YORK

by Marcel P. Bergeron

ABSTRACT

A finite-difference model containing seven layers was developed and used to simulate ground-water flow in a 3.8 square mile area near a landfill at the Hyde Park chemical waste site, north of the city of Niagara Falls. The site is underlain by, in descending order (1) a sequence of till and lacustrine deposits, 1 to 34 feet thick, (2) the Lockport Dolomite, a moderately permeable fractured rock aquifer 40 to 120 feet thick, (3) the Rochester Shale, a unit of low permeability about 60 feet thick, and (4) a sequence of carbonates, shales, and sandstones 240 feet thick. The site is bounded by the Niagara River gorge to the west, the Niagara Power Project forebay canal to the north, twin buried conduits of the power project to the east and the Niagara River to the south.

The model simulates flow in the surficial deposits, the Lockport Dolomite, and the Rochester Shale. Steady-state simulations were made with an average annual recharge rate of 2 inches per year at the Landfill and 6 inches per year elsewhere. The calibrated model matched most measured water levels within 5 to 10 ft in the till and lacustrine deposits and in the Lockport Dolomite.

Results of the simulations indicate the following: (1) Regionally ground water in the Lockport Dolomite flows westward toward the Niagara River gorge, northward toward the Niagara Power Project forebay canal, and eastward toward the twin buried conduits. Near the landfill the simulated configuration of the water table indicates that ground water in the Lockport flows northwestward to the Niagara River gorge.

(2) Horizontal hydraulic conductivity values used in the best-fit simulation ranged from 4.9 to 15 feet per day in the upper part of the Lockport and 1.0 to 3.0 feet per day in the lower part. Ratios of horizontal to vertical hydraulic conductivities ranged from 10:1 to 100:1 in the upper part of the Lockport and 55:1 to 1000:1 in the lower part. Vertical hydraulic conductivity of the Rochester Shale used ranged from 0.002 feet per day west of the landfill near the gorge to 0.0002 feet per day east of the landfill.

(3) The uppermost 15 ft of the Lockport Dolomite, where saturated, comprises 35 to 45 percent of the transmissivity of the total unit and has the greatest potential for lateral migration of ground water from the landfill. However, the water budget calculated by the model indicates that about 95 percent of water recharged to the Lockport migrates downward to lower parts of the formation. Ground water discharging from the Lockport Dolomite through the Rochester Shale to the permeable carbonates (Irondequoit and Reynales Formations) beneath amounts to about 83,000 cubic feet per day or 59.5 percent of water recharged.

INTRODUCTION

The Hyde Park landfill is a 15-acre chemical waste-disposal site just north of the city of Niagara Falls (fig. 1). During 1953-75, about 80,000 tons of chemical wastes were buried at the site; these included mirex[1], lindane, trichlorophenol (TCP), and pesticides containing dioxin. In December 1979, the U.S. Environmental Protection Agency (USEPA) and the State of New York filed suit against the site owner, alleging that the wastes posed a health danger to area residents. The three groups entered into negotiations to address the problem of chemical migration from the site and, in January 1981, they filed a consent decree (proposed agreement) with the U.S. District Court (western New York) to remedy the site situation. Court hearings were held through the fall of 1981, and the consent decree was finally approved in May 1982.

One of the issues raised at the court hearing was how water moves through the ground-water system underlying the waste site, which is comprised of a series of fractured bedrock units overlain by surficial till and lacustrine deposits. A principal topic of discussion was the effectiveness of vertical and horizontal (bedding plane) joints in underlying rocks as paths for ground-water movement.

[1] Use of trade names in this report is for identification purposes only.

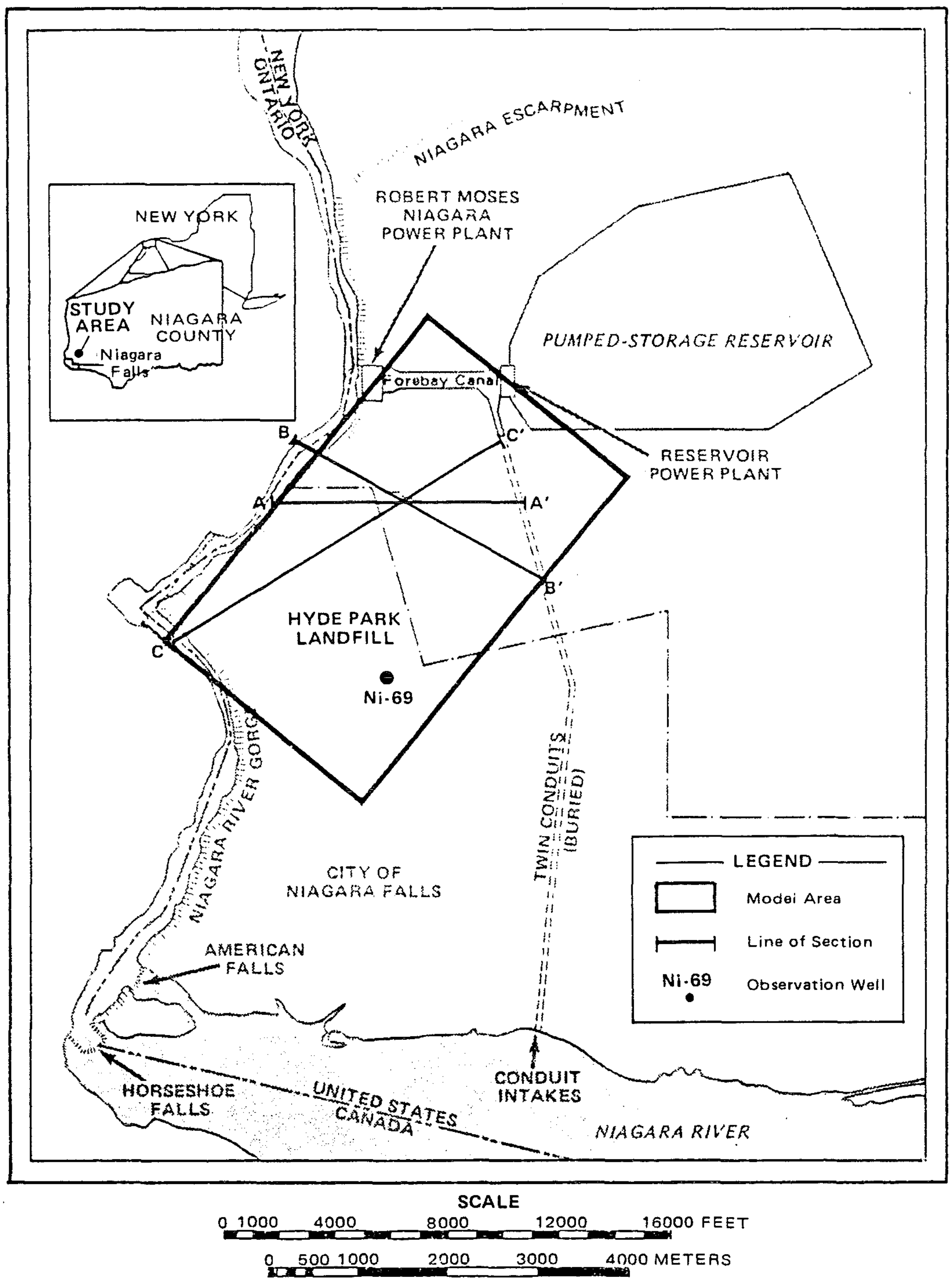

Figure 1 LOCATION OF STUDY AREA

In May 1983, the U.S. Geological Survey entered into an Interagency Agreement with USEPA to evaluate ground-water flow patterns in the Hyde Park landfill area. The principal goal of this investigation is to describe the characteristics of the ground-water flow system in the area of the Hyde Park landfill. To achieve this goal the area of investigation was expanded from the specific area of the landfill to include the natural and man-made hydrologic boundaries that affect the pattern and rates of ground-water flow. The study area is shown in figure 1.

Specific objectives of the study include (1) identification of the major hydrologic boundaries, (2) definition of the quantity and distribution of water entering or leaving the ground-water system at these boundaries, (3) definition of the three-dimensional patterns of ground-water flow in the Lockport Dolomite and the overlying surficial deposits, and (4) evaluation of the magnitude of ground-water leakage from the Lockport Dolomite to the underlying aquifer units through the Rochester Shale.

Purpose and Scope

This report describes the geology and hydrology of the study area and their relationships to the Hyde Park chemical-waste site. The report also describes the development and calibration of a finite-difference, three-dimensional model used to simulate ground-water flow in a 3.8 mi^2 area surrounding the landfill site (fig. 1). Results of the model analysis presented in this report include steady-state water-table and potentiometric head surfaces simulated within surficial unconsolidated deposits and the Lockport Dolomite. The inflow and discharge of ground water from these units at nearby hydrologic boundaries computed from steady-state model simulation are also presented. Listings of selected model data input and output resulting from model simulation are included at the end of the report.

Previous Work

Information used in the construction and calibration of the model described in this report was based mainly on data included in reports by Johnston (1964) on the ground-water hydrology of the Niagara Falls area and by Conestoga-Rovers and Associates on work and data collected near the Hyde Park chemical site from 1979 to the present under contract to the site owner.

Acknowledgments

The computer simulation and preparation of this report were supported by an interagency agreement between the U.S. Geological Survey and the U.S. Environmental Protection Agency. The author thanks Dr. Joseph Spatola of the U.S. Environmental Protection Agency (Region II) and his staff for providing pertinent reports and data used herein.

HYDROGEOLOGIC SETTING

Hydrogeologic Framework

The Hyde Park waste-disposal site is just north of the city of Niagara Falls, approximately 2,000 ft east of the Niagara River gorge (fig. 1). The site altitude is about 610 ft. The location of the Hyde Park waste site and its relationship to underlying unconsolidated deposits, various bedrock units, and the Niagara River gorge are shown in east-west (A-A'), northwest-southeast (B-B'), and southwest-northeast (C-C') geologic sections through the site in figures 2A, 2B, 2C, and 2D. These sections are based on geologic information from recent test borings by Conestoga-Rovers and Associates near the site and from regional characteristics of bedrock stratigraphy in the Niagara Falls area given in table 5 at end of the report.

Test borings at and near the site indicate that the chemical wastes are buried within a sequence of predominantly fine-grained unconsolidated deposits. The total thickness of the sequence ranges from 1 to 34 ft. This sequence consists of three types of sediments: (1) laminated lake sediments of silt and clay that contain thin beds of sand and(or) gravel, (2) silty clay till, and (3) a mixed zone of sand and till directly above the weathered bedrock.

The bedrock beneath the unconsolidated till and lacustrine deposits to the level of the Niagara River is composed of a 420-ft sequence of alternating beds of limestone, dolomite, shale, siltstone, and sandstone (fig. 2B). Near the landfill vicinity, the unconsolidated deposits are directly

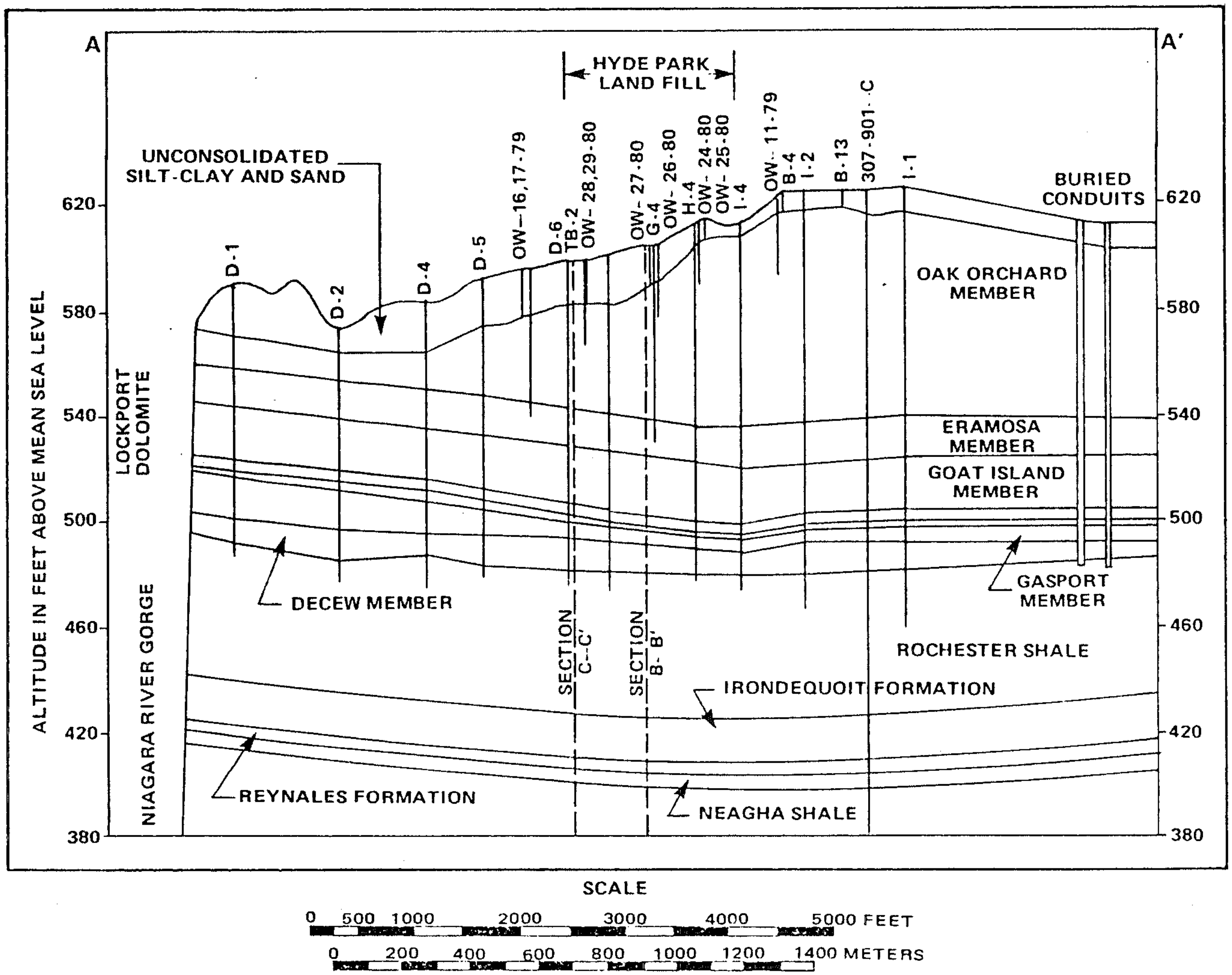

Figure 2A EAST-WEST GEOLOGIC SECTION A—A'

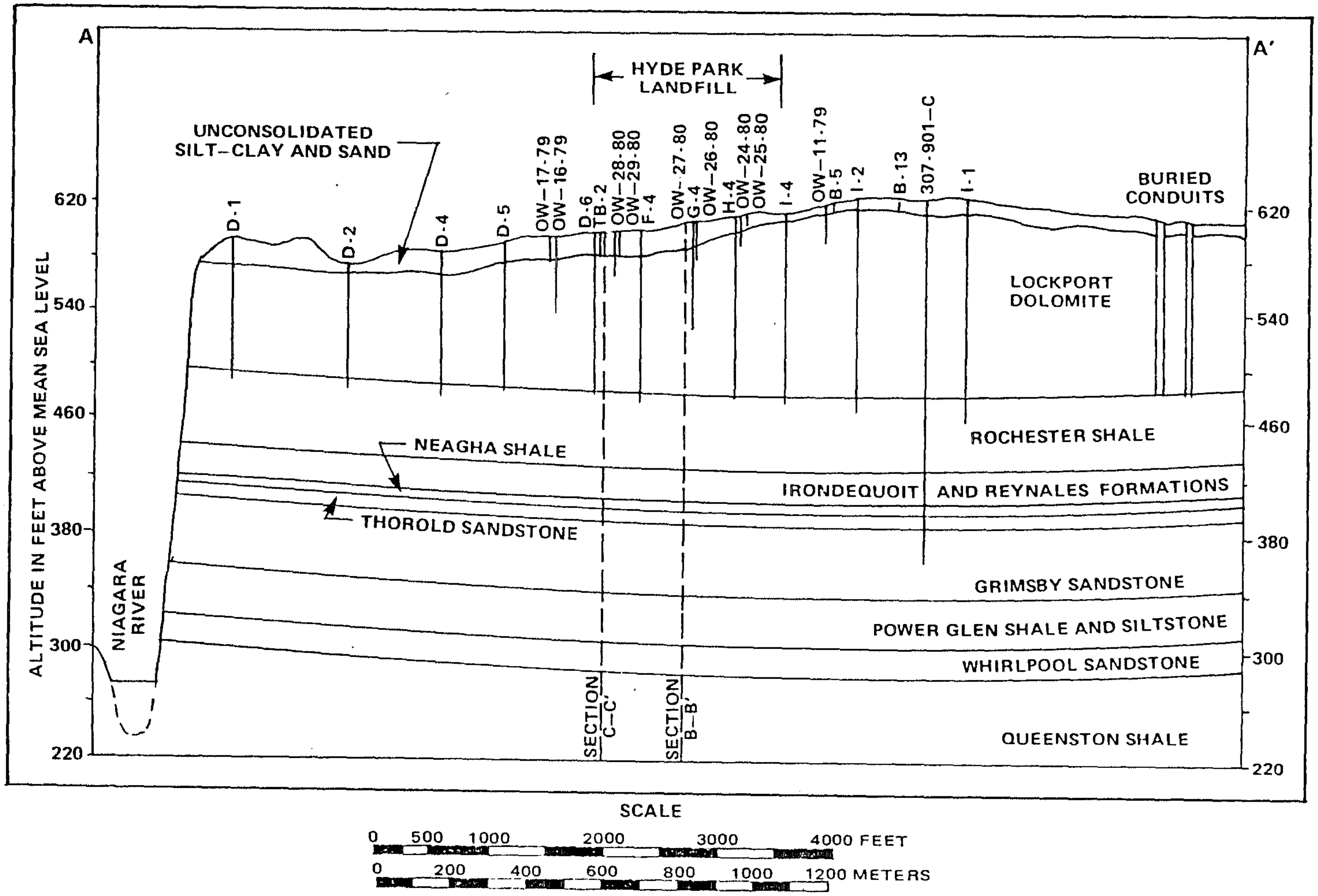

Figure 2B EAST-WEST GEOLOGIC SECTION A–A'

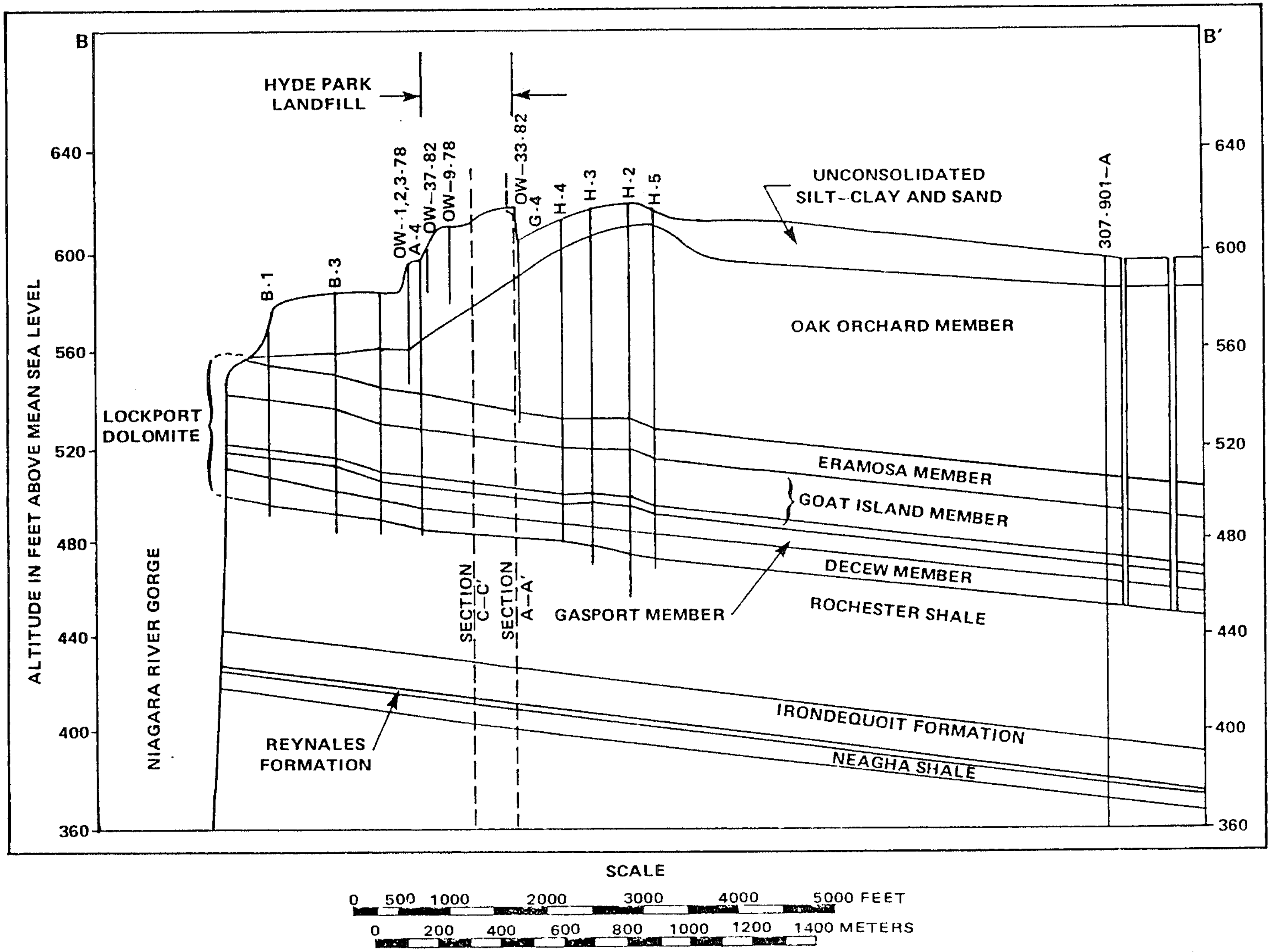

Figure 2C NORTHWEST-SOUTHEAST GEOLOGIC SECTION B—B'

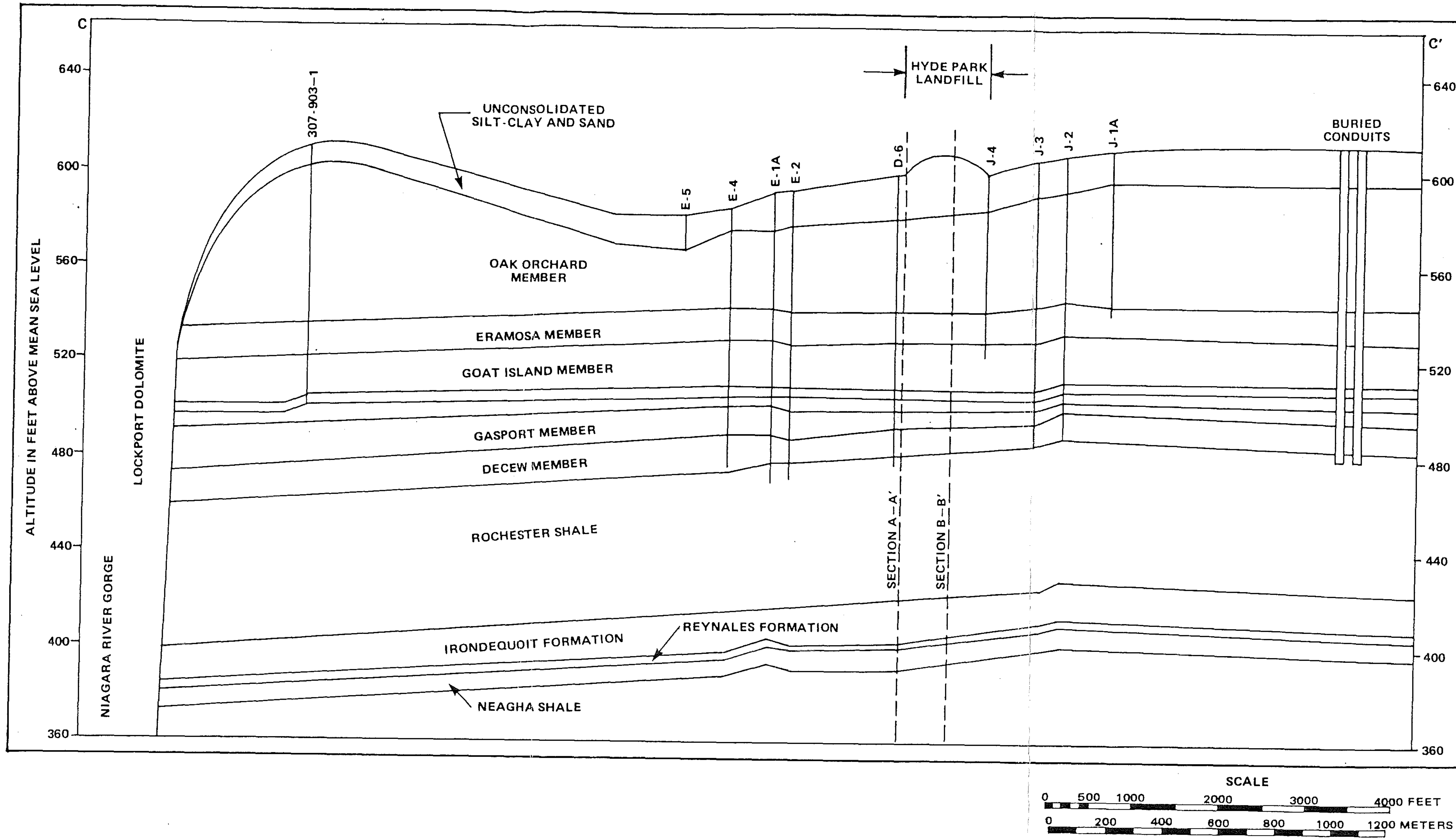

Figure 2D SOUTHWEST-NORTHEAST GEOLOGIC SECTION C–C' underlain by the Lockport Dolomite, a dark-gray to brown, massive to thin-bedded dolomite. Near Hyde Park, the Lockport ranges from 60 to 120 ft thick. On the basis of rock characteristics and fossil evidence, the Lockport is divided into the following members (Zenger, 1965) from top to bottom: Oak Orchard Member, Eramosa Member, Goat Island Member, Gasport Member, and DeCew Member. The stratigraphic position of these units is shown in figures 2A, 2C, and 2D. The characteristics of these members are summarized in the generalized stratigraphic descriptions given in table 5 (at end of report).

The Lockport Dolomite is underlain by a sequence of dark gray calcareous shale referred to as the Rochester Shale. Regionally, the Rochester Shale is about 60 ft thick and dips 30 ft/mi south-southeastward. The surface altitude of the Rochester Shale ranges from 585 ft at the Hyde Park site to 425 ft along the Niagara River south of Niagara Falls (fig. 3).

Below the base of the Rochester Shale to the level of the Niagara River is a 240-ft sequence of bedrock made up of limestone, dolomite, shale, siltstone, and sandstone. The stratigraphic position and approximate thickness of these bedrock units are illustrated in an east-west geologic section A-A' shown in figure 2B. General characteristics and descriptions of these rocks are given in table 5 (at end of report). Of all these rocks, an 18 to 20 ft sequence of carbonate rocks belonging to the Irondequoit and Reynales formation was emphasized in this study. These units directly underlie the Rochester Shale, and collectively represent the first aquifer unit below the Lockport Dolomite.

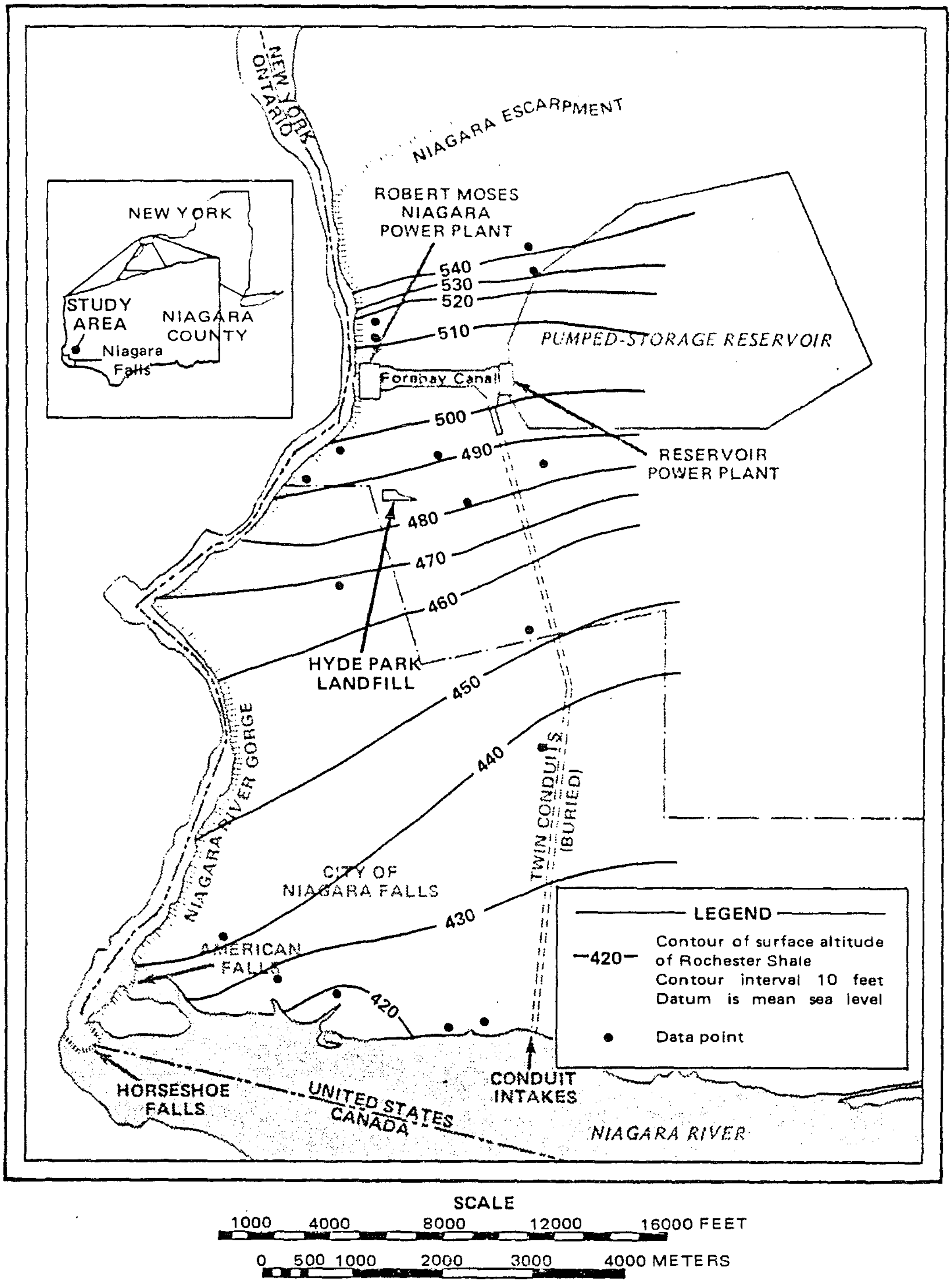

Figure 3 SURFACE ALTITUDE OF ROCHESTER SHALE IN NIAGARA FALLS

The bedrock surface (fig. 4) slopes northwestward across the waste site. Maximum relief of the bedrock surface near the site is about 57 ft, ranging from 615 ft above sea level 800 ft east of the site to 558 ft above sea level 1,600 ft west of the site. Bedding planes within the Lockport Dolomite dip to the south-southeast at about 30 ft/mi (Johnston, 1964, p. 14). This dip reflects the regional dip of all bedrock units in the Niagara Falls area.

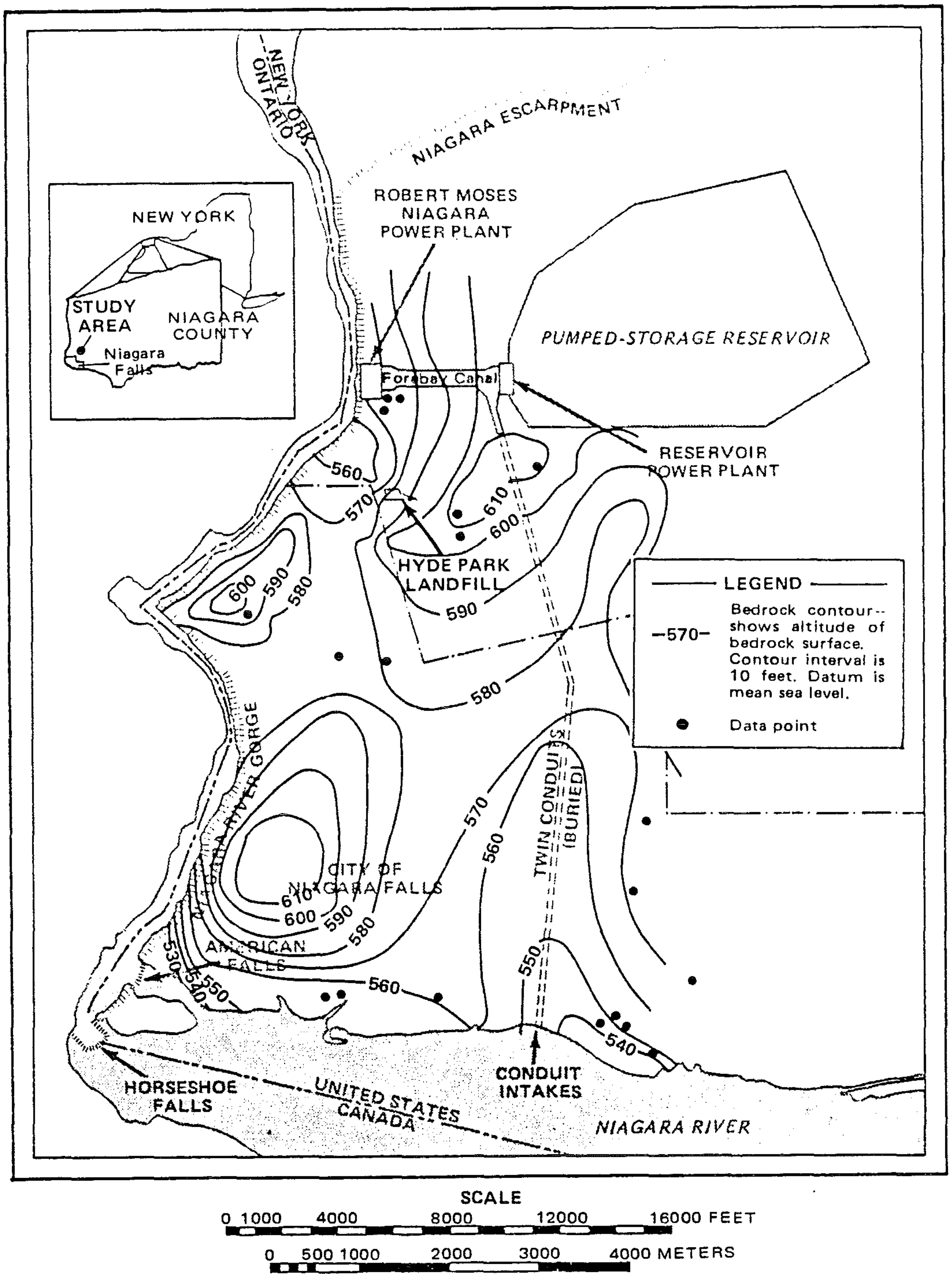

Figure 4 BEDROCK SURFACE ALTITUDE IN NIAGARA FALLS AREA

Water-Transmitting Properties

Unconsolidated Deposits

The shallow unconsolidated deposits are predominantly fine-grained and have low hydraulic conductivity; they rarely yield even modest amounts of water to wells for domestic use. Hydraulic-conductivity values derived from water-level recovery tests in wells tapping these deposits range from 0.0014 to 0.27 ft/d (table 1).

Lockport Dolomite

The Lockport Dolomite is moderately permeable and is considered the principal aquifer unit in the Niagara Falls area. Ground water in the Lockport moves through three types of openings--horizontal bedding joints, vertical joints, and small cavities resulting from the dissolution of gypsum (Johnston, 1964). The character of these openings changes with depth to form two distinct zones. At shallow depths, near-vertical joints and bedding plane joints, enlarged by dissolution of dolomite, form a moderately permeable zone 10 to 15 ft thick at the top of the rock. The thickness of this zone is fairly uniform, regardless of which rock member forms the upper surface. Below the fracture zone, the vertical joints decrease in number and size, and ground water flows predominantly through solution-enlarged bedding joints. The surrounding matrix is mostly a fine-grained dolomite with very low permeability.

Aquifer tests in wells tapping the Lockport Dolomite (Johnston, 1964, table 3, p. 33) have indicated a wide range of transmissivities (90 to 9,000 ft^2/d) and hydraulic conductivities (1 to 70 ft/d). A representative value of transmissivity in the Niagara Falls area was obtained from an aquifer test in which an 18,000-ft section of a dewatered conduit excavation was

Table 1.--Hydrogeologic characteristics and hydraulic properties of unconsolidated deposits and bedrock in the Hyde Park area.[1]

Water-bearing unit	Thickness (feet)	Lithologic description	Hydrogeologic characteristics	Hydraulic properties
Undifferentiated lake deposits	0-20	Laminated clay and silt and thin beds of fine sand.	Clay and silts have low permeability and yield little water.	Hydraulic conductivity range: 0.0014 to 0.27 ft/d.[2]
Till ("Hardpan")	0-10	Mixture of boulders and pebbles in a matrix of sand, silt, and clay.	Water occurs principally in thin sand lenses in till and a "wave-washed zone" at the top of the bedrock.	
Lockport Dolomite	90-130	Dark-gray to grayish-brown massive to thin bedded dolomite, locally containing algal reefs, small masses of gypsum, limestone, and shaly beds at base.	Ground water occurs principally in water-bearing zones parallel to bedding which are much more permeable than the surrounding rock. The upper 10 to 15 feet is the most permeble interval and contains vertical joints and small cavities formed by solution of gypsum. Wells yield 10 to 100 gal/min mostly.	Transmissivity from pump test is highly variable (90-9,000 ft^2/d). Average transmissivity[3] is 300 ft^2/d probable hydraulic conductivity range: 5-15 ft/d (upper 15 feet); 1-2 ft/d (lower part)
Rochester Shale	60	Dark-gray calcareous shale.	Very low permeability shale. Yields no significant water to wells.	Unknown. Hydraulic conductivity assumed to be 2 to 3 orders of magnitude less than that of Lockport Dolomite.

1 Table modified from Maslia and Johnston (1982, p. 5).

2 Based on well-recovery test data from Conestoga-Rovers Associates.

3 Based on steady-state analysis of 18,000-ft section of dewatered conduit penetrating the Lockport Dolomite; average gradient (0.017 ft/ft) and average pumping rate (1,400,000 gal/d) (Johnston, 1964).

considered as a well (Johnston, 1964, p. 34). The test results estimated the transmissivity to be about 300 ft^2/d (table 1). Because the conduit penetrated an average thickness of 100 ft of the Lockport Dolomite, this transmissivity results in an average hydraulic conductivity of 3 ft/d. Conductivity of the upper 10 to 15 ft of the Lockport is probably higher (5 to 15 ft/d) and that of the lower part is probably lower (1.0 to 3.0 ft/d).

Recent drilling in the Lockport Dolomite has led to several observations (Occidental Chemical Corporation, 1983, v. I, p. 42-43). These observations are based on pumping tests that were used to define yield in the Lockport Dolomite. Tests were conducted in 15-ft intervals throughout the entire thickness of the unit.

1. The top 15 ft of Lockport Dolomite consistently yields water when pumped.
2. The second (15 to 30 ft) and third (30 to 45 ft) zones also yield water, but the fourth (45 to 60 ft) zone does not.
3. The 15-ft zone above the Gasport Member (fig. 2A-2C) generally yields water. Massive beds of the Gasport do not yield water.
4. A 15-ft zone at the contact between Rochester Shale and the DeCew Member of the Lockport Dolomite (fig. 2A-2C) yields water at about half of the locations where it has been encountered.

These observations indicate that some zones related to certain massively bedded units in the Lockport Dolomite do not have sufficient permeability to yield water when pumped. The zones appear to correlate with massive beds found in the upper and lower parts of the Goat Island member and the Gasport member. These units most likely are confining layers and restrict the vertical movement of water between more transmissive zones in the sequence. This conclusion is supported by the fact that seepage has been observed in beds just above outcrops of these massive units in numerous locations along the Niagara River gorge.

Rochester Shale

The Rochester Shale is a sequence of low permeability shales which yield no significant water to wells. At exposures of Rochester Shale in the gorge, seepage and springs originate at the contact between the Lockport Dolomite and Rochester and little or no water discharges from the Rochester itself. This evidence indicates that the Rochester is a massive unit with properties similar to those of a confining unit.

No information is available on the hydraulic characteristics of the Rochester Shale in the Hyde Park area, but pressure packer and slug tests at various depths in the corresponding formations in Ontario, Canada, have shown horizontal hydraulic conductivities between 0.01 and 0.25 ft/d (R. A. Findlay, Environment Canada, to Vacys J. Saulys, U.S. Environmental Protection Agency, written commun., Oct. 21, 1982). The applicability of these values to the Rochester Shale near the Hyde Park site is uncertain.

Deeper Aquifers

Little is known about the water-transmitting properties of units below the Rochester Shale because they have not been developed as sources of water. The abundance of vertical and bedding joints exposed in outcrops of these units and at quarries suggest that these units are as permeable as the overlying Lockport Dolomite (Johnston, 1964, p. 42). However, the relatively low permeability of the Rochester Shale should control leakage to these units except in the vicinity of the gorge, where vertical joints (stress release joints) in the Rochester Shale are frequent. Johnston (1964, p. 42) indicated that, because of reduced recharge, the upper part of more permeable sandstones and limestones below the Rochester is dry in many places. Wells completed in these rocks generally have only yielded 2 to 3 gal/min.

Ground-Water Recharge and Flow Patterns

Recharge

Near the Hyde Park waste site, precipitation infiltrates into fine-grained unconsolidated surficial deposits before entering the moderately weathered and permeable fractured upper layer of the Lockport Dolomite. Areal distribution of recharge in the Hyde Park area is unknown. LaSala (1967) estimated an average recharge rate of 6.3 in/yr for sandy areas in upstate New York with an annual precipitation of 35 in/yr. Based on model simulation, Maslia and Johnston (in press) estimated the average annual recharge at Hyde Park, where the annual precipitation is 32 in/yr, to be 6 in/yr.

Hydrologic Boundaries

The ground-water system near the Hyde Park waste-disposal site is bounded on all four sides by natural or man-made hydrologic boundaries. These are (1) the Niagara River gorge to the west, which penetrates to the level of the Queenston Shale (figs. 1 and 2A), (2) the Niagara Power Project Forebay Canal to the north, which extends into the Rochester Shale, (3) the buried conduits of the Niagara Power Project to the east, which fully penetrate the Lockport Dolomite, and (4) the Niagara River to the south which penetrates into upper parts of the Lockport Dolomite. These boundaries are each marked by deeply incised channels which are partially filled with water. These channels are either naturally eroded, as in the case of the Niagara River gorge, or excavated, as in the case of the forebay canal or the conduits.

At the Niagara River gorge, the ground-water system down to the level of the Queenston Shale outcrops above the water line in the river and is exposed to atmospheric pressure. Consequently, ground water in these areas drains into the gorge and the discharge is controlled by the altitude of the point of discharge. Ground water near the forebay canal above the water line in the canal will discharge into the canal in a similar manner. However, below the water line in the canal, ground-water discharge to the canal is controlled by the altitude of the water line.

The interaction of the ground-water system with the buried conduit system of the Niagara Power Project is slightly different than its interaction with the Niagara River gorge and the forebay canal. The buried conduits were constructed in the early 1960's to divert water from the upper reach of Niagara River above the American and Horseshoe Falls to the power-generating facilities of the Robert Moses Power Plant. The system consists of two concrete conduits that are situated at the base of trenches excavated through the Lockport Dolomite to the top of the Rochester Shale. The conduits are covered to land surface with about 45 to 50 ft of relatively coarse backfill material. The backfill material is saturated. Head measurements made in the backfill material at two pump houses of the conduit system suggest that water levels in the backfill are influenced by the relation of stage in the upper reach of the Niagara River and the water level in the forebay canal. Heads measured on one occasion indicated a slight hydraulic gradient from the south part of the conduits near the Niagara River north toward the forebay canal. This hydraulic gradient is unlike the gradient and flow pattern observed in the Lockport which suggests the level of saturation in the backfill is independent of the ground-water system. In the reach near the Hyde Park landfill, the average water level in the backfill material was estimated to be about 545 ft above mean sea level.

At the conduits near the landfill, the bedrock surface altitude (fig. 4) ranges from 580 to 610 ft. Consequently, parts of the ground-water system are well above the backfill saturation level. Above this level, ground water drains into the backfill and the discharge is controlled by the elevation of the point of discharge and the hydraulic properties of the bedrock since the bedrock permeability is probably much lower than the coarse backfill material. Below the backfill saturation level to the top of Rochester Shale, ground-water discharge to the conduit system is controlled by the saturation level of the backfill.

South of the landfill above the American and Horseshoe Falls (fig. 1), the Niagara River penetrates upper parts of the Lockport Dolomite and provides a potentially unlimited supply of recharge to the Lockport Dolomite. Because the Lockport is thickest in this area and, more importantly, conditions are favorable for infiltration of water from the River, wells in an area about a half-mile wide adjacent to the River above the falls have substantially higher yields than wells elsewhere in the area.

Ground-Water Flow Patterns

Lockport Dolomite

The potentiometric surface of the Lockport Dolomite in the Niagara Falls area was estimated using both recent water-level data collected in the vicinity of the landfill and some data given in Johnston (1964). The resultant average surface, representing a period from 1960 to the present, is given in figure 5. Because data are collected from different times and different vertical intervals, this map should only be used to get a general indication of flow patterns in the Lockport. In general, ground water in the Lockport Dolomite moves laterally toward the major hydrologic boundaries in the Niagara Falls area: 1) The Niagara River Gorge, 2) the Niagara Power Project forebay canal, and 3) the buried conduit system of the Power Project. In an area between the landfill and the buried conduits, water levels rise to a maximum altitude of just over 610 ft and form a ground-water divide generally trending north-south just east of the landfill. In some areas the potentiometric surface in the Lockport falls below the top of the bedrock, making the Lockport an unconfined aquifer. In some areas (fig. 5) the potentiometric surface falls below the upper 15 ft of the Lockport which is probably the most transmissive zone in the unit. The estimated area in which the Lockport is unconfined is indicated in fig. 3 by the shaded patterns.

Considerable water-level data have been collected near the landfill since 1975, enabling an improved definition of the potentiometric surface in the immediate vicinity of the landfill. A map of the potentiometric surface of the upper part (uppermost 15 ft) of the Lockport near the landfill in March 1983 is shown in figure 6. The contours are based on measurements in wells tapping the upper 15 ft of the Lockport Dolomite. The potentiometric

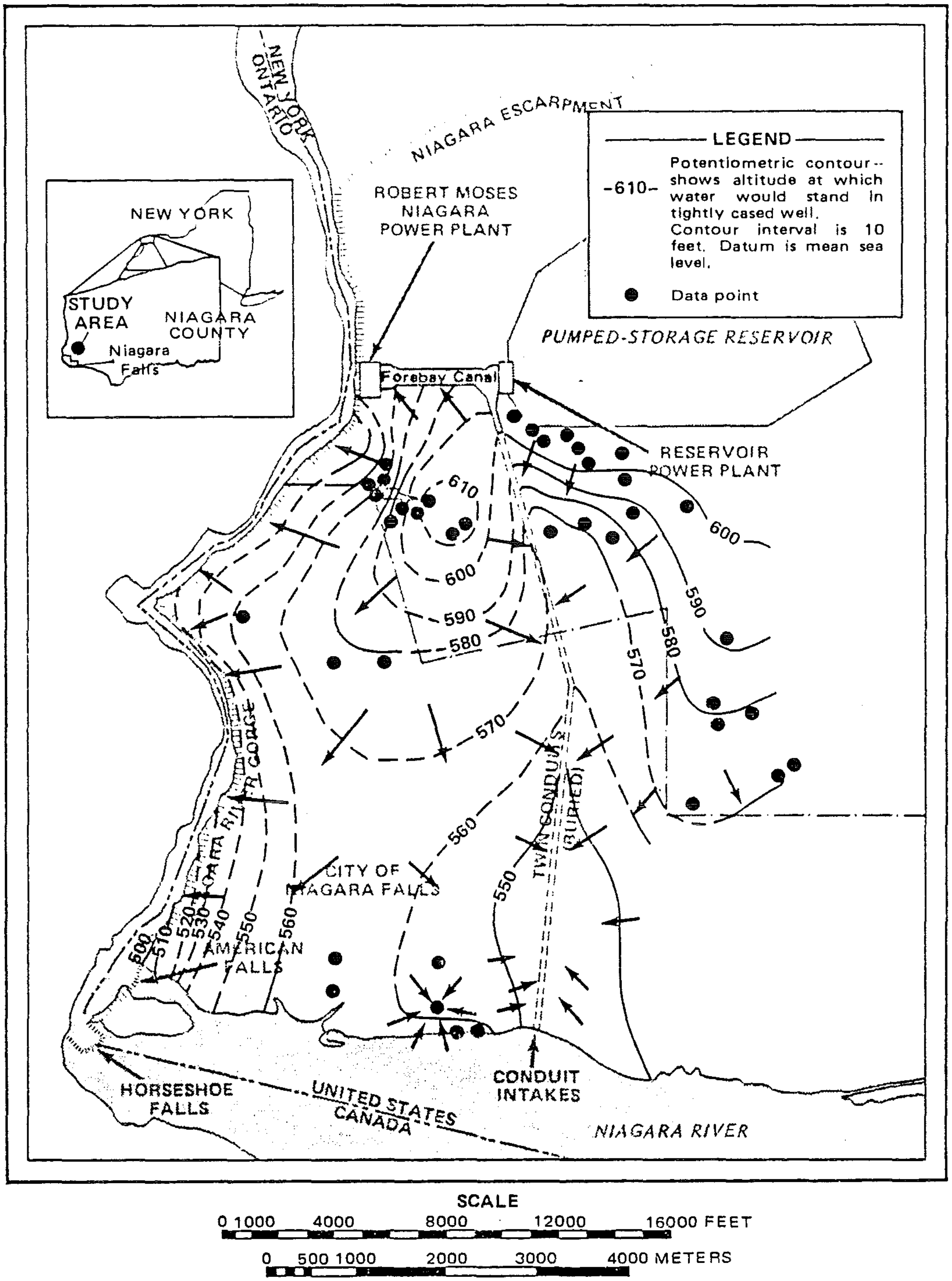

Figure 5 AVERAGE POTENTIOMETRIC SURFACE OF LOCKPORT DOLOMITE IN NIAGARA FALLS AREA (1960-1983)

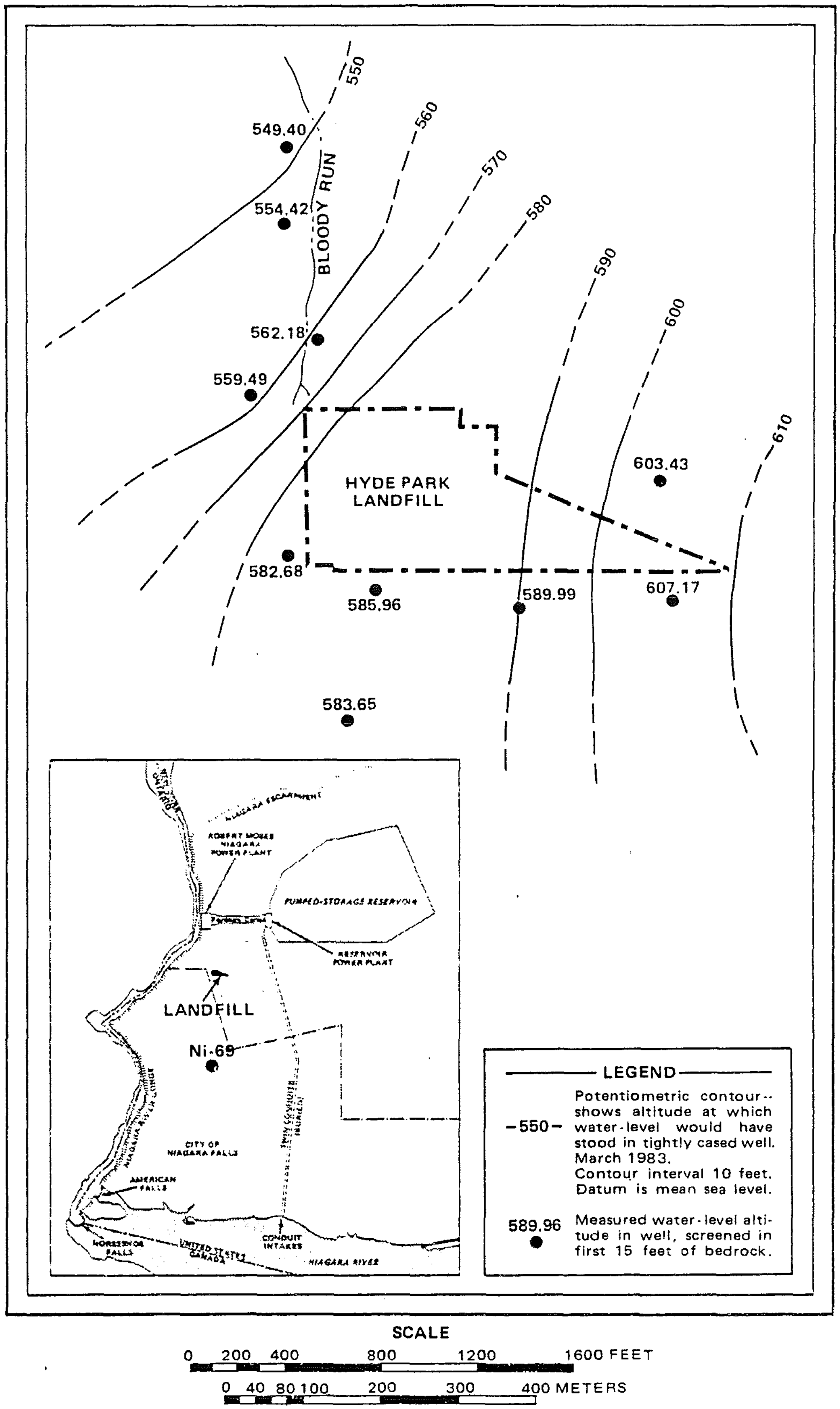

Figure 6 POTINTIOMETRIC SURFACE (MARCH 1983) OF THE UPPER PART OF LOCKPORT DOLOMITE AT THE HYDE PARK LANDFILL

contours reflect an average head distribution within the upper permeable zone of the Lockport. Water level contours in figure 6 suggest that water in the upper part of the Lockport Dolomite beneath the landfill flows northwestward toward the Niagara River gorge. The ground-water divide is located just east of the area shown in figure 6.

The vertical distribution of head beneath the landfill is shown in the hydrogeologic section in figure 7. The data indicates head drops of 5 to 10 ft between the base of the unconsolidated deposits and the upper 15 ft of bedrock (fig. 7) and that water in the unconsolidated deposits moves downward into the bedrock. Abrupt changes in water levels and steplike increases or decreases in yields of wells tapping successive units below the upper part of the Lockport Dolomite indicate that the permeable zones containing solution-enlarged bedding joints in deeper parts of the Lockport act as virtually separate aquifers (Johnston, 1964, p. 29-31). An example of a large head decrease with depth in the Lockport near the landfill is illustrated in figure 7. Water-level data in figure 7 show a 22-ft change in head between interface well OW-19 and well OW-18, which taps a deeper water-bearing zone in the Lockport. These data substantiate the assumed horizontal layering of the Lockport Dolomite.

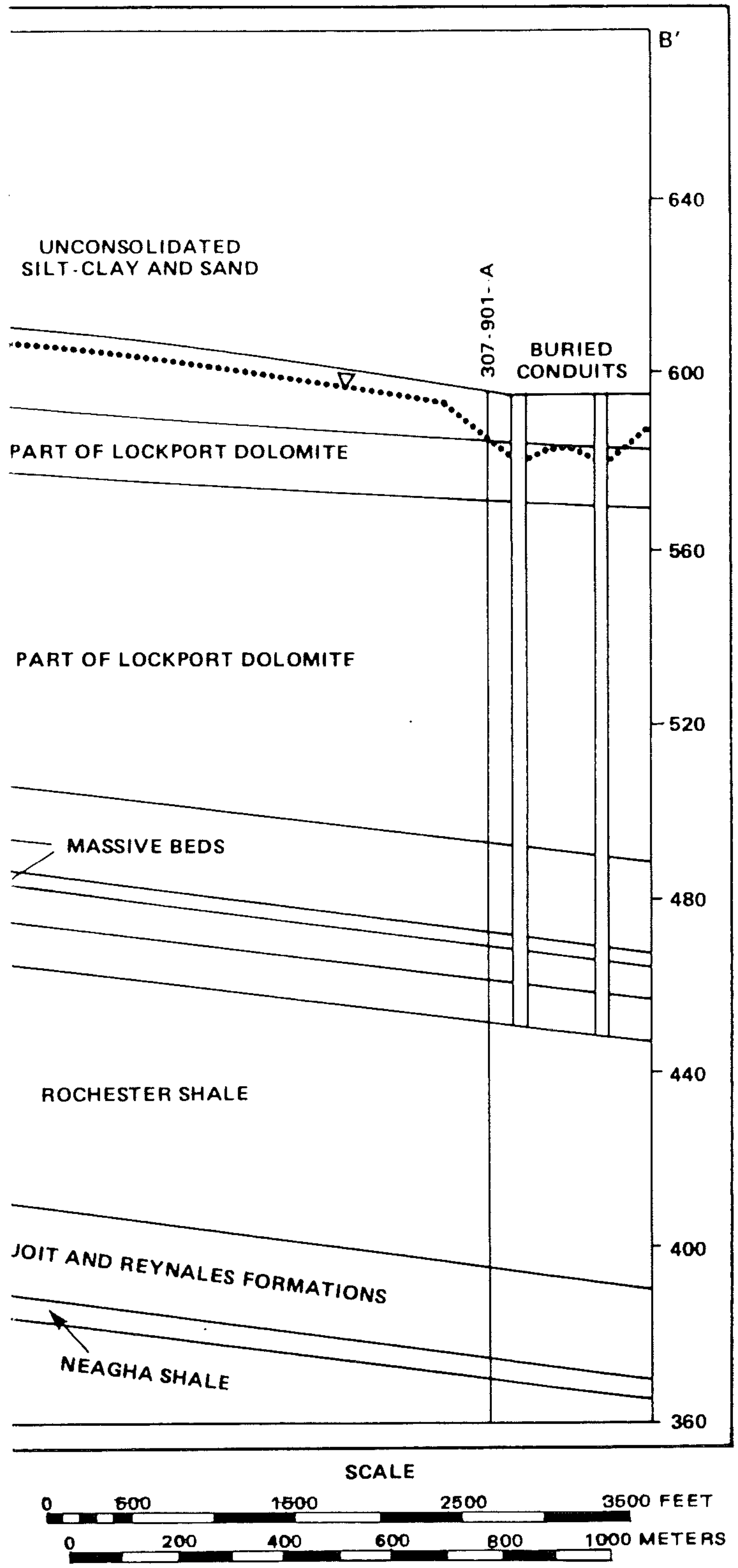

Figure 7 GEOLOGIC SECTION SHOWING HYDROGEOLOGIC UNITS, DEPTHS AND LOCATION OF OBSERVATION AND TEST WELLS, AND AVERAGE MEASURED WATER LEVELS (DECEMBER 1982-MAY 1983)

Rochester Shale

Observations of seepage and springs at the contact between the Lockport Dolomite and Rochester Shale at exposures in the Niagara River gorge suggests that the Rochester itself has little lateral water-transmitting properties. Because of its low relative permeability, the Rochester is more like a confining bed and has a tendency to restrict vertical movement of water to lower formations. Based on numerical simulation, Maslia and Johnston (in press) have concluded that the nearly impermeable Rochester Shale probably contains minor vertical joints that allow water to recharge underlying formations at a very low rate except near the gorge where the shale has a higher density of vertical joints.

Irondequoit and Reynales Formations

Carbonate rocks of the Irondequoit and Reynales formations form the first aquifer unit below the Rochester Shale. The potentiometric surface of the Irondequoit and Reynales aquifer was estimated (see figure 8A) to evaluate the amount of vertical leakage through the Rochester Shale. Because no water-level data are available in this unit in the study area, the surface was estimated from the elevation of discharge points from this unit along the gorge and the Niagara escarpment and from a pattern of flow within the unit. Because the Irondequoit and Reynales Formations are separated from the Lockport Dolomite by about 60 ft. of Rochester Shale, the hydrologic effects of the forebay canal and buried conduits would be less pronounced within these lower units than in the Lockport. In all likelihood, the pattern of flow in these units would resemble that in the Lockort Dolomite before construction of industrial wells and the Niagara Power Project, as depicted by Johnston (1964, p. 54). An interpretation of the direction of ground-water flow in the Irondequoit and Reynales Formation based on the locations of nearby hydrologic boundaries is depicted in figure 8B. The direction of flow shows minimal hydrologic effects from the forebay canal and buried conduits but indicates increased recharge and mounding northeast of the landfill, which might be caused by the head in Niagara Power Project pumped-storage reservoir. This effect is inferred from Johnston's (1964, p. 6 and fig. 16) description of the hydraulic effects of reservoir flooding on water levels in the upper part of the Lockport Dolomite.

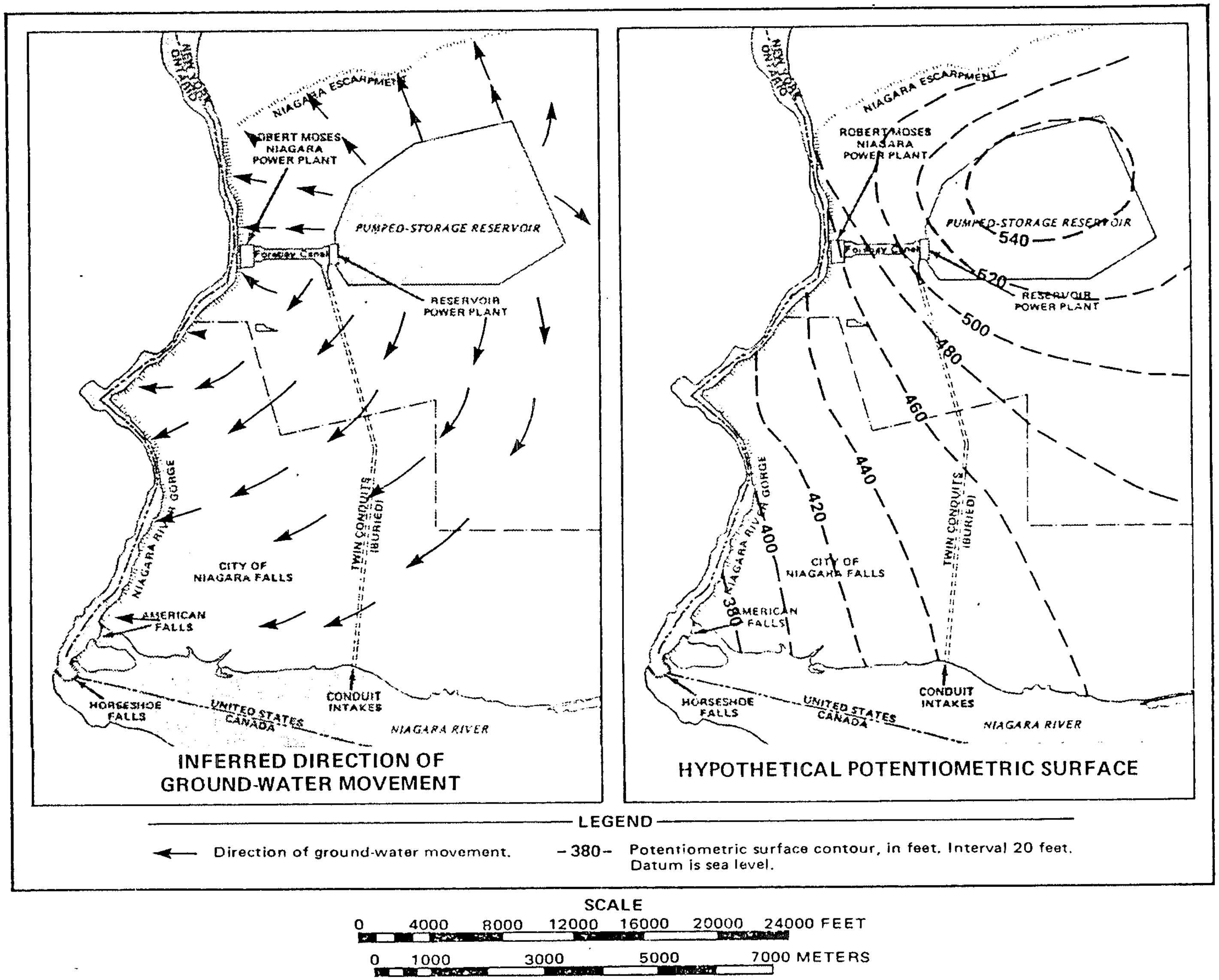

Figure 8 INFERRED DIRECTION OF GROUND-WATER MOVEMENT AND HYPOTHETICAL POTENTIOMETRIC SURFACE IN THE IRONDEQUOIT AND REYNALES FORMATIONS USED IN DIGITAL MODEL

THREE-DIMENSIONAL SIMULATION OF AQUIFER SYSTEM

Digital modeling techniques were used to simulate ground-water flow within the aquifer system. Simulation was useful in evaluating patterns of flow near the Hyde Park landfill and in delineating potential directions of leachate migration that are not apparent from available data.

Model Selection and Design

A three-dimensional model developed by McDonald and Harbaugh (1983) was selected to simulate flow within the aquifer system. The model uses finite difference techniques to numerically approximate the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t} \pm W(x,y,z,t),$$

where:

h = hydraulic head, or potentiometric head (L),

K_{xx} = principal component of hydraulic conductivity tensor in the x direction (L/T),

K_{yy} = principal component of hydraulic conductivity tensor in the y direction (L/T),

K_{zz} = principal component of hydraulic conductivity tensor in the Z direction (L/T),

$W(x,y,z,t)$ = volumetric flux per unit volume (1/T),

S_s = specific storage (dimensionless)

x,y,z = space coordinates,

t = time coordinate or index,

L = unit length, and

T = unit time

Model Grid

The Hyde Park area is modeled with a rectangular block-centered finite difference grid that represents a 3.83-mi^2 area surrounding the landfill (fig. 9). The grid contains 896 grid blocks. Variable grid spacing was selected to provide detail at the Niagara River gorge, at the landfill, and other hydrologic boundaries (forebay canal and buried conduits). Block areas range in size from 562,500 ft^2 (750 ft x 750 ft) along the model boundaries to 62,500 ft^2 (250 ft x 150 ft) in the landfill vicinity. Block sizes were increased by no more than a factor of 1.5 in any direction.

Model Layers

For simulation purposes, the ground-water system underlying the Hyde Park site was divided into seven separate aquifer layers. A schematic representation of these aquifer layers is given in figure 10. The top layer of the model represents horizontal flow in the fine-grained unconsolidated deposits that mantle the Lockport Dolomite. Model layers 2 through 6 were used to simulate flow in the Lockport Dolomite and layer 7 represented a specified head in the Irondequoit and Reynales formations, the first aquifer unit below the Rochester Shale. Layer 7 was the hydrologic base of the model simulation.

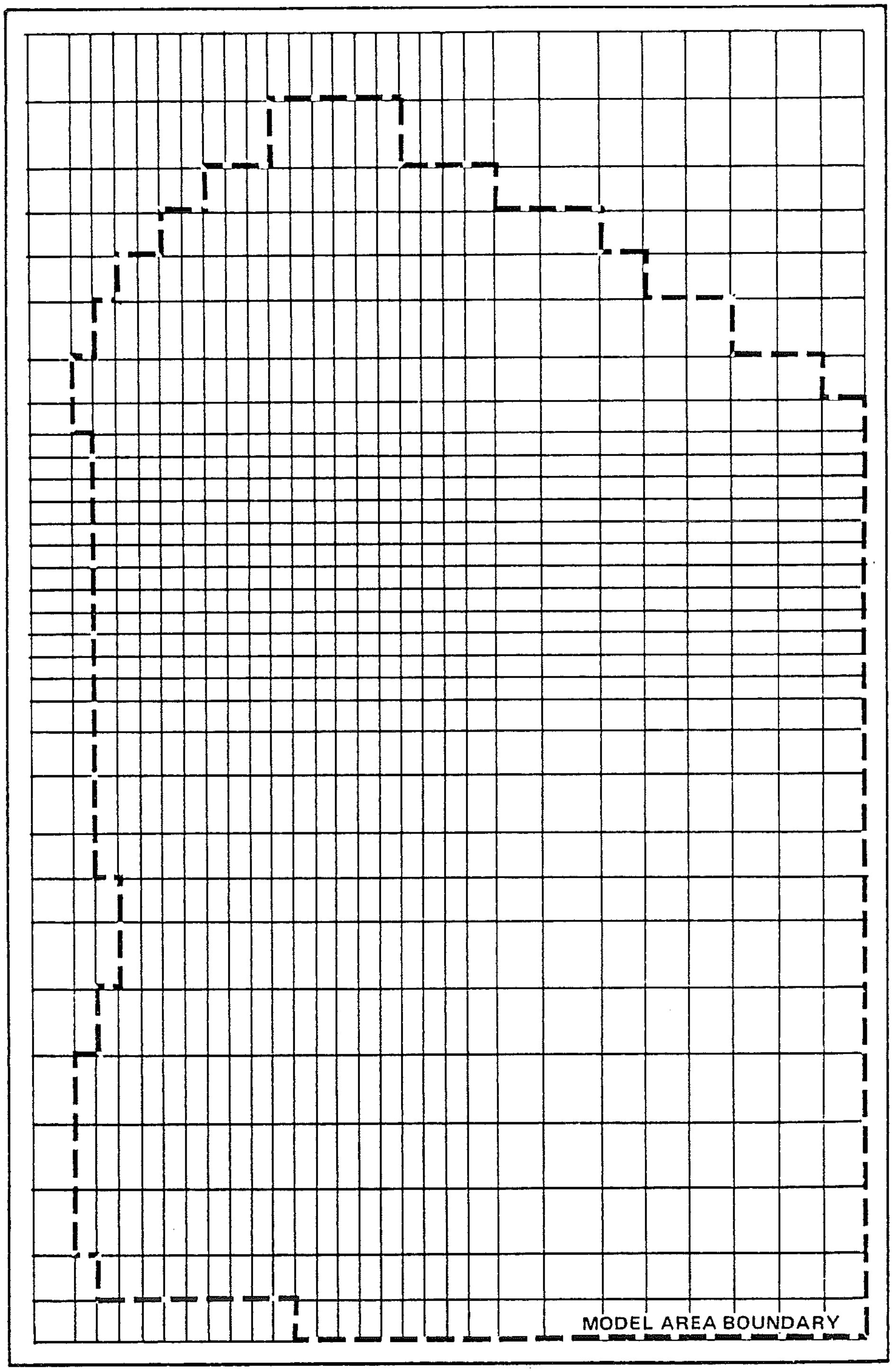

Figure 9 FINITE–DIFFERENCE GRID USED IN DIGITAL MODEL

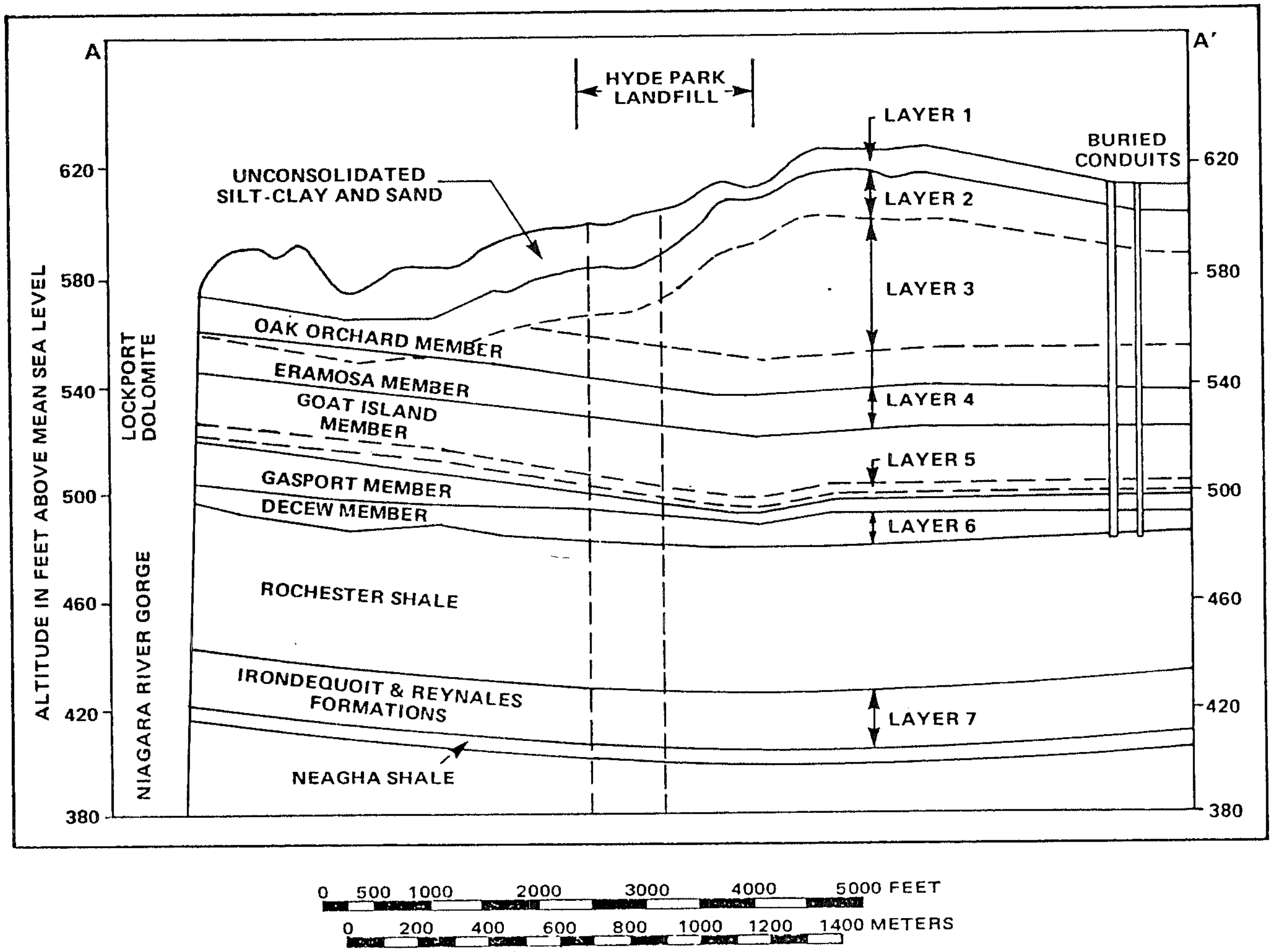

Figure 10 GENERALIZED GEOLOGIC SECTION SHOWING MODEL LAYERING

Lockport Dolomite

The aquifer layering scheme used to represent the Lockport Dolomite was based on the assumption that horizontal flow in the Lockport occurs only in zones which have open bedding-plane joints or fractures. These zones were considered aquifer layers. Massive zones in the rock were considered to act as confining layers which only allow vertical flow between aquifer zones. On the basis of these assumptions, horizontal flow in the Lockport Dolomite was not considered in the massive beds of the upper and lower parts of the Goat Island Member and the Gasport Member.

Aquifer layers were selected to closely correlate with zones that contain open bedding-plane joints and yield water when pumped. Layer 2 represents the permeable uppermost 15 ft of the Lockport. Layers 3 and 4 represent the less permeable thickness above massive upper parts of the Goat Island Member. The bottom of layer 4 coincides with the top of the Goat Island Member. Layer 4 has a maximum thickness of 30 ft except where the total thickness of rock between the top of the Goat Island and the bottom of layer 2 is less than 30 ft; in these areas layer 4 was assigned the difference. Thickness of model layer 3 is simply the distance between the bottom of layer 2 and the top of layer 4. In areas where the thickness of layer 3 is calculated to be less than zero, a minimal thickness of 1 ft was simulated to allow water to flow through layer 3 to layer 4 from layer 2. Representation of layer 3 and 4 in the manner described above makes these zones subparallel to the top of the Goat Island and consequently subparallel to bedding joints. This representation is consistent with the concept that flow along open bedding joints is the primary mechanism for lateral groundwater movement below the upper 15 ft of the Lockport. The thickness of model layers 3 and 4 used in the model are given in Appendix A.

Layer 5 represents a water-bearing zone that coincides with thin- to medium-bedded middle parts of the Goat Island Member and was estimated to be about 4 ft thick. Horizontal flow in the nonwater-yielding zones of the upper and lower parts of the Goat Island Member and the Gasport Member (fig. 10) were not simulated in the model. Layer 6 represents flow in a water-yielding zone, estimated to be about 10 ft thick, that straddles the contact between the DeCew Member and the Rochester Shale.

Irondequoit and Reynales Formations

To evaluate the potential for ground-water leakage from the Lockport Dolomite to water-bearing units below the Rochester Shale, the relatively permeable limestone and dolomite of the Irondequoit and Reynales Formations, which underlie the Rochester Shale (table 5), were simulated as model layer 7. The Rochester Shale has a relatively low permeability and is not considered a water-yielding unit in the Niagara Falls area; therefore, horizontal flow within this unit was not simulated in the model. The head distribution of the Irondequoit and Reynales Formations shown in figure 8A was used and was held constant throughout all simulations. Simulation of the Irondequoit and Reynales Formations in this manner represents a head-dependant leakage boundary condition and forms the bottom hydrologic boundary of the model. The water-transmitting properties of the Rochester Shale in the vertical direction are represented by the vertical leakage used between model layer 6 and 7, as explained later.

Model Data Input

Transmissivity values of all model layers were initially derived by multiplying the assumed thickness of each model layer by the horizontal hydraulic conductivity values used in table 2. These values were used in a cross-sectional finite element model by Maslia and Johnston (in press) that divided the flow system into four separate hydrogeologic units--the unconsolidated deposits, the upper part of the Lockport, the lower part of the Lockport, and the Rochester Shale. Values for the unconsolidated deposits and the landfill were applied in model layer 1; hydraulic conductivity values for the upper Lockport Dolomite were used in model layer 2; and values for the lower Lockport Dolomite were used in model layers 3 through 7.

Vertical flow between aquifer layers was simulated using equivalent vertical hydraulic leakance of the materials separating two aquifer layers. Vertical leakance is defined as the effective vertical hydraulic conductiity of material separating two aquifer layers divided by the thickness of these materials. Vertical hydraulic conductivity values used in initial simulations were based on anisotropy values given in table 2, which indicate a high degree of anisotropy in the Lockport Dolomite and the Rochester Shale. Massive units of the Goat Island and Gasport Members were represented in the vertical leakance between layers 4 and 5, and between layers 5 and 6. The thickness used for the Goat Island member was 20 ft. The thickness of the Gasport Member was variable ranging from 2 to 21 ft. The thickness of the Gasport used in the model at each node is given in Appendix A. The Rochester Shale was represented in the leakance between layers 6 and 7. The thickness of the Rochester Shale used in the calculation was 60 ft.

Table 2.--Hydrologic properties and boundary conditions used in the best-match Hyde Park simulation by Maslia and Johnston (in press).

Hydrologic property	Value or description
Hydraulic conductivity (K_{xx}); in ft/d:	
Till	0.028
landfill	0.011
upper part of Lockport Dolomite	4.9 to 6.6
lower part of Lockport Dolomite	1.5 to 2.0
Rochester Shale	0.020
Anisotropy (K_{xx}/K_{zz}):	
Till	2.5:1
landfill	2.5:1
upper part of Lockport Dolomite	100:1
lower part of Lockport Dolomite	1000:1
Rochester Shale	10:1
Recharge (in/yr):	
Areal recharge	6.0
Areal recharge to landfill (in/yr)	2.0
Boundary condition:	
Bottom of Rochester Shale	outflux, (-0.00055 ft/d)
Niagara River gorge	seepage face
Buried conduits	seepage face
	constant head (555 ft)
	outflux (-0.001 ft/d)

Vertical jointing is prominent in all rocks exposed along the Niagara River gorge (Johnston, 1964). To simulate this condition in the model, the vertical hydraulic conductivity of all rock units within 250 ft of the Niagara River gorge was made significantly higher than elsewhere. In this area, the vertical hydraulic conductivity used to calculate the vertical leakance was based on an anisotropy ratio of 10:1.

Areal recharge in all simulations was fixed at 6 in/yr except at the landfill. This rate is consistent with values developed by La Sala (1967) and was also used by Maslia and Johnston (in press) in their best-match simulation of observed data in the Hyde Park area. Because a layer of relatively low permeability caps the landfill, a lower recharge value of 2 in/yr was applied at the landfill.

Boundary Conditions

Model boundary conditions were selected to reflect real hydrologic boundaries or to minimize the effect of artificial boundaries on results of any stresses simulated in the area of interest. Schematic sections, shown in figure 11, illustrate all boundary conditions used in the model. The real hydrologic boundaries in the area are the Niagara River gorge to the west, the Niagara Power Project forebay canal to the north, and the buried conduits of the Power Project to the east.

The Niagara River gorge penetrates through all bedrock units to the Queenston Shale in the study area. This particular boundary was simulated as a drain boundary. Drain discharges (Q_d) were calculated from the following equation:

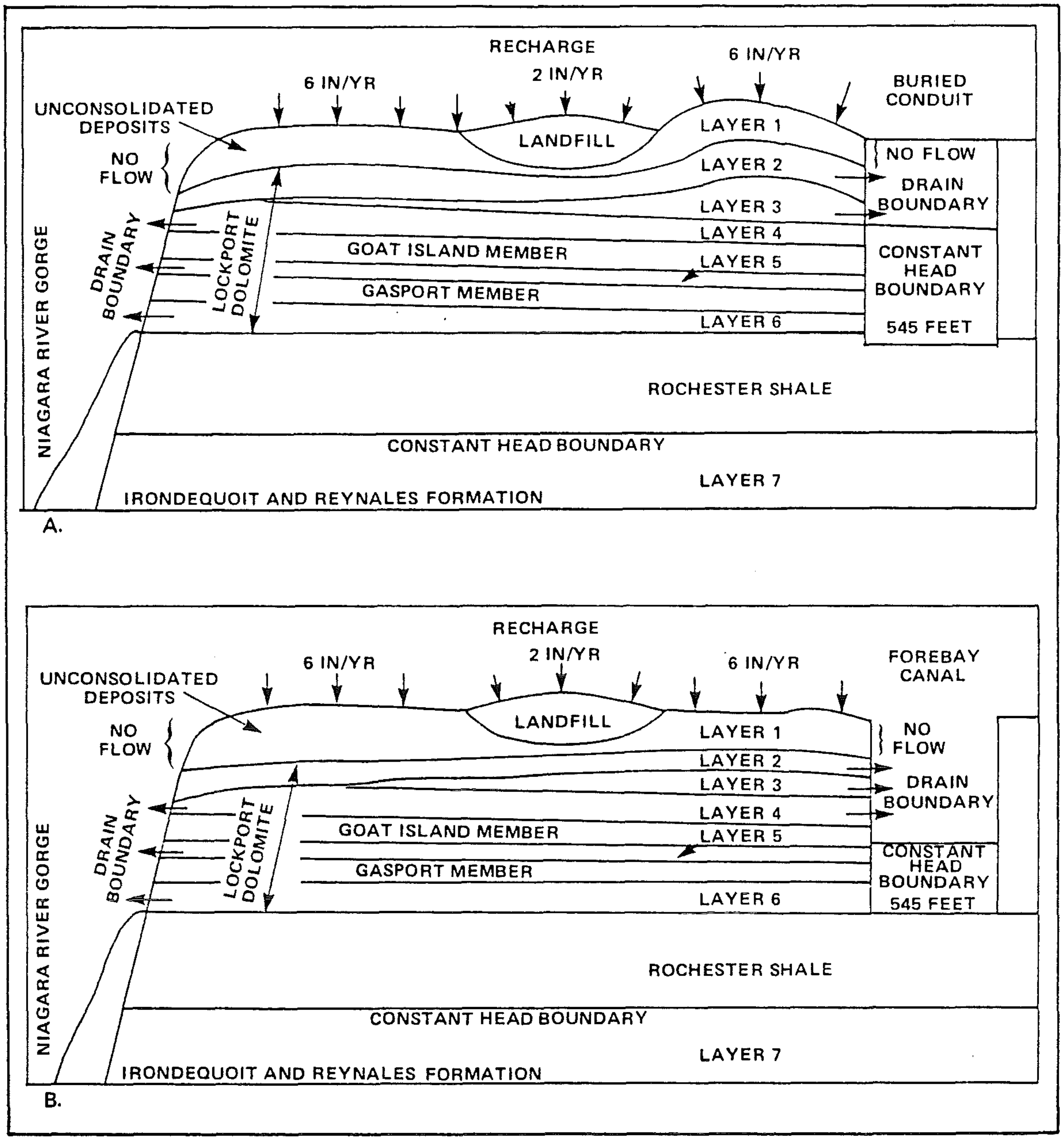

Figure 11 SCHEMATIC SECTIONS SHOWING BOUNDARY CONDITIONS IN THE DIGITAL MODEL: A. WITH BURIED CONDUIT; B. WITH FOREBAY CANAL

$$Q_d = C_d \cdot \Delta h$$

where: C_d is the drain conductance which is equal to the effective hydraulic conductivity divided by the length of flow path controlling the amount of water drained multiplied by the estimated cross-sectional area of the block. The length of the flow path was estimated by using half of the grid block width.

Δh (change in head) is the difference between the simulated aquifer head and a drain altitude. The drain altitude was an assumed water-level altitude in the aquifer layer at the drain boundary. The drain altitude generally ranged from 2 to 5 ft above the aquifer-layer bottom.

A listing of all drain nodes for each model layer with their associated drain conductance and elevations are given in Appendix A.

In most of the aquifer layers, the forebay canal and the buried conduits were also represented by drain boundaries. However, where the water level in the canal or the conduits was above the aquifer-layer bottom, these boundaries were approximated by specified constant heads. Water-level measurements in the backfill material of the buried conduit system and water-level records for the forebay canal indicate that the average water level at these facilities is about 545 ft above sea level. This value was specified at these boundaries.

No physical hydrologic boundaries are present immediately south of the landfill, except for the Niagara River just upstream of Horseshoe Falls and American Falls (fig. 1). However, to minimize both the area of simulation and the effect of artificial boundary conditions, the southern boundary of the model was positioned about 1.5 mi north of the southern reach of the Niagara River (fig. 9). Although this boundary does not represent a real hydrologic boundary, it can be adequately represented by constant head values.

Constant heads in layer 2 were based on the water-level distribution in the upper Lockport Dolomite shown in figure 7. Specified heads in other aquifer layers were estimated based on an assumed head change of about 25 ft between the top and base of the Lockport Dolomite. This gradient is consistent with head changes observed in wells near the landfill. The head drop between model layers was distributed to reflect the stratigraphic position of the model layer with respect to the entire thickness of the Lockport. In vicinity of the Niagara River gorge and the buried conduits, constant heads were adjusted to reflect the effect of the drain or constant head boundary simulated.

The estimated potentiometric surface in the Irondequoit and Reynales Formations, shown in figure 8A was used as an initial head distribution for model layer 7 and was held constant in all simulations. In this manner, model layer 7 represents a head-dependent leakage boundary and a hydrologic base in the model. Despite the uncertainties in using this potentiometric surface as the hydrologic base of model, it provides a reasonable set of data for evaluating the amount of ground-water leakage from the Lockport Dolomite to underlying aquifer units.

The distribution of constant heads in various layers of the model are specified in the boundary arrays presented in Appendix A. Constant head nodes are indicated by negative values. The specified heads of these nodes are given in the final head arrays given in Appendix B.

Model Calibration

The purpose of this ground-water simulation was (1) to collaborate the present understanding of the flow system, (2) to quantify ground-water discharges to nearby hydrologic boundaries, and (3) to refine estimates of the water-transmitting properties of the aquifer system. To accomplish these tasks, a steady-state flow model was calibrated to water levels measured between December 1982 and May 1983. This period was selected for calibration because several measurements had been made in the upper 15 ft of the Lockport Dolomite in numerous test holes drilled by Conestoga, Rovers, and Associates during this time. This data supplemented previous data and provided additional information for calibration.

Calibration of the model was done to steady state because the aquifer system has been in a state of dynamic equilibrium and no significant pumping has occurred near the landfill in recent years. A hydrograph of an observation well tapping the upper part of the Lockport Dolomite about 1 mi south of the landfill (fig. 12) shows that water levels in the Lockport fluctuate 3 to 4 ft per year (the total fluctuation was 6 ft in the 1958-83 record) related to seasonal changes in recharge and discharge in the aquifer. However, these changes fluctuate around an average value, and are a good indication of steady-state conditions. The average water level in the well (fig. 12) from December 1982 through May 1983 is only slightly above the 10-year average, which indicates the period selected for calibration is fairly representative of average conditions in the flow system.

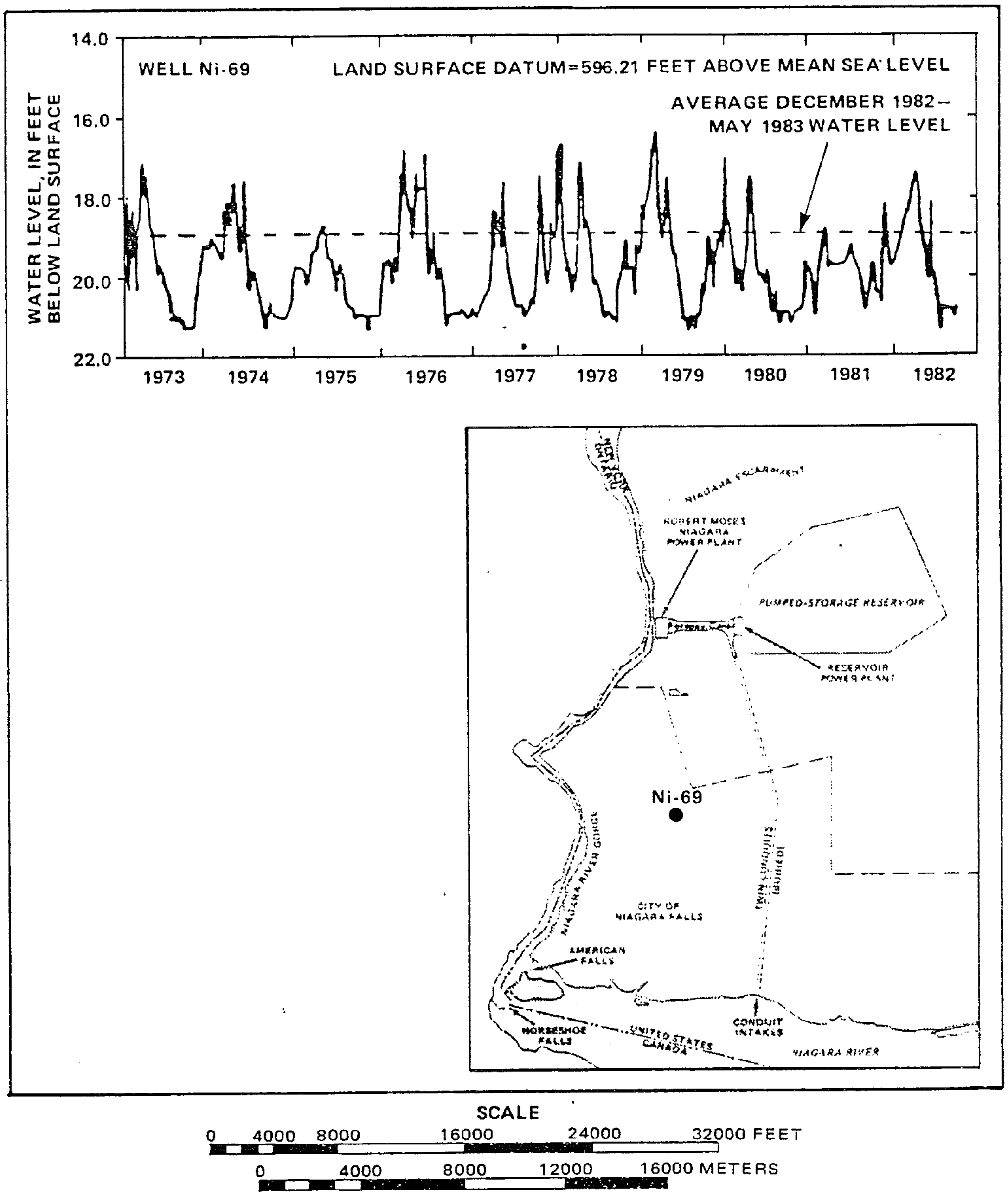

Figure 12 WATER LEVELS IN UPPER PART OF LOCKPORT DOLOMITE (1973-1982) AT OBSERVATION WELL Ni-69

Calibration Adjustments

Most of the calibration simulations were run to evaluate a range of variations in anisotropy and hydraulic conductivity. Values of horizontal hydraulic conductivity and ratios of anisotropy considered during calibration are detailed in table 3.

In the best-fit simulation, horizontal hydraulic conductivities of all model layers were very similar to the initial estimates. Hydraulic conductivity of the fine-grained unconsolidated deposits was 0.028 ft/d, a slightly lower value of 0.0011 ft/d was used for the landfill value to reflect the effects of the layer of relatively low permeability that caps the landfill and the high-density liquid from the chemical waste and leachate buried in the landfill. An anisotropy ratio (Kxx:Kzz) of 10:1 was used in all areas. Final hydraulic conductivity values used in the model for layer 1 are given in Appendix A.

Heads in the Lockport Dolomite (model layers 2 through 6) were most accurately reproduced with a hydraulic conductivity of 4.9 to 15.0 ft/d in the upper Lockport (model layer 2) and 1.0 to 3.0 ft/d in the lower Lockport (model layers 3 through 6), except in the area of a bedrock high southwest of the landfill (fig. 3). The values (6.7 and 2.0 ft/d) were applied in the upper and lower parts of the Lockport, respectively, along a 2,500-ft-wide band of rock along the Niagara River south and west of the landfill to reflect the increased density of joints near the Niagara River Gorge. Values of 15.0 and 3.0 ft/d were used in the upper and lower parts of the Lockport, respectively along the bedrock valley trending from an area along the western edge of the landfill to the Niagara River Gorge. Final hydraulic conductivity values of layer 2 and transmissivity values of layers 3, 4, 5, and 6 are given in Appendix A.

Table 3.--Hydraulic conductivity and anisotropy values used in Hyde Park model calibration

[Hydraulic conductivity values in ft/d. Recharge = 2.0 in/yr at landfill, 6.0 in/yr elsewhere.]

Hydrogeologic unit and model layer	Initial values	Range considered in calibration min. - max.	Final values or range
Unconsolidated deposits (layer 1)			
Horizontal hydraulic conductivity	0.028	0.0044 - 0.028	0.028
Horizontal hydraulic conductivity at landfill	0.011	0.0044 - 0.028	0.011
Anisotropy[1]	2.5:1	1:1 - 100:1	10:1
Lockport Dolomite, upper part (layer 2)			$1.7 \times 10^{-3} - 5.3 \times 10^{-3}$
Horizontal hydraulic conductivity	4.9	3.0 - 20.0	4.9 - 15.0
Anisotropy[1]	100:1	5.1 - 1000:1	10:1 - 100:1
Lockport Dolomite, lower part (layer 3-4)			
Horizontal hydraulic conductivity	1.5	0.5 - 5.0	1.0 - 3.0
Anisotropy[1]	1000:1	5.1 - 1000:1	55:1 - 550:1
Lockport Dolomite, lower part (layer 5)			
Horizontal hydraulic conductivity	1.5	0.5 - 5.0	1.0 - 3.0
Anisotropy[1]	1000:1	100:1 - 10,000:1	100:1 - 1000:1
Goat Island Member			
Vertical hydraulic conductivity	0.0015	0.00015 - 0.015	0.0010 - 0.010
Gasport Member			
Vertical hydraulic conductivity	0.0015	0.00015 - 0.015	0.0010 - 0.010
Lockport Dolomite, lower part (layer 6)			
Horizontal hydraulic conductivity	1.5	0.5 - 5.0	1.0 - 3.0
Anisotropy[1]	1000:1	100:1 - 10,000:1	100:1 - 1,000:1
Rochester Shale			
Vertical hydraulic conductivity	0.002	0.00001 - 0.005	0.0002 - 0.002
Irondequoit and Reynales (layer 7)			
Horizontal hydraulic conductivity	1.5	0.5 - 3.0	1.0 - 2.0
Anisotropy[1]	1000:1	100:1 - 10,000:1	100:1 - 1000:1

[1] Ratio of horizontal to vertical hydraulic conductivity (K_{xx}/K_{zz})

Vertical hydraulic conductivities used in the best simulation indicate the Lockport Dolomite to be strongly anisotropic. Ratios of anisotropy (Kxx:Kzz) with minor exceptions were 100:1 in the upper part of the Lockport (model layer 2). Ratios of 550:1 (model layers 3 and 4) and 1,000:1 (model layers 3 through 6) were used in the lower part of the Lockport. Except in the area of the bedrock high southwest of the landfill (fig. 3), anisotropy values of 135:1 (layers 3 and 4) and 250:1 (layers 5 and 6) were used along a 2,500 ft band of rock along the Niagara River south and southwest of the landfill. Higher vertical hydraulic conductivity values were also used in the first 250 ft from the Niagara River gorge, where ratios of anisotropy were 10:1 in the upper part of the Lockport and 55:1 (layers 3 and 4) and 100:1 (layers 5 and 6) in the lower part of the Lockport. These increases in vertical conductivity near the gorge were intended to reflect a greater density of vertical (stress release) joints near the gorge face. Final values used in the model of vertical leakance between layers 1 and 2, 2 and 3, 3 and 4, 4 and 5, and 5 and 6 are given in Appendix A.

A large range of vertical hydraulic conductivities (table 3) was used to evaluate the potential for ground-water leakage from the Lockport Dolomite through the Rochester Shale to underlying water-bearing units. Final values of vertical hydraulic conductivity of the Rochester Shale was 0.0002 ft/d. Slightly higher values of 0.0004 to 0.0008 ft/d were used in the first 2500 ft along the gorge south and west of the landfill, except in the area of the bedrock high southwest of the landfill (fig. 3). Values of 0.0012 were used in the bedrock valley trending from an area along the west edge of the landfill to the Niagara gorge to reflect a slightly higher degree of vertical jointing in this area. Values of 0.003 ft/d were used in the first 250 ft from the gorge face. These values were intended to represent the effect of increased vertical jointing in these areas. These values are slightly lower than vertical conductivities used by Maslia and Johnston (in press) in their best fit simulation. The difference in values is attributable to different boundary conditions used in the respective models to simulate flow at the base of the Rochester Shale. The Maslia and Johnston model used a specified flux, whereas the model in this study uses a head-dependent leakage boundary. Final values used in the model of vertical leakance between 6 and 7 which reflect the hydraulic properties of the Rochester Shale are given in Appendix A.

Model Results

Water Levels

To demonstrate the match between simulated and observed model-generated water levels, heads of model layers 1, 2, and 5 are shown in figures 13, 14, and 15, respectively. Deviations of simulated water levels from some water levels measured in wells considered to be screened in the horizon represented by each model layer are shown. Final values simulated at individual nodes for all other model layers are given in Appendix B. The simulated head distributions can be compared to figure 5 to assess how well it matches previously discussed concepts of hydraulic gradients and flow patterns. In general, the simulated head distributions compare favorably with most field measurements and match many observed heads within 5 to 10 feet. All heads are matched within 15 ft.

The simulated configuration of the water table in model layer 1 shown in figure 13 reproduces the observed ground-water divide east of the landfill. The position of this mound indicates that all ground water recharged near and flowing through the landfill will flow northwestward toward the Niagara River gorge. However, because the low permeability of this unit inhibits the lateral movement of water, water in the surficial deposits eventually migrates downward and recharges the Lockport Dolomite. In fact, in areas bordering the gorge as well as near the forebay canal, and the buried conduits, these surficial deposits are dry (see fig. 13) and the water-table surface drops below the surficial deposits into upper parts of the Lockport Dolomite.

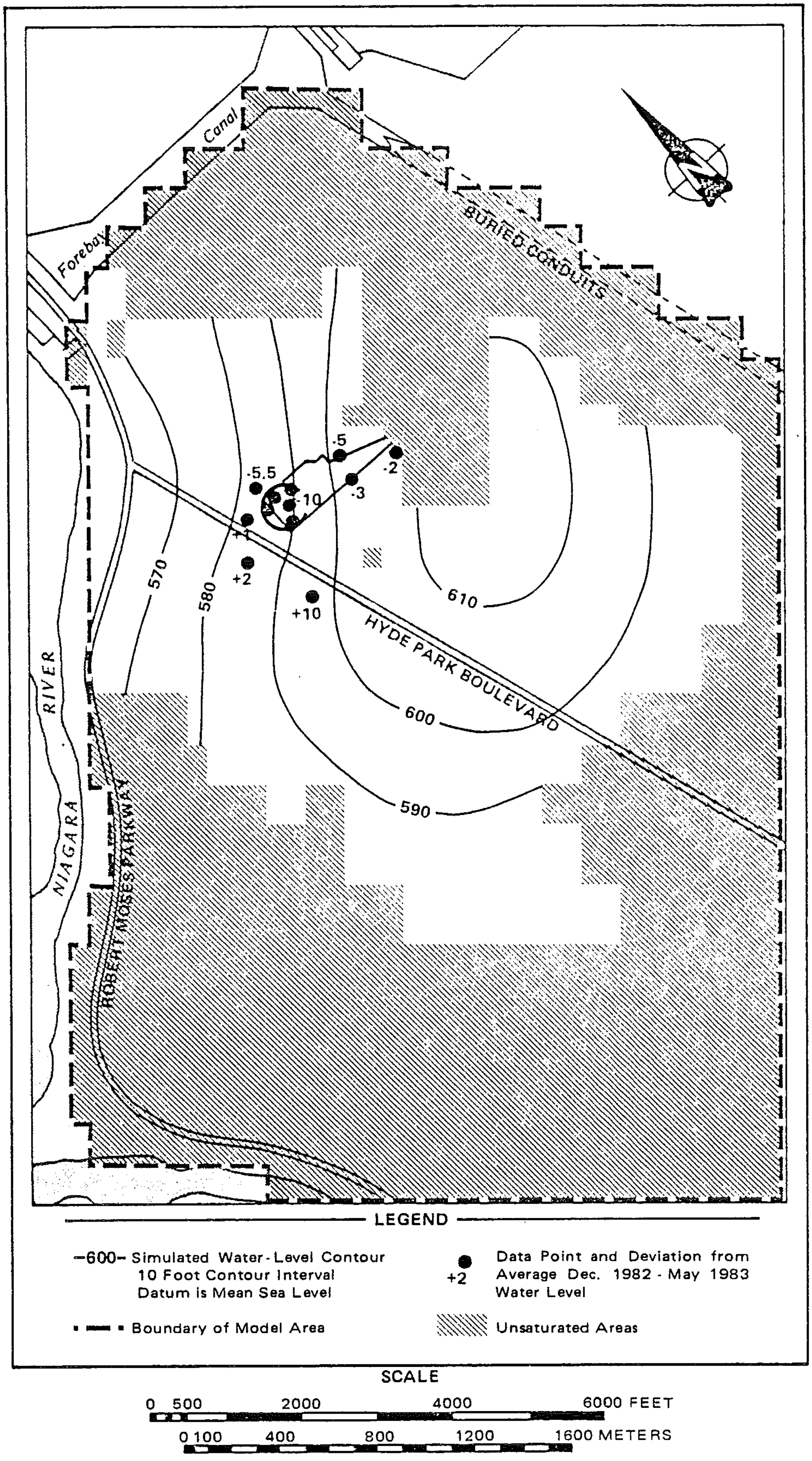

Figure 13 SIMULATED WATER-TABLE ALTITUDE AND DEVIATION FROM AVERAGE MEASURED WATER LEVELS (DECEMBER 1982-MAY 1983) IN LAYER 1 (UNCONSOLIDATED DEPOSITS)

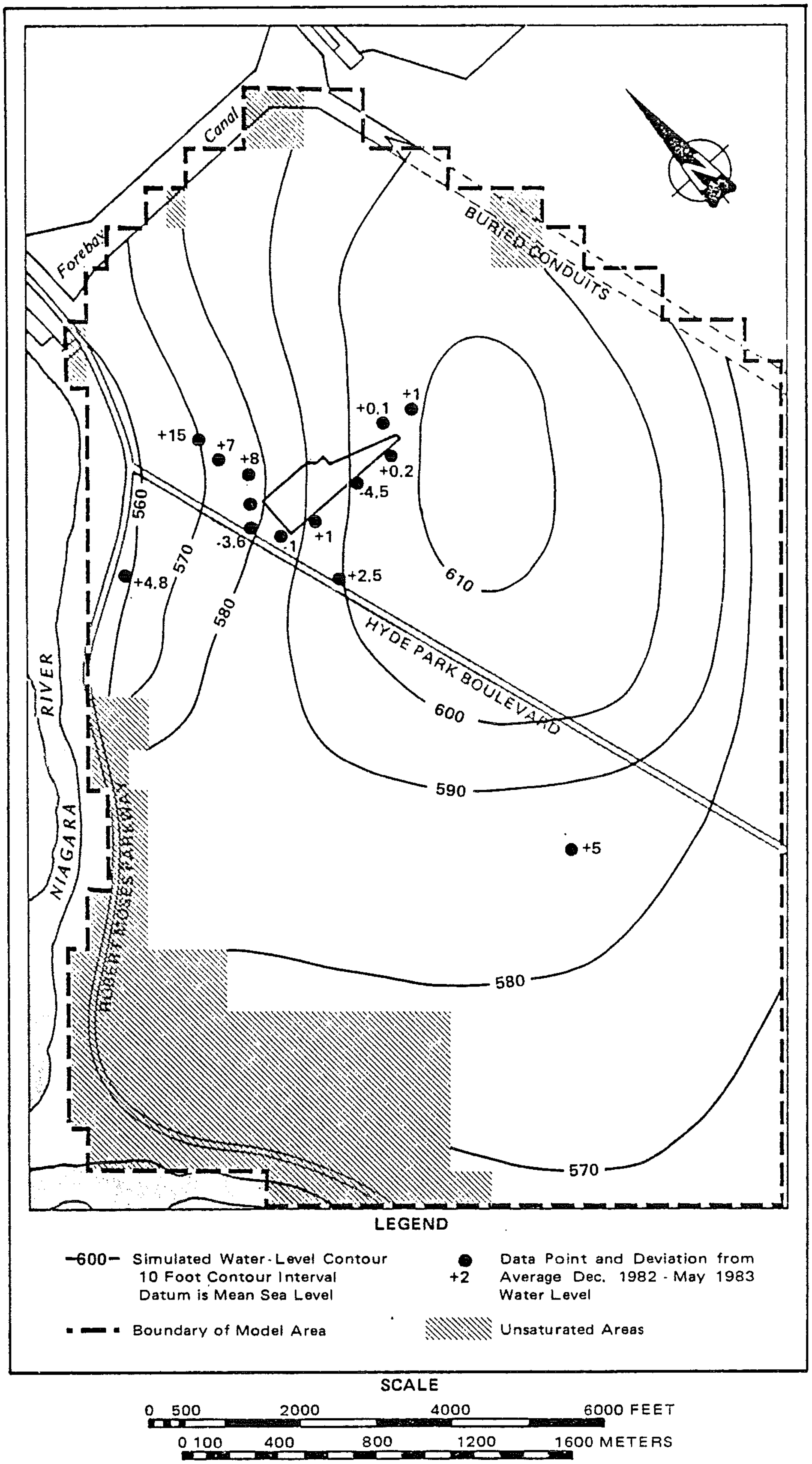

Figure 14 SIMULATED POTENTIOMETRIC HEAD DISTRIBUTION AND DEVIATION FROM AVERAGE MEASURED WATER LEVELS (DECEMBER 1982-MAY 1983) IN LAYER 2 (UPPER PART OF LOCKPORT DOLOMITE)

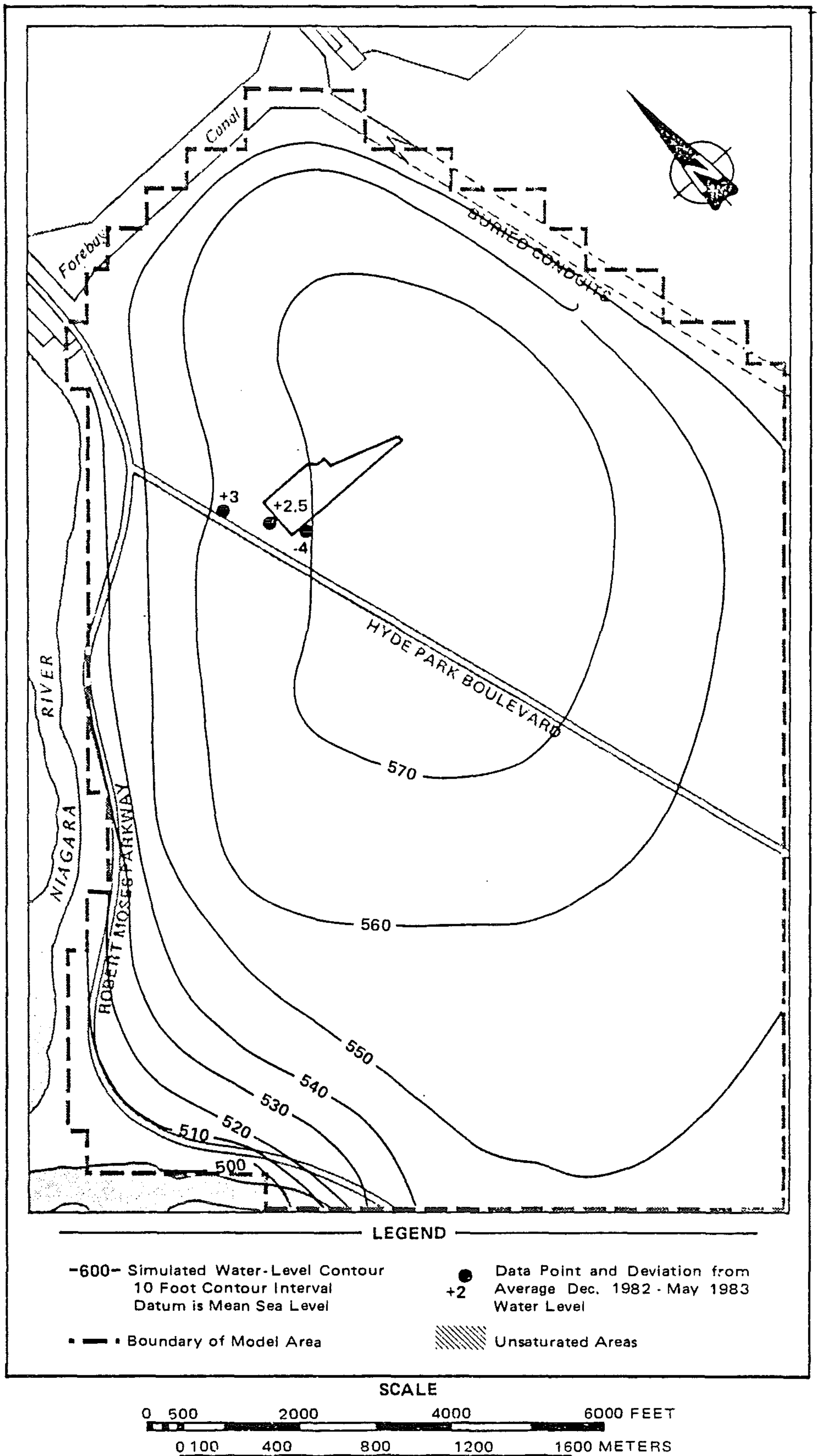

Figure 15 SIMULATED POTENTIOMETRIC HEAD DISTRIBUTION AND DEVIATION FROM AVERAGE MEASURED WATER LEVELS (DECEMBER 1982-MAY 1983) IN LAYER 5 (LOWER PART OF LOCKPORT DOLOMITE)

The simulated head distribution in model layer 2 (fig. 14) indicates that ground water in the uppermost 15 ft of the Lockport Dolomite (model layer 2) flows laterally toward the Niagara River gorge, the forebay canal, and the buried conduit system. The simulated position of the ground-water divide east of the landfill is very similar to the observed position depicted in figure 5. Near the landfill, water in the upper part of the Lockport Dolomite will migrate laterally northwestward to the Niagara River gorge.

A comparison of the simulated head distribution in figure 14 and the bedrock surface altitude (fig. 4) indicates that, in the vicinity of the landfill, the upper 15 ft of the Lockport is a confined aquifer. However, closer to the gorge, the forebay canal and the buried conduits, beyond where the surficial deposits (layer 1) are saturated the head in the aquifer drops below the top of the bedrock and the aquifer becomes unconfined. Nearer to the boundaries, the water table surface drops below the aquifer bottom and the aquifer becomes dry. The dry area for model layer 2 is shown in figure 14.

A comparison of simulated heads in model layer 2 (fig. 14) with those simulated deeper in the Lockport, such as model layer 5 (fig. 15) suggests that water in the upper part of the Lockport moves vertically downward, presumably along near vertical joints, under the influence of hydraulic gradients. In the vicinity of the landfill, a head decline of 20 to 25 ft is simulated between layer 2 and 5. This head decline compares favorably with the difference in water-levels (22 ft) observed in previously mentioned wells OW-18 and OW-19 (fig. 7).

Ground-Water Budget

The inflow and discharge of ground water computed from the calibrated steady-state simulation of average December 1982-May 1983 conditions are presented in table 4. All the water entering the simulated aquifer system (139,840 ft^3/d) is derived from direct infiltration from precipitation. Areally, this amounts to about 5.7 in/yr with 2 in/yr being applied at the landfill and 6 in/yr being used elsewhere. Of the total discharge from the model area about 15 percent (21,038 ft^3/d) is at the Niagara River gorge, 6.4 percent (8,956 ft^3/d) is at the forebay canal, and 9.4 percent (13,114 ft^3/d) is at the buried conduits. About 13,500 ft^3/d (9.6 percent) is discharged out of the model area as underflow at constant heads simulated south and southeast of the landfill. The remainder discharges downward through the Rochester Shale to the Irondequoit and Reynales formations.

The permeable uppermost 15 ft of the Lockport Dolomite has the highest hydraulic conductivity and where saturated represents 35 to 45 percent of transmissivity of the Lockport. Thus, the zone apparently would have the greatest potential for lateral migration from the landfill. However, the water budget calculated from the model indicates that about 95 percent (132,830 ft^3/d) of water recharged to this zone migrates downward, presumably along open vertical joints, to lower parts of the formation. Ground-water discharge from the Lockport Dolomite through the Rochester Shale to underlying water-bearing units (Irondequoit and Reynales formations), given as the vertical leakage in table 4, amounts to about 83,229 ft^3/d. Areally, this amounts to about 3.4 in/yr or about 59.6 percent of the recharge from precipitation. This amount of flow compares favorably with the amount of outflow (-0.00055 ft/d or 2.4 in/yr) used by Maslia and Johnston (table 2) in their best-fit simulation of the ground-water from near the landfill.

Table 4.--Detailed water budget of the steady-state model calibrated to December 1982 - May 1983 conditions

Sources (ft^3/d)					Total
Areal recharge					139,840

Discharges (ft^3/d)	Niagara River Gorge	Southern boundary	Forebay Canal	Buried conduits	
Till and lacustrine					
Layer 1	--	--	--	--	
Upper part of Lockport					
Layer 2	--	4,774	311	1,925	7,010
Lower part of Lockport					
Layer 3	--	5,478	377	817	6,672
Layer 4	3,345	1,993	2,453	9,024	16,815
Layer 5	3,680	238	4,246	1,243	9,407
Layer 6	14,013	1,020	1,569	105	16,707
Subtotal	21,038	13,503	8,956	13,114	56,611
Vertical leakage from Lockport Dolomite through Rochester Shale to Irondequoit and Reynales Formations (layer 7)					83,229

Because no field data are available to substantiate the magnitude of this flow, a series of simulations were used to evaluate the sensitivity of heads in model layers above the Rochester to the assumed water-level distribution of the Irondequoit and Reynales formations (fig. 8A). This head surface represents a head-dependent leakage boundary at the model base. To evaluate this boundary, a number of simulations were made while raising and lowering the estimated potentiometric surface of the Irondequoit and Reynales formation by 10 ft. Conclusions of these sensitivity analyses are that although the head-dependent leakage boundary simulated in model layer 7 is a sensitive parameter, the effect of changes in the estimated potentiometric surface of the Irondequoit and Reynales formations can be compensated for by adjustments in the vertical hydraulic conductivity of the Rochester Shale to match observed conditions. When the surface is raised, heads in model layers above the Rochester Shale increase in response and the vertical hydraulic conductivity of the Rochester must be increased to adequately match observed water levels. When the surface is lowered, water levels in units above the Rochester Shale decrease in response and the vertical permeability of the Rochester Shale must be increased to match observed heads.

Results of the simulation suggest that a number of vertical hydraulic conductivities of the Rochester Shale in combination with values of different potentiometric surfaces of Irondequoit and Reynales formations can be used to adequately match observed heads. However, the amount of vertical flow transmitted from the Lockport Dolomite through the Rochester Shale to the Irondequoit and Reynales Formations in each simulation did not deviate appreciably from the simulated amount (83,229 ft^3/d) given in table 4.

SUMMARY AND CONCLUSIONS

A finite-difference model containing seven aquifer layers provides an adequate simulation of the horizontally layered aquifer system in the Hyde Park area. On the basis of model results, ground-water conditions can be summarized as follows:

1. The simulated configuration of the water table in the unconsoliated deposits indicates a ground-water divide east of the landfill and that all ground water recharged near and flowing through the landfill will flow northwestward toward the Niagara River gorge. However, the low permeability of these deposits inhibits lateral movement of water and all water in this unit migrates downward to recharge the Lockport Dolomite. These surficial deposits are dry in areas bordering the Niagara River gorge, the forebay canal, and the buried conduits.

2. Ground water in the Lockport Dolomite flows laterally toward and discharges to the Niagara River gorge, the forebay canal, and the buried conduits. In the vicinity of the landfill, water in the Lockport moves northwestward toward the Niagara River gorge.

3. Horizontal and vertical hydraulic conductivities used in the best simulation indicate that the Lockport Dolomite is strongly anisotrophic. Horizontal values used ranged from 4.9 to 15 ft/d in the upper part of the Lockport and 1.0 to 3 ft/d in the lower part. Ratios of anisotropy used ranged from 10:1 to 100:1 in the upper part of the Lockport and 55:1 to 550:1 (layers 3 and 4) and 100:1 to 1000:1 in the lower part.

4. The permeable uppermost 15 ft of the Lockport Dolomite is the zone with the highest hydraulic conductivity and thus the greatest potential for lateral migration from the landfill. However, the water budget calculated by the model indicates that about 95 percent of water recharged to the Lockport also migrates downward, presumably along open vertical joints and fractures, to lower parts of the formation.

5. Leakage from the base of the Lockport Dolomite was approximated by simulating a head dependent leakage boundary below the Rochester Shale. An estimated water-level distribution in the Irondequoit and Reynales formation was used. Vertical hydraulic conductivity of the Rochester Shale used in the best-fit simulation was 0.0002 ft/d except near the gorge which was 0.002 ft/d. Ground-water discharging from the Lockport Dolomite to the Irondequoit and Reynales formations through the Rochester Shale amounts to about 83,000 ft^3/d or about 59.5 percent of the recharge from precipitation in the model area.

The model presented in this report was used as a tool to better understand the ground-water system in and around the area of the Hyde Park landfill and proved very useful in understanding the layered nature of the fractured bedrock medium, the patterns of ground-water flow, and the overall water budget of the system. Additional data on the water transmitting properties of the highly fractured bedrock zones, head in the Irondequoit and Reynales formation, vertical conductivity of the Rochester shale, and head data in specific aquifer zones at the base of the Lockport (equivalent to model layers 5 and 6) are needed to refine the model's representation of the system.

Table 5.--Generalized description of Paleozoic sedimentary rocks in the American Falls vicinity, Niagara Falls, N.Y.

[Modified from American Falls International Board, 1974.]

Series	Group	Formation	Member	Thickness (ft)	Lithology
	LOCKPORT GROUP	Lockport Formation	Oak Orchard member	70+	Dolomite, medium-gray to medium dark-gray; thin- to thick-bedded, numerous irregular shale and stylolitic shale partings, slightly argillaceous; chert nodules and white dolomite crystals are common. The member is finely crystalline and sugary textured. Vugs commonly are filled with calcite, gypsum and sphalerite. Stromatolite domes are present. The rock is moderately hard.
			Eramosa member	14	Dolomite, medium-gray to grayish-brown; thin- to medium bedded with numerous bituminous and carbonaceous stylolitic shale partings and stylolites. White porous chert and coarsely crystalline dolomite masses are common; gypsum, anhydrite, fluorite and sphalerite occur in lesser amounts. The member is very finely crystalline and sugary textured. The rock is moderately hard. Occasional vugs are filled with calcite and gypsum.
			Goat Island member	26-30	Dolomite, medium-gray in upper, dark-gray in middle and light-gray to light tannish-gray in the lower part, occasionally mottled; massive in upper and lower part and thin- to medium-bedded in the middle, slightly to very argillaceous with abundant shale and stylolitic shale partings in the middle. The member is finely to medium crystalline and sugary textured. The lower part is coarsely crystalline, pitted and vuggy; the vugs are occasionally filled with secondary dolomite crystals. The rock is moderately hard.
			Gasport member	18-20	Dolomite to dolomite-limestone, light- to medium-gray; massive with abundant stylolites and discontinuous shale partings throughout; slightly argillaceous in the upper and conglomerate with pebbles of DeCew lithology in the base. The member is finely to coarsly crystalline and sugary textured. The rock is moderately hard. Vugs and pits are filled occasionally with gypsum.
			DeCew member	10	Dolomite, medium- to dark-gray; thin- to medium-bedded with an occasional thick bed; argillaceous with wavy irregular shale partings that contain well developed slickensides; stylolites and stylolitic shale partings are common; occasionally masses and nodules of gypsum occur. The member is finely crystalline to crystalline with a well-cemented mosaic texture. The rock is moderately hard. Outcrops contain a "flow" or "enterolithic" structure.
(SILURIAN) SERIES	GROUP	Rochester Formation	zone 1	1-2	Shale, medium dark-gray; laminated to platy, slightly dolomitic, dense and moderately hard. This zone is a transition from the Rochester below to the DeCew above.
			zone 2	13+	Shale, medium dark-gray to dark-gray; laminated to blocky and contains discontinuous partings and bands of light-gray dolomitic limestone. Clay minerals are illite, chlorite, kaolinite and traces of montmorillinite; the zone also contains scattered pyrite and gypsum masses near the base. Microcrystalline dolomite is interspersed with finely cyrstalline illitic clay and quartz. The rock is moderately hard.
			zone 3	6+	Dolomitic shale and shaly dolomite, medium dark-gray to dark-gray; thin-bedded in upper and basal, massive in the middle; shale partings occur in the upper and lower parts. Illitic clay, traces of chlorite, kaolinite and silt size quartz grains are dispersed throughout the zone. The rock is dense, contains very few pores, and is moderately hard.
			zone 4	25-29	Shale, medium- to dark-gray; laminated to blocky and contains numerous discontinuous partings and bands of light-gray dolomitic limestone; gypsum partings are abundant. Nodules of calcite and gypsum occur occasionally. The clay minerals are illite, chlorite, kaolinite and mixed layerd clay. The zone has a dense, microcrystalline texture. Portions of the zone are fairly well cemented with dolomite; other parts are more shaly and rapidly fracture upon drying. The rock is moderately hard.
			zone 5	6-10	Shale, medium- to dark-gray; laminated, dolomitic and contains occasional gypsum partings, white calcite nodules, numerous discontinuous partings and bands of limestone and thick beds of shaly dolomite. Silt size quartz grains are scattered throughout. Clay minerals are illite, chlorite, kaolinite and mixed layerd clay. The texture of the zone is microcrystalline. The rock is moderately hard.
			zone 6	4-5	Shale, medium- to dark-gray; laminated to blocky; contains light-gray laminae and bands of calcite and dolomite. The blocky shale contains gypsum partings. Quartz grains are common; pyrite and marcasite occur with carbonaceous matter as a replacement of organic matter. The clay minerals are illite, chlorite and kaolinite. The rock is moderately hard.

NIAGARA	CLINTON	Irondequoit Formation	Unnamed member	6-9	Limestone, light-gray with pinkish tint, medium-bedded to massive with frequent wavy irregular green or black shale partings near the top. The member is coarsely crystalline. The rock is moderately hard. A few vugs and small pores are present.
			Rockway member	10-11	Dolomite, varies from light- to medium-gray in the upper part to brown in the middle and brownish-gray at the base; thin- to thick-bedded in the upper, massive in the middle and thin-bedded at the base; argillaceous to very argillaceous at the base. Dark-gray shale partings and a few gypsum nodules occur throughout the member. The member varies from dense to finely crystalline and has a sugary texture. The rock is moderately hard.
					Unconformity
		Reynales Formation	Hickory Corners member	2-3	Limestone, light- to medium-gray; argillaceous, calcitic and highly siliceous; numerous wavy, dark-gray shale partings and bands produce a pseudonodular appearance. The texture of the member is very finely crystalline to dense. The rock is moderately hard.
		Neahga Formation		6	Shale, dark greenish-gray, platy to fissile with a waxy appearance; shaly sandstone at base. Masses of pyrite and gypsum partings occur along the bedding planes; calcite and dolomite occur in small amounts and quartz is the most abundant non-clay mineral. Illite is the dominant clay mineral with lesser amounts of chlorite, kaolinite and mixed layered clay. The rock is soft and flakes readily during wet-dry cycles. Slickensides are present.
	MEDINA GROUP	Thorold Formation		9	Sandstone, light-gray to greenish-gray; medium-bedded to massive; irregular green shale partings occur throughout. The sandstone is orthoquartzitic. The texture of the formation is very fine grained. Silt size to fine-grained quartz particles are cemented with secondary silica. The rock is hard.
		Grimsby Formation	zone b	8	Sandstone, pink to reddish-brown; thin- to thick-bedded, hematitic, calcareous. The texture varies from fine to medium grain. The rock is moderately hard to hard. A weathered zone frequently occurs at the top of the formation.
			zone a	43	Siltstone and sandstone with interbeds of shale, variegated from red to pale green; pink, white or mottled siltstone or sandstone with red shale and red sandstone interbeds. Gypsum partings occur in shale beds. The sandstone is fine- to medium-grained and well cemented. The siltstone and shale vary from soft to moderately hard.
		Power Glen Formation		34	Shale with siltstone beds and stringers of silty limestone and dolomite; dark-gray to grayish green shale and siltstone, and light-gray limestone and dolomite; laminated to banded. Quartz is the most abundant non-clay mineral. Clay minerals consist of illite, chlorite and small amounts of montmorillonite and mixed layered clay. The rock is slightly soft to moderately hard.
		Whirlpool Formation		18	Sandstone, light-gray to white; medium-bedded and cross-bedded; fine- to medium grained. The quartz grains are frosted and well rounded, and are well cemented by secondary silica. Feldspar grains altered to kaolinite are abundant. Occasional green shale inclusions and chloritic shale partings occur throughout. The rock is slightly soft to moderately hard.
					Unconformity
ORDOVICIAN SERIES Cincinnatian Group	RICHMOND GROUP	Queenston Formation		100+	Shale (technically classified as a claystone) reddish-brown (ferric) shale with interbeds and nodules of green (ferrous) shale; massive to blocky. The shale is silty and is cemented by dolomite and calcite. Scattered gypsum nodules occur throughout; quartz is a common constituent. Clay minerals are illite, chlorite, kaolinite, montmorillonite and mixed layered clay. The shale is highly compacted and moderately hard. Numerous small, high angle slickensides are stained with iron oxide.

Note: The stratigraphy is compiled from Zenger (1965 and 1966), Fisher (1966) and Kilgour (1966), from stratigraphic studies by U.S. Army Engineer District, Buffalo, New York and from petrographic descriptions by the U.S. Army Engineer Division, Missouri River. The Rochester Formation zonation was developed for this study by the Buffalo District.

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