03.07.00.0009

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

October 1997

Prepared for

Northrop Grumman Corporation

Prepared by
Geraghty & Miller, Inc.

88 Duryea Road
Melville, New York 11747

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

October 31, 1997

Prepared by GERAGHTY & MILLER, INC.

Robert Porsche
Scientist/Hydrogeologist

Douglas A. Smolensky (by RP)
Douglas A. Smolensky
Associate/Hydrogeologist

Carlo San Giovanni
Carlo San Giovanni
Principal Scientist/Project Manager

Michael F. Wolfert
Michael F. Wolfert
Project Director

\\gm_plain\data\aproject\grumman\ny0008.042\reports\regmod-f.doc

CONTENTS

CONTENTS (continued)

TABLES

FIGURES

FIGURES (continued)

FIGURES (continued)

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

1.0 INTRODUCTION

Geraghty & Miller, Inc., on behalf of Northrop Grumman Corporation (formerly known as the Grumman Aerospace Corporation), has developed a three-dimensional groundwater flow model for the Northrop Grumman site and surrounding area. The model represents the culmination of years of investigative efforts and insights gained by numerous parties regarding the groundwater flow system beneath the Northrop Grumman site and surrounding area. This modeling effort was conducted in accordance with standard and accepted scientific and engineering practices for the development of groundwater flow models as documented and established by the U.S. Geological Survey (USGS) and the American Society of Testing and Material (ASTM).

The model has been thoroughly reviewed and used by numerous agencies and consultants for private parties, including: the New York State Department of Environmental Conservation (NYSDEC), the New York State Department of Health (NYSDOH), NUS Haliburton (consultant to the US Navy), Holzmacher, McClendon, and Murrel, P.C. (consultant to Bethpage Water District), and Leggette, Brashears, and Graham and Conestoga-Rovers and Associates (consultants to Occidental Chemical Corp.). The model construction, calibration, and use has been thoroughly presented (in numerous meetings) to the above mentioned parties. In addition, the model (in electronic format) has been distributed to the same parties for their review and use.

1.1 BACKGROUND

In 1983, the Grumman Aerospace Corporation and U.S. Naval Weapons Industrial Reserve Plant (NWIRP) sites located in Bethpage, New York were jointly included on the

NYSDEC's State Superfund List as class 2a. In December 1987, this classification was changed to 2. In 1984, the Occidental Chemical Corporation (OCC)/RUCO Polymer Corporation Site (a neighboring property to the west) was included on the U.S. Environmental Protection Agency's (USEPA) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priority List (NPL) under Section 120 of CERCLA. Subsequently, a Federal Facilities Agreement addressing the investigation and remediation of environmental impacts associated with the US Navy Bethpage site was negotiated. Under this agreement the Navy site remained under jurisdiction of the NYSDEC Superfund group, the Grumman site was also under the jurisdiction of the NYSDEC Superfund group, and the Ruco Polymer site was under the jurisdiction of the USEPA. The agreement reached was intended to ensure that environmental impacts associated with past and present activities at the Bethpage sites are thoroughly and adequately investigated so that appropriate response actions can be formulated, assessed, and implemented.

The groundwater system at, and in the vicinity of the Bethpage sites has been designated as a "sole source" aquifer system whereby all major aquifers are considered as a single groundwater resource. Within this hydrogeologic setting, plans for groundwater remediation and water-supply activities must consider the effects of such actions on the groundwater system as a whole. Failure to adopt such an integrated approach risks expending remedial effort without the beneficial result of maintaining a high potable yield from the aquifer for water-supply purposes. The "systems approach," whereby the complexities of the groundwater system are evaluated as intricately related processes, will therefore be used in the modeling effort to allow for assessment of the effects of various remedial scenarios and water-supply alternatives on the groundwater resource. The three-dimensional groundwater flow model will be used as a tool for evaluation of these scenarios and alternatives. The model will be the foundation on which evaluations at both the regional and local scales will be made.

1.2 SOURCES OF INFORMATION

Numerous investigations performed at both the regional and local scales have provided information and data used in this modeling effort. Many of those investigations are referenced throughout this document; however, the key investigations and specific topics they address are summarized below.

Hydrogeology/Hydrology: Isbister (1966), Smolensky et al. (1989), Smolensky and Feldman (1990), Warren et al. (1968), Miller and Frederick (1969), Franke and Cohen (1972), McClymonds and Franke (1972), Bailey et al. (1985), Peterson (1987), Doriski (1986), Lindner and Reilly (1983), Feldman et al. (1992)

Modeling: Franke and Getzen (1976), Getzen (1977), Reilly et al. (1983), Reilly and Buxton (1985), Buxton and Modica (1992), Buxton and Smolensky (In Press), Smolensky and Feldman (1995), Buxton et al. (1991)

In addition to the reports listed above, many records and unpublished data (e.g., well logs, water-level measurements) were researched, evaluated, and used. Most of these data were on file at the U.S. Geological Survey (USGS) or the NYSDEC.

1.3 REPORT OBJECTIVES AND FORMAT

The objectives of this report are to document the construction and calibration of the Northrop Grumman groundwater flow model, and to present the output (i.e. heads, potentiometric surface maps) of the simulation of the groundwater flow regime under calibrated, steady-state conditions.

This report has been divided into six major sections that logically follow and build upon preceding sections. A description of each section is provided below.

Sections 1 and 2 present an introduction, background information, and development of the conceptual model of the groundwater system.

Section 3 describes the development of a plan and strategy to model groundwater flow. It includes a description of technical objectives and the modeling approach as well as a discussion of the model code chosen and the rationale for its use.

Section 4 documents the construction of the model. It includes a discussion of discretization, boundary conditions, and hydrologic/hydrogeologic input parameters. This section is tailored to a reader who is familiar with models or the quantitative aspects of hydrogeology.

Section 5 discusses the calibration and verification of the flow model. It also includes a discussion of the sensitivity analysis. This section is tailored to those who are familiar with models or the quantitative aspects of hydrogeology.

Section 6 summarizes the modeling effort.

2.0 CONCEPTUAL GROUNDWATER MODEL

A conceptual groundwater model is simply an understanding of the structure and operation of a given groundwater system. In the Northrop Grumman area, the groundwater system is defined by its hydrogeologic framework, hydraulic parameters, and boundary conditions (including pumping wells and recharge basins). The interrelation of these three factors govern groundwater flow patterns within the system. This section provides a summary of these factors and a brief description of the Northrop Grumman site in order to characterize the conceptual model of the flow system and to provide an understanding of the stresses affecting groundwater quality and quantity in the Northrop Grumman area.

2.1 SITE LOCATION

The Northrop Grumman site (including both the property owned by Northrop Grumman and the property owned by the Federal Government [US Navy] and operated by Northrop Grumman) is located in Bethpage, Nassau County, New York, in the southeast quadrant of Nassau County (Figure 2-1). The Northrop Grumman site includes or has included large office buildings, recreational playing fields, various manufacturing buildings, storage areas and warehouses, and an airstrip (Smolensky and Feldman 1989). The area surrounding the site is primarily residential with some commercial development and transportation corridors. The Northrop Grumman site has an irregular shape that comprises an area of approximately 600 acres.

2.2 HYDROGEOLOGIC FRAMEWORK

The following section describes the configuration of the aquifers and confining units that comprise the groundwater system in the vicinity of the Northrop Grumman site, and describes and compares their water-transmitting properties. This description relates geologic structure to the distribution of water-transmitting properties throughout the groundwater system in the vicinity of the site and is referred to as the hydrogeologic framework.

This summary of the hydrogeologic framework of the site and the surrounding area is based on a review of site data and publications, including the following USGS publications: Smolensky et al. (1989), and Smolensky and Feldman (1990). The site is underlain by approximately 1,200 ft of unconsolidated sediment overlying bedrock. The unconsolidated deposits are subdivided from youngest to oldest (from land surface downward) as follows:

- Upper Pleistocene deposits (Upper Glacial aquifer).
- Matawan Group-Magothy Formation (Magothy aquifer).
- Raritan Formation (Raritan confining unit and Lloyd aquifer).

This sequence dips to the southeast below Long Island. A description of each unit is provided below. Table 2-1 summarizes the stratigraphy beneath the site and provides general information regarding water-transmitting properties.

2.2.1 Upper Glacial Aquifer

The Upper Glacial aquifer is comprised of Upper Pleistocene sediments that were deposited in a glacio-fluvial environment during the Wisconsin glaciation. Pleistocene sediments near and at the Northrop Grumman site consist of outwash deposits (fluvial transport), and moraine material (north of the site). The unconsolidated Upper Glacial deposits are approximately 75 ft thick beneath the site (Smolensky and Feldman 1990). The Upper Pleistocene (Wisconsin) deposits consist of medium-to-coarse grained sand and gravel; some fine-grained sand and silt and local clay lenses are also present. In addition to the glacially derived deposits, a "reworked Magothy" zone (a transitional interval between the Magothy and Upper Glacial aquifers generally located within the lower portion of the Upper Glacial aquifer) may be present locally.

2.2.2 Magothy Aquifer

The Magothy aquifer (continental deposits of the late Cretaceous Magothy Formation Matawan Group undifferentiated) at the Northrop Grumman site unconformably underlies Pleistocene deposits. The Magothy Formation at the site is generally composed of fine-to-medium, gray to white, sand mixed and interbedded with silt and clay, and locally contains pebbles or small lenses of gravel. The lower 75 ft interval of the Magothy aquifer (basal Magothy) has been documented to consist of coarser material. Geologist's logs from wells that penetrate the Magothy aquifer describe zones of solid clay. Attempts to correlate these clay zones show them to be discontinuous and of variable thickness. These clay lenses reflect the highly stratified character of the deposits and contribute to the high degree of anisotropy in the aquifer.

The surface configuration of the Magothy aquifer reflects the severe erosion that occurred during several episodes of Pleistocene glaciation. The well data and geologic correlations indicate that the highest altitude of the Magothy aquifer surface is almost 100 feet above mean sea level (msl) (approximately 1 mile to the northeast of the Northrop Grumman site). The surface of the Magothy slopes from the northeast to the west to its lowest elevation in the area (more that 25 ft below msl). The Magothy also generally slopes down to the south towards the south shore of Long Island. Maximum thickness of the Magothy aquifer at the site is approximately 650 ft.

2.2.3 Raritan Confining Unit

The Raritan Clay underlies the Magothy aquifer at an approximate elevation of 600 ft below msl. The confining unit is approximately 175 ft thick (Smolensky and Feldman 1990). The Raritan Clay is comprised of clay, silt and sandy clay with some thin zones of fine sand. The clay may be red, yellow, gray, or white.

2.2.4 Lloyd Aquifer

The Lloyd aquifer underlies the Raritan confining unit and immediately overlies the bedrock. The Lloyd aquifer is approximately 300 ft thick (Smolensky and Feldman 1990). It consists predominantly of coarse to fine sands and some clay. The upper surface of the Lloyd aquifer dips to the southeast, similar to the dip of the bedrock surface.

2.2.5 Bedrock

The bedrock is probably of Precambrian or Paleozoic age and consists primarily of schist and gneiss. The bedrock slopes to the southeast and represents an advanced erosional surface with little relief. It is overlain by a tough white clay that was derived from the bedrock through weathering.

2.3 WATER-TRANSMITTING PROPERTIES

McClymonds and Franke (1972), estimated the distribution of hydraulic conductivity for each of the three major aquifers by evaluation of specific capacity data and pumping tests throughout Long Island. In addition to the data in McClymonds and Franke (1972), results of several pumping tests conducted in the southern half of Nassau county were also used to provide information on water-transmitting properties of specific aquifers within the aquifer system (Lindner and Reilly 1983).

The Upper Glacial aquifer has the highest estimated values of horizontal hydraulic conductivity (up to approximately 300 feet/day [ft/d]) of the three major aquifers, which reflect the sand and gravel deposits comprising the aquifer. North of the site, abrupt changes in conductivity occur around the area of the Ronkonkoma terminal moraine. Although horizontal conductivities are defined, it should be noted that these values approximate an average conductivity for the entire aquifer thickness or significant portions thereof. However, abrupt vertical changes in the lithology of the deposits results in variations of vertical conductivity values at different depths. Stratification in these deposits is common and has a pronounced effect on the vertical hydraulic conductivity of the deposits. The anisotropy (ratio of horizontal to vertical hydraulic conductivity) of the Upper Glacial aquifer is approximately 10:1, however, anisotropy values for the aquifer have been reported as low as 3:1 or 4:1.

The Magothy aquifer can be divided vertically into three approximate zones with contrasting ranges of horizontal hydraulic conductivity. The upper Magothy zone is representative of the Upper Glacial aquifer/ upper Magothy aquifer transition zone and has a value of approximately 200 ft/d. The middle Magothy aquifer zone generally contains more silt and clay and has conductvities between 30 and 70 ft/d. The basal Magothy zone is slightly more permeable due to higher gravel content and has conductivities ranging from 60 to 100 ft/d. Vertical conductivities for the three zones are 2 to 15 ft/d, 0.4 to 1.2 ft/d, and 0.6 to 1.2 ft/d, respectively. These anisotropy values reflect the highly stratified character of the Magothy aquifer. Aquifer tests from the underlying Lloyd aquifer are uncommon; however, some available regional data indicate conductivity ranges of 35 to 75 ft/d and an anisotropy ratio of 100:1.

Little data are available to estimate vertical hydraulic conductivities of the Raritan confining unit; however, its high clay and silt content would suggest vertical conductivities several orders of magnitude lower than those for adjacent aquifers. Franke and Cohen (1972) and Franke and Getzen (1976) estimated the average vertical hydraulic conductivity of the Raritan confining unit to be approximately 0.001 ft/d.

Estimates of specific yield (effective porosity) for outwash deposits on Long Island are as follows: 0.18 (Getzen 1977), 0.22 (Reilly and Buxton 1985), 0.24 (Warren et al. 1968), 0.24 (Perlmutter and Geraghty 1963), and 0.30 (Franke and Cohen 1972). Estimates as low as 0.10 have been proposed for morainal deposits (Getzen 1977). Specific storage for the Magothy aquifer is approximately 6.0 x 10^{-7}/ft (Reilly and Buxton. 1985).

2.4 BOUNDARY CONDITIONS AND GROUNDWATER FLOW

The fresh groundwater beneath Long Island exists as a distinct well-defined system, bounded completely by natural hydrologic boundaries. The Northrop Grumman site and surrounding area are part of this system and share some common hydrologic boundaries. The system is bounded above by the water table and many streams and fresh surface-water bodies; it is bounded below by consolidated bedrock. The entire system is bounded laterally by salty groundwater and surface-water bodies. Under natural conditions, all water enters and leaves the system across these boundaries. The occurrence of precipitation in the hydrologic environment is described below as an aid in understanding the function of major boundaries in the operation of the groundwater system.

Recharge is derived solely from precipitation, which falls at a long term average rate ranging from 41.5 to 43 inches per year (in/yr) (Miller and Frederick 1969; Bailey et al. 1985) in the vicinity of the Northrop Grumman site. Recharge enters the saturated groundwater system at the water table, the upper boundary of the groundwater system. In Nassau County, it is estimated that between 50 and 52 percent of precipitation recharges the saturated groundwater system. In addition to direct recharge from precipitation, approximately 20 percent of the public supply water used in the area is returned to the groundwater system as leakage from the sewer systems (Smolensky and Feldman 1990). Only 1 percent of precipitation is lost to overland runoff because of the high infiltration capacity of the unconsolidated deposits at land surface and the relatively flat topography; the remaining 47 to 49 percent is lost to evapotranspiration. Groundwater recharge was estimated as follows: direct recharge from precipitation, approximately 52 percent of 43 inches per year or 0.0051 ft/day. In addition, 20 percent of 3,166,781 cubic feet per day of groundwater pumped from public supply wells is returned to the groundwater system as leakage and non-consumptive water use, which amounts to approximately 0.00105 ft/day. The total recharge rate is therefore estimated to be 0.00615 ft/day.

The consolidated bedrock that underlies the unconsolidated deposits of Long Island is considered the bottom boundary of the groundwater system. There is no evidence of any water-bearing zones within the bedrock and therefore, this bottom boundary is considered impermeable.

Long Island is surrounded by tidal water bodies that form the lateral boundaries of the fresh groundwater system. Groundwater discharges from the Upper Glacial aquifer along the shoreline directly to the near shore bottom of these saltwater bodies. Assuming the characteristics of a typical static and sharp freshwater/saltwater interface in the aquifer, groundwater in deeper portions of the Upper Glacial aquifer will flow upward along the interface to the discharge zone, the thickness of which is only a portion of the entire thickness of the Upper Glacial deposits.

At the offshore position of the freshwater/saltwater interfaces in the Magothy and Lloyd aquifers, fresh groundwater flows vertically upward across the overlying confining units. Where the overlying groundwater is salty, the water discharges from the fresh groundwater system and mixes with the salty groundwater. These areas are referred to as subsea discharge boundaries and identify Long Island as a classic staggered interface hydrogeologic environment. North and south of the site (near the shorelines) groundwater in the Magothy and Lloyd aquifers flows towards subsea discharge boundaries. Confining units that are present near these boundaries impede groundwater discharge upward to the shoreline; as a result, the freshwater/saltwater interface is displaced seaward.

Under natural conditions, river flow is maintained year-round by groundwater seepage (baseflow) from the Upper Glacial aquifer into the river or stream channel. The portion of stream flow derived from overland runoff is very small because of Long Island's relatively flat topography and the high infiltration capacity of soils. The rate of seepage is controlled by the difference in head between the local aquifer and the stream bed, the channel geometry, and the water-transmitting properties of the aquifer and bed material. Therefore, baseflow and the length of flowing stream vary with changing conditions in the groundwater system. When the water table falls to a level below the channel elevation, seepage stops and the channel becomes dry. No streams or rivers exist in the immediate vicinity of the Northrop Grumman site.

Groundwater in the Upper Glacial aquifer beneath and in the vicinity of the Northrop Grumman site generally exists under unconfined conditions. However, if locally continuous low permeability zones exist within the aquifer, semi-confined conditions will prevail locally. Where the Magothy aquifer is in direct hydraulic connection with the Upper Glacial aquifer and not separated by a distinct confining unit, conditions within the Magothy are semi-confined to unconfined. Although the Magothy aquifer does not contain regionally extensive continuous clay layers, its many clay lenses tend to increase the degree of confinement with depth.

Groundwater in the Lloyd aquifer exists under confined conditions. The low vertical hydraulic conductivity of the overlying Raritan confining unit (approximately 0.001 ft/d) greatly limits the downward movement of water into the Lloyd aquifer. Because only a small percentage of the groundwater that flows through the system ever enters the Lloyd aquifer, the aquifer is very sensitive to groundwater pumpage. For this reason, and because of the abundance of potable groundwater in the overlying aquifers, the Lloyd aquifer is not used as a source of water-supply in the vicinity of the Northrop Grumman site.

An east/west trending groundwater divide is located to the north of the site with resultant regional groundwater flow in the vicinity of the Northrop Grumman site being primarily to the south (Figure 2-2). Under natural conditions, groundwater eventually discharges either into streams located along the south shore of Long Island or directly to the Great South Bay and Atlantic Ocean as underflow.

The horizontal direction of groundwater flow is locally influenced by active supply wells, recharge basins, and natural hydrogeologic conditions. Pumping wells locally depress the water table, while recharge basins may produce local groundwater mounding. Within the Northrop Grumman site boundary, surface discharge occurs at several recharge basin locations. At these locations, artificial recharge results in the formation of localized groundwater mounds. In the vicinity of the mounds, shallow groundwater flows radially away until it becomes more strongly influenced by regional groundwater flow patterns. It then flows in a southerly direction until it is either captured by pumping wells, or is discharged naturally from the groundwater system.

The vertical component of groundwater flow at and in the vicinity of the Northrop Grumman site is downward. To the south however, in areas proximal to rivers and streams, and in areas further south underlain by regional confining units such as the Gardiners Clay, the direction is upward, at least locally. In addition, near the north and south shores the direction is also upward. This interpretation of vertical flow is supported by well cluster data, numerous regional investigations, and the widely accepted conceptualized model of the Long Island groundwater system.

Although pumping wells and active recharge basins are boundary conditions, they are considered to be internal artificial boundaries and are therefore not described in this section. These boundaries are discussed in Section 4.4 (Groundwater Pumpage and On-Site Recharge).

3.0 MODELING STRATEGY

This section presents the objectives of the modeling effort, as well as the concepts and strategies used to simulate groundwater flow at, and in the vicinity of, the Northrop Grumman site. Given the various technical objectives, potential model uses, and varying scales of interest discussed in the following sections, as well as the physical and chemical complexities of flow and transport, a clear modeling plan and strategy was required and therefore, developed. This modeling plan and strategy was followed throughout the modeling effort to allow the model to be used confidently as a tool for meeting the various technical objectives.

3.1 TECHNICAL OBJECTIVES

The technical objectives of the modeling effort are described below.

3.1.1 Regional

The regional model was developed to provide a tool for evaluation of groundwater flow, contaminant transport, and remedial alternatives, where such processes, concerns, or actions may have impacts that extend across extensive areas beyond the site boundary. The model was also developed to evaluate those impacts as a function of depth within the groundwater system. This model is considered the foundation from which all subregional or site-specific models will be developed. As such, it will ensure that all subsequently developed groundwater models are both hydrogeologically and hydrologically consistent with each other and with regional interpretations and processes. This consistency will be critical in areas where site-specific data is inadequate or lacking.

One objective of the regional model is that its design enables it to be, in many instances, an appropriate tool for addressing specific concerns that apply over a large geographical area. It is critical, therefore, that not only knowledge of both the physical system and the existing groundwater problems/concerns at the site be incorporated into the development of the regional model, but also that the model be developed with foresight as to what the potential remedies or future scenarios might be. It may be appropriate for the discretization scheme to be driven not only by the physical and chemical processes that occur in the system, but also by the remedies and scenarios that may be expected to be simulated.

3.1.2 Site-Specific

It may be determined that the regional model may not be an appropriate tool for use in evaluating all specific concerns. Geraghty & Miller has assumed that such a determination will be based on differences in scale. Specifically, the discretization scheme used in the regional model may not allow for accurate or adequate simulation of various transport processes that occur or must be addressed at a very site-specific scale. Such limitations could be related to either horizontal and/or vertical discretization. For example, transport simulations involving dispersive processes, require use of the Peclet number as a stability criterion. The Peclet number is a function of grid cell spacing and dispersivity. In cases where grid spacing is large relative to dispersivity, the Peclet number criterion may be violated, introducing unacceptable levels of numerical dispersion. In such cases, the horizontal and/or vertical discretization scheme may need to be refined.

3.1.3 Uses of the Model

Some of the potential uses of the model are described below.

3.1.3.1 Feasibility Study

One of the benefits of having the model available for use will be the ability to test the feasibility of various groundwater remedial scenarios. The model will be used to evaluate the impacts of combinations of remedial pumping and recharging scenarios; to optimize existing well pumpage to contain, control, and/or remediate groundwater; to assess specific no-action scenarios; and to evaluate other feasibility options.

3.1.3.2 Remedial Design

Following the selection of specific groundwater remedies, the groundwater flow model will be used to assist in final remedial designs. Assuming that groundwater extraction will be considered as a preferred remedy, modeling efforts may include running simulations to locate the optimal location(s), screened intervals, pumping rates, etc. for proposed extraction wells. These simulations may be used to approximate potential influent concentrations to treatment facilities, potential concentration changes over time, and expected length of the treatment period.

3.2 SIMULATION APPROACH

This modeling effort and model design were structured to address critical groundwater issues at and around the Northrop Grumman site. The approach adopted to model the groundwater system in these areas emphasizes consistency in addressing both regional and subregional/site-specific issues. An important aspect of the overall technical approach adopted includes definition of the scale of the model.

Several factors should be given serious consideration during definition of the scale of a discrete representation of a groundwater system in a numerical model. These factors include both considerations for system geometry and considerations for adequate resolution of the distribution of head throughout the system.

Resolution of the hydrogeologic framework in the vicinity of the site obviously will affect the accuracy of the model. Representation of internal features such as the shape and extent of aquifers and thickness of layers and their spatial relationship, will have a major impact on the pattern and distribution of groundwater flow. The external geometry of the system is defined by the configuration of its natural boundaries or selected artificial hydrologic boundaries.

Additional geometric considerations include the location and shape of characteristics imposed by humans. These factors are often involved in simulations of stressed conditions or predictions used to evaluate resource-management strategies and remedial scenarios. At the Northrop Grumman site, such characteristics include pumping wells or centers and recharge basins.

An additional consideration in defining the scale of the model's representation is spatial changes in hydraulic head in the groundwater system. At the Northrop Grumman site, where gradients change rapidly (such as near wells or basins) the model may require finer grid spacing to accurately describe changes in gradient. Errors in the simulation of steep gradients are related to truncation error, which is inherent in finite-difference approximations and is discussed in greater detail in Bear (1972) and Remson et al. (1971).

3.3 MODEL CODE

The modular finite-difference groundwater flow code, known as MODFLOW, developed by the USGS (McDonald and Harbaugh 1988), was selected for the groundwater flow model. MODFLOW is publicly available, widely used, and features extensive documentation. The program is capable of simulating transient or steady-state flow in two or three dimensions for many different types of boundary conditions, including specified head, specified flux, and head-dependent flux. MODFLOW simulates groundwater flow using a block-centered finite-difference formulation. Model layers, which may be of variable thickness, may be simulated as confined, unconfined, or a combination of both. MODFLOW can simulate various external stresses, such as extraction or injection wells, areal recharge, evapotranspiration, drains, and streams or rivers. In the program, the finite-difference equations are solved using the strongly implicit procedure, the slice-successive over relaxation method, or the preconditioned conjugate gradient method.

All of these features make MODFLOW well suited for modeling the groundwater flow system at the Northrop Grumman site. The hydrogeologic framework and the dynamics of the system require a code capable of simulating three-dimensional flow with dipping layers. The unconfined nature of the upper portion of the aquifer necessitates a code option for simulating a free-water surface and groundwater/surface-water interactions. Simulation of various boundary conditions (specified flux and free-surface) is required, as is the ability to simulate the distribution of various aquifer and hydrologic parameters. MODFLOW meets all of these requirements.

4.0 MODEL CONSTRUCTION

The steps followed to construct the model are described in this section.

4.1 DISCRETIZATION

Computer programs such as MODFLOW approximate the mathematical equations for groundwater flow by numerical discretization techniques. MODFLOW uses the method of finite differences to approximate the groundwater flow equations. Spatial discretization consists of subdividing the entire model domain into a grid or mesh of blocks or cells. In the discretized system, hydraulic heads are computed at the center of each grid block. In general, computational accuracy increases as the number of rows and columns in the grid increase (cells become smaller).

In most cases, the need for computational accuracy in a computer model is greatest in the area of greatest concern, which, in this instance, is the Northrop Grumman site and areas to the west (OCC/RUCO site) and south (downgradient flow direction from the site). Therefore, a variable-spaced grid (one in which the finite-difference mesh is designed with smaller grid blocks in areas of interest and grades to larger blocks near the edges of the model) was used in this model. Grid design must address all three dimensions and, therefore, includes not only the horizontal grid, but also the vertical layering scheme. The actual grid was designed considering several additional factors as follows:

- The level of detail of the data available to define the hydrogeologic framework and hydraulic characteristics.

- The ability to define and represent boundary conditions and stresses placed on the system.

- The amount and distribution of hydraulic head data from which the model was to be calibrated.

- The desired resolution of model output.

- Computation effort and model stability.

The finite-difference grid developed after careful consideration of project goals and the factors discussed above consists of 104 rows, 68 columns, and eight layers. The model simulates regional groundwater flow in three dimensions over an area approximately 32,000 feet from north to south and 21,000 feet from west to east. The model grid is shown on Figure 4-1. Dimensions of cells along row (west-east) and column (north-south) directions range from 150 to 1,000 ft. The finest grid resolution is generally used on-site with lateral grid cell dimensions of 150 by 150 ft to enhance computational accuracy and produce results at the desired level of detail. The emphasis on fine-scale discretization on-site and in areas immediately to the south corresponds to critical areas with respect to model uses. A general rule-of-thumb was followed when increasing the grid spacing systematically from areas of finer resolution to areas of coarser resolution, in order to minimize numerical dispersion. Generally, the variation in grid spacing progressed such that the maximum change in spacing did not exceed 1.5 times the abutting grid spacing.

The groundwater flow model was constructed to simulate groundwater flow throughout the entire saturated thickness of the Upper Glacial and Magothy aquifers. As such, the aquifer system was divided into eight layers of grid cells in the vertical direction. The model was discretized vertically by specifying bottom elevations to define the bottom surface of each model layer. Table 4-1 presents the model layering scheme correlated with a generalized stratigraphic column. Vertical discretization was determined through careful consideration of the vertical distribution of calibration target wells, vertical distribution of pumping stresses, adequate vertical gradient resolution, and major hydrostratigraphic contacts. A threshold of maximum change in vertical grid dimensions was not specifically considered. Eight model layers sufficiently represent the system to the level of detail of the data. The model discretization is a balance among cost-effectiveness, available data, and the resulting accuracy of the model. Increased vertical discretization would not necessarily improve the quality of the calibration. The majority of the hydrologic data that the model is based on corresponds to Model Layers 1 through 4; thus, these shallow layers of the model are more finely discretized. Generally, in the vicinity of the site, the layer thicknesses gradually increase between Model Layers 5 and 8. Finer discretization of the lower layers (Model Layers 7 and 8) is not likely to improve the overall calibration of the model since there are relatively few calibration targets in these layers.

Model Layer 1, an unconfined layer, is approximately 20 feet thick throughout the model with the top defined by the water table. Because the top is simulated as a free-surface, the thickness of the layer will vary as the water table rises and falls. The elevation of the interface between Upper Glacial and Magothy was based on findings in Smolensky and Feldman (1990) and from available well logs.

Model Layers 1 and 2 generally correspond to the Upper Glacial aquifer. The bottom elevation of Model Layer 2 (in discrete format) is shown on Figure 4-2 The general north to south slope of the contact between the Upper Glacial aquifer and the Magothy aquifer is evident. Also evident are two local areas where the glacial deposits exist are lower elevations than would normally be expected (in the northwest corner and in a small pocket in the mid-western area) This relatively detailed vertical discretization was necessary to properly utilize groundwater monitoring data from wells with different screen elevations

Model Layer 3 is generally representative of the upper portion of the Magothy aquifer. The bottom elevation of Model Layer 3 was set at -50 feet mean sea level (msl). Model Layers 4, 5, and 6 correspond to the mid-Magothy aquifer. The bottom elevations of Model Layers 4, 5 and 6 were set at -140 msl, -235 msl, and -365 msl, respectively. Model Layer 7 has a variable thickness. Model Layer 8 is representative of the basal Magothy. It has a constant thickness of approximately 70 feet. The bottom of the layer coincides with the upper surface of the Raritan Confining unit and slopes from approximately -450 msl at the northern model boundary to approximately -700 msl at the southern model boundary.

Given the density of data available for system conceptualization and model construction, the hydraulic gradients, the boundary conditions to be simulated, the level of detail desired for model output, and the general objectives of the regional modeling effort, the level of discretization described above is appropriate.

4.2 BOUNDARY CONDITIONS

The boundary of a groundwater system can be thought of as a continuous closed surface that completely encloses the system of interest. Successful simulation of that groundwater system requires that all points on the boundary surface be defined or approximated. During the development of a numerical model, the selection of boundary conditions typically involves considerable simplification of actual groundwater system boundaries. This section describes the lateral, upper, and lower model boundary conditions used in the Northrop Grumman flow model. Although pumping wells, and recharge basins are technically considered a type of model boundary (internal boundaries), they are not discussed in this section; they are discussed in detail in Section 4.4 (Groundwater Pumpage and On-Site Recharge).

Generally, boundary conditions describe groundwater head and/or flow at the boundaries of the model area. A variety of boundary conditions was used in the construction of the Northrop Grumman three-dimensional model. In general, these boundary conditions include constant head and constant flux. In a constant head boundary condition, the head remains fixed at a given value throughout all model simulations. Constant head cells were placed along the lateral boundaries of the model area. In a constant-flux boundary condition, the groundwater flow rate into or out of the model cell is assumed to be constant. Constant flux cells represent pumping wells, recharge areas, and the special condition of "no flow" (a boundary where the flux is always zero).

The lower boundary of the model corresponds to the upper surface of the Raritan confining unit. This unit is characterized by solid and silty clay with few lenses and layers of sand. The low vertical hydraulic conductivity (approximately 0.001 ft/day) and overall thickness (about 175 ft) of the Raritan Clay cause this unit to act as a regional confining unit, which severely restricts the flow of groundwater vertically through it. This boundary was, therefore, modeled as a constant-flux or no-flow boundary. A flow analysis on a representative cross section through the entire thickness of the Long Island groundwater system was performed by Buxton and Modica (1992). This analysis, which generally approximated groundwater conditions along the Nassau-Suffolk county border, showed that although some groundwater does flow through the Raritan confining unit (between the Magothy and Lloyd aquifers), the amount has been estimated to be only approximately 2 to 3 percent of the total water flowing in the system. This analysis supports the approach of simulating this upper surface of the Raritan confining unit as the bottom boundary of the model.

The groundwater flow model was constructed to simulate groundwater flow throughout the entire saturated thickness of the Upper Glacial and Magothy aquifers. As such, the upper boundary of the model corresponds to the water table and is simulated as a free surface. This boundary represents the interface between the saturated flow field and the atmosphere (neglecting the capillary zone). It is the only boundary that is not fixed in its position, as it may rise and fall based on hydrologic changes in the system.

No natural lateral groundwater system boundaries exist in the vicinity of the Northrop Grumman site. To minimize the introduction of error that could potentially be introduced in the definition and specification of lateral model boundaries, the lateral boundaries assigned in the model were chosen to be at significant distances from the site. The northern model boundary generally corresponds to the regional groundwater divide that is oriented west-east and is located approximately 10,000 ft north of the site (see Figure 2-2). From a regional perspective, the location of this divide has not changed with time, and therefore, it was chosen as the northern model boundary. South of the groundwater divide, under natural conditions, all recharge to the groundwater system eventually discharges to the Great South Bay/Atlantic Ocean or streams located along the south shore of Long Island. Within the modeled area, this general north to south flow pattern has also not changed appreciably over time. Therefore, the location of representative flow lines east and west of the site were used to select the eastern and western model boundaries. These boundary locations were chosen considering both their distance from the site (approximately 10,000 and 9,000 ft to the western and eastern model boundaries, respectively) and their general orientation relative to the site and the groundwater divide. Finally the southern boundary location was chosen at sufficient distance from the site (approximately 14,000 ft). The southern boundary does not correspond directly to any natural boundaries.

Because the locations of the lateral model boundaries for the most part do not correspond exactly to the location of specific limiting flow lines or the groundwater divide, the specification of boundary conditions at each of the selected locations was accomplished by assigning constant head values. Through the use of constant head boundaries, minor departures from the actual location of limiting flow lines and the groundwater divide compared to the model selected locations could be compensated for. Regional water-level maps published by the USGS (Doriski 1986) and groundwater monitoring data obtained from the Nassau County Department of Public Works were used to specify the hydraulic head at the lateral model boundaries. Long-term hydrographs of water levels from monitoring wells in the vicinity of the site show that the regional elevation of the potentiometric surfaces of the Upper Glacial and Magothy aquifers and the hydraulic gradients within each aquifer do not vary greatly from year to year (negelecting the impact of the regional drought of the mid 1960's). Therefore, water levels that are representative of average conditions were used to assign head values to each constant head boundary cell.

With respect to overall vertical groundwater flow between aquifers, assignment of constant head values along model boundaries in the Upper Glacial and Magothy model layers was consistent with the conceptual model of regional vertical groundwater flow between the Upper Glacial and Magothy aquifers. Generally, assigned head values for these model layers reflect the regional vertical downward gradients between the Upper Glacial and Magothy aquifers in the vicinity of the recharge area/groundwater divide, and the regional lessening of downward vertical gradients between aquifers as distance from the divide increases. The regional potentiometric maps described in the preceeding paragraph indicate a regional vertical hydraulic gradient from the water table down to the Magothy aquifer. The head difference (which causes the hydraulic gradient) between the water table and the potentiometric surface of the Magothy is approximately 2.5 feet at the northern boundary of the model, approximately one foot near the area of interest, and approximately 0.5 feet at the southern model boundary. The head difference was assigned (at all lateral model boundaries) across all eight model layers based on the thickness and vertical hydraulic conductivity of each of the boundary cells in each model layer.

For Model Layer 1, assigned constant head values along the northern model boundary from northwest to northeast ranged from 82.42 ft msl to 80.42 ft msl, respectively. Along the western model boundary, from the groundwater divide in the northwest to the southern boundary, assigned constant head values decreased from 82.42 ft msl to 36.92 ft msl, respectively. Along the eastern model boundary, from the groundwater divide in the northeast to the southern model boundary, assigned constant head values decreased from 80.42 ft msl to 35.92 ft msl, respectively. Along the southern model boundary, assigned constant head values ranged from 36.92 ft msl to 35.92 ft msl from west to east.

4.3 PARAMETER ZONATION

Hydraulic parameter values for the final calibrated flow model are described in this section. Some of the parameter values used in this model (e.g., hydraulic conductivity and recharge) were initially estimated and later adjusted during calibration (see Section 5.0 [Model Calibration]).

Simulation of groundwater flow requires the definition of hydraulic parameters in each model cell. The following model input parameters are defined and discussed below: horizontal and vertical hydraulic conductivity and areal recharge. In the modeling approach used in this study, parameters are defined by zones of equal value. Zones are identified with both an integer number and a parameter value. Each cell in the model is then assigned a zone for each parameter. For example, hydraulic conductivity Zone 11 is assigned a horizontal hydraulic conductivity value of 275 ft/d.

4.3.1 Hydraulic Conductivity

Hydraulic conductivity values used in the model were initially based on published values for geologic formations on Long Island (McClymonds and Franke 1972), on results of aquifer tests (Lindner and Reilly 1983), on previous modeling efforts of the area (Smolensky and Feldman 1995), and on other regional modeling efforts in Nassau County (Reilly and Buxton 1985, Buxton and Smolensky [in press]). Initial values and distributions were adjusted during model calibration. Final calibrated horizontal (K_h) and vertical (K_v) hydraulic conductivity values varied greatly across the three-dimensional model domain. Overall, 5 zones of hydraulic conductivity were used in the model to define hydraulic conductivity variations.

Horizontal hydraulic conductivity (300 ft/day) and vertical hydraulic conductivity (60 ft/day) values corresponding to that of the Upper Glacial aquifer were assigned in most of Model Layer 1. In the northeast, where Upper Magothy type deposits exist at elevations that are typical of only glacial deposits, hydraulic parameters that are representative of this reworked/transitional zone were included. A horizontal hydraulic conductivity of 200 ft/day and a vertical hydraulic conductivity of 15 ft/day (values representative of the transitional zone between Upper Glacial and upper Magothy aquifers) were assigned (see Figure 4-3). The hydraulic conductivity distribution in Model Layer 2 differs from that in Model Layer 1 in that the area representative of the transitional zone extends further south (see Figure 4-4).

Model Layer 3 is generally representative of the upper portion of the Magothy aquifer (see Figure 4-5). In most of this layer, the horizontal hydraulic conductivity (120 ft/day) and the vertical hydraulic conductivity (2.0 ft/day) correspond to the type of hydraulic properties common in the upper Magothy. In a few relatively small areas the hydraulic conductivity corresponds to that of the Upper Glacial (where glacial deposits have been reported to locally exist at lower than normal elevations).

Model Layers 4, 5, 6, and 7 correspond to the mid-Magothy aquifer. The horizontal hydraulic conductivity and vertical hydraulic conductivity were set at 50 ft/day and 0.8 ft/day respectively.

Model Layer 8 is representative of the basal Magothy. The horizontal hydraulic conductivity (80 ft/day) and the vertical hydraulic conductivity (1.2 ft/day) correspond to the increase in coarse material typical of the basal zone.

4.3.2 Areal Recharge

Recharge to the model area occurs only at the water table (Model Layer 1) and can technically be considered to be a constant flux boundary condition. Each active cell in the uppermost model layer receives a constant influx of water, which is computed by the model by multiplying the area of the grid cell by the recharge rate. Recharge is discussed as part of parameter zonation because recharge is defined in the model with zones of equal value.

Recharge enters the saturated groundwater system at the water table, the upper boundary of the groundwater system. Recharge is derived solely from precipitation, which falls at a rate ranging from 41.5 to 43 inches per year (in/yr) (Miller and Frederick 1969; Bailey et al. 1985) in the vicinity of the Northrop Grumman site. In Nassau County, it is estimated that between 50 and 52 percent of precipitation recharges the saturated groundwater system. In addition to direct recharge from precipitation, approximately 20 percent of the public supply water used in the area is returned to the groundwater system as leakage from the sewer systems (Smolensky and Feldman 1990). Only 1 percent of precipitation is lost to overland runoff because of the relatively flat topography and high infiltration capacity of the unconsolidated deposits at land surface; the remaining 47 to 49 percent is lost to evapotranspiration. Groundwater recharge was estimated as follows: direct recharge from precipitation, approximately 52 percent of 43 inches per year or 0.0051 ft/day. In addition, 20 percent of 3,167,051 cubic feet per day of groundwater pumped from public supply wells is returned to the groundwater system as leakage and non-consumptive water-use (approximately 0.00105 ft/day). The total recharge rate is therefore estimated to be 0.00615 ft/day.

4.4 GROUNDWATER PUMPAGE AND ON-SITE RECHARGE

Active pumping wells simulated in the Northrop Grumman model were represented by constant-flux internal boundary conditions at cells corresponding to each well's horizontal and vertical location (screen zone). Active pumping wells within the model domain included industrial wells located on-site and public supply wells located off site. Figures 4-6 and 4-7 show locations of on-site and off-site pumping wells, respectively. Tables 4-2 and 4-3 summarize pumpage used in the calibrated model for on-site and off-site pumping wells, respectively. These tables also summarize the model cell location (row, column, layer) of each well used in the calibrated model, as well as the distributed pumping rate in cases where a well is screened within more than one model layer.

Pumping rates used in the calibrated model were based on pumpage records provided by Northrop Grumman and on available pumpage records from local public water suppliers.

Pumpage records from 1991, 1992, and 1993 were reviewed and averaged for use during model calibration. Averages of pumpage are suitable for model calibration because seasonal variations in the data are minimized. The on-site wells are screened in model layers 5, 6, and 7 and pump a total of 880,741 cubic ft per day (approximately 4,600 gpm). The public supply wells are primarily screened in model layers 5, 6, and 7 and pump a total of 3,166,781 cubic ft per day (16,450 gpm).

The vertical distribution of pumpage in the calibrated model was proportionately distributed among appropriate, corresponding model layers in cases where a screened zone extended beyond the thickness of a single model layer. As summarized in Tables 4-2 and 4-3, active on- and off-site supply wells are screened in, and withdraw water from, the Magothy aquifer (primarily Model Layers 5, 6, and 7). None of the on-site supply wells identified within the model area is screened in Model Layer 8.

The sources of on-site artificial recharge (discharge to basins) simulated in the calibrated model are summarized in Table 4-4. Most of the supply water withdrawn at the Northrop Grumman site is returned to the groundwater system via recharge basins. Records of discharge to basins for the years 1991, 1992, and 1993 were reviewed and used in the model as part of the calibration. Discharge rates over the three year period were averaged and simulated as discharge to Model Layer 1 (the model layer corresponding to the water table) at the appropriate locations. Total basin discharge is approximately 818,000 cubic ft per day or 4,250 gpm. This rate is approximately 92 percent of the rate pumped from on-site wells. It was assumed that a small percent of the water pumped was lost during the use and transmission of the water prior to final discharge at one of the on-site basins.

5.0 MODEL CALIBRATION

The following three sections describe the calibration of the groundwater flow model.

5.1 GENERAL CALIBRATION PROCEDURE

Calibration of a numerical groundwater flow model is the process of obtaining a reasonable match between observed or measured field conditions and model-generated or simulated conditions. The calibration procedure is generally carried out by varying estimates of hydraulic properties and boundary conditions from a set of initial values until an acceptable match of simulated results to observed conditions is achieved. Examples of hydraulic properties that may be varied from a set of initial estimates are hydraulic conductivity and recharge. The measured or observed field conditions to be matched are commonly referred to as calibration targets. Calibration targets are used to evaluate the results generated by the model for a given set of input parameters. Observed hydraulic head data measurements are examples of calibration targets used in the Northrop Grumman model.

5.2 STEADY-STATE FLOW MODEL CALIBRATION

This section describes the flow model calibration using MODFLOW.

5.2.1 Calibration Targets

The groundwater flow model was calibrated to steady-state average groundwater conditions represented by groundwater levels measured during two synoptic water-level events (Spring [April] and Fall [September] of 1993). The data for each observation well was averaged to represent conditions under pumping conditions for the calibration period. The early spring and early fall periods are considered the periods of light and heavy on-site pumping. By averaging the data from these periods, the calibration targets are representative of average conditions that would be observed under average pumping. This approach therefore, is also consistent with the approach of applying average pumping rates to the supply wells (see section 4.4. Pumpage and On-site Recharge).

Precipitation records for Long Island (obtained from the NOAA database) were also reviewed to ensure that groundwater recharge from precipitation for the period 1991 through 1993 was representative of average conditions. Precipitation data for 1991, 1992, and 1993 were 43.46, 44.29, and 40.84 inches per year, respectively. The average for the three year period is 42.83 inches per year, essentially the same rate (43.0 inches per year) reported for long-term average conditions.

The model contains a total of 129 head calibration targets. Although the targets are not evenly distributed throughout the entire model domain, they are widely distributed nonetheless, and they thoroughly cover the areas of greatest concern. Vertically, the majority of head calibration targets (106 of 129) are located within the Upper Glacial aquifer (see Figure 5-1 for locations of head calibration targets in the Upper Glacial aquifer). Note that for the purpose of this discussion, Upper Glacial targets are defined as those existing in Model Layers 1, 2, and 3. Within the Upper Glacial aquifer 59, 11, and 36 calibration targets are located in Model Layers 1, 2, and 3, respectively. Of the 106 calibration targets in the Upper Glacial aquifer, 63 of 106 are located on-site. Within the Magothy aquifer, 8, 3, 4, 6, and 2 calibration targets are located in Model Layers 4 through 8, respectively. Of the 23 calibration targets in the Magothy aquifer, 8 of 23 are located on-site (see Figure 5-2 for locations of head calibration targets in the Magothy aquifer). It should be noted that many of the target locations are observation well clusters, therefore, it may appear on Figures 5-1 and 5-2 that there are less targets than stated.

5.2.2 Calibration Results

Four criteria were considered for the steady-state calibration:

1. Simulated flow patterns will adequately reproduce the flow patterns observed in the field (i.e., groundwater flow lines inferred from groundwater level contours).

2. The average of residuals (residual mean and absolute residual mean), where a residual is defined as the difference between an observed and a simulated water level, will be within 5 percent of the range in target heads.

3. The variation of residuals (residual standard deviation) will be within 10 percent of the range in target heads.

4. The distribution of residuals within the model will not show any spatial bias.

The criteria listed above were satisfied during model calibration. Simulated flow patterns match both local groundwater flow patterns in the areas of greatest concern (on-site and in areas downgradient to the south), and regional patterns over the entire model domain. The simulated water-table configuration (Model Layer 1) and calibration residuals for the Upper Glacial aquifer are shown on Figure 5-3. The simulated regional water-table configuration reproduces the regional gradients and flow directions inferred on many of the regional maps presented by the USGS (such as, Doriski 1986). The regional maps developed by others, however, do not reflect the local scale impacts of discharge to on-site basins nor the local impacts of pumping wells. This is not an oversight but rather a function of the regional nature of the maps. The simulated groundwater flow patterns and features of the flow field at the regional and site-wide scales, as described below, are consistent with observed conditions and the conceptual model of the groundwater flow system.

A review of the simulated water-table configuration at the regional scale shows water table elevations above 80 ft msl (at the northern extent of the model) that correspond to the east-west trending groundwater divide located north of the site. To the south of this divide, groundwater flows southerly towards the Great South Bay/Atlantic Ocean. Shallow groundwater passing beneath the site generally flows to the south, eventually discharging to surface-water bodies (streams located near the south shore) or the southern shoreline discharge boundary. Mounding of the water table in the vicinity of the recharge basins is evident, with groundwater flowing radially away from these recharge areas until it becomes more a part of the regional flow system. The basin impact is clearly seen on-site in three basin areas; to the northeast, along the western boundary, and along the southern boundary. A review of the simulated potentiometric surface for the Magothy aquifer at the regional scale also indicates an east-west trending groundwater divide located to the north of the site. Generally, the regional simulated flow patterns for the Magothy are similar to those for the Upper Glacial aquifer, with groundwater flowing to the south of the divide (Figure 5-4). The differences between the maps are seen as cones of depression around pumping wells and the absence of mounding around recharge basin locations and the general increase in the elevation of the water table at the site (due to the recharge basins).

As discussed in Section 5.2.1 (Calibration Targets), the steady-state flow model calibration involved an evaluation of model-generated residuals. A residual was calculated for each head calibration target by subtracting the model-calculated water level from the observed water level (calibration target). A residual near zero signifies a close match between the model results and the observed field condition. The sign of the residual, positive or negative, is as important as the magnitude of the residual. Negative residuals occur where the model-calculated water levels are higher than observed. Conversely, positive residuals indicate that the model-generated water levels are lower than observed. Simulated heads, observed heads, and calculated residuals for each head calibration target are provided in Table 5-1. Table 5-2 summarizes the head calibration statistics by model layer for the entire model area.

The residual mean for the calibrated model was -0.18 ft, as indicated in Table 5-2, and is a negligible percent of the total change in head across the model area (more than 40 ft.) This value, which is close to zero, implies that positive residuals (areas where model-generated water levels are low) and negative residuals (areas where model-generated water levels are high) are relatively balanced within the model domain. The absolute residual mean for the calibrated model was 0.91 ft and is about two percent of the total change in head across the model area. The absolute residual mean is included as an additional measure to evaluate the quality of calibration without compensating errors from the addition of positive and negative residuals. In addition to a residual mean close to zero, the residual standard deviation should be low. The model residual standard deviation was 1.15 ft, which means that most model residuals are in error by no more than 1.15 ft. The residual standard deviation of 1.15 ft is three percent of the total change in head across the model area.

A scatterplot was also constructed for the calibrated model to evaluate patterns and relationships between various calibration targets with respect to residuals. Figure 5-5 shows the scatterplot of observed water levels versus model-calculated water levels with a 45-degree line superimposed for comparison. The scatterplot supports the acceptability of the calibration in that the majority of targets fall along or near the 45-degree line and related targets do not exhibit groupings far from the 45-degree line. The scatterplot, in conjunction with the residual ranges posted on Figure 5-3 and listed in Table 5-1, supports the indication that the distribution of positive and negative residuals does not exhibit significant spatial bias.

5.2.3 Volumetric Flow Budget

As part of the numerical solution effort, MODFLOW output includes a volumetric budget of all inflows, outflows, and changes in groundwater storage. The components must satisfy the continuity equation:

$$\text{inflow} = \text{outflow} +/- \text{changes in storage.}$$

Because steady-state conditions were simulated (i.e., no change in storage) all inflows must balance outflows to ensure model accuracy and stability. The model-calculated percent discrepancy between inflows and outflows for the Northrop Grumman flow model was 0.05 percent. This discrepancy indicates that mass was conserved and that the simulation was steady-state. Closure criteria was set at 0.0001 and the Strongly Implicit Procedure (SIP) was used as the solution package.

Inflow to the model included areal recharge (3,425,500 ft^3/d), on-site recharge through recharge basins (817,979 ft^3/d), and an influx from constant heads along the model boundaries (1,472,200 ft^3/d). Model outflows primarily were withdrawal by pumping wells (3,693,600 ft^3/d [this does not include pumpage from wells located within lateral model boundary cells]), and flow to constant head boundaries, primarily along the southern model boundary (2,019,300 ft^3/d). These flows are consistent with the conceptualization of the groundwater flow system.

5.3 SENSITIVITY ANALYSIS

A series of tests were performed to analyze the sensitivity of the simulations made with the model to key parameters input to the flow model. The sensitivity analyses were performed by changing a single parameter at a time while maintaining all other input parameters constant. The simulated aquifer response was compared to the calibrated model output to provide a quantitative estimate of the magnitude of potential error associated with changes in individual input parameters.

Sensitivity analyses focused primarily on horizontal and vertical hydraulic conductivities of the hydrogeologic units, and recharge from precipitation. In each simulation, only one of the parameters (or zone for a specific conductivity value) was varied. Horizontal and vertical hydraulic conductivities of the Upper Glacial aquifer (Model Layers 1, 2, and 3) and the Magothy aquifer were chosen because of the relative uncertainty associated with those values. In addition, sensitivity analyses were performed by others (to whom the model has been distributed) for no-flow boundary conditions as opposed to constant-head boundary conditions (results indicated insignificant changes in simulated water levels at the site). In all, 14 sensitivity runs were simulated.

The results of the sensitivity analyses are summarized in Table 5-3. For each sensitivity run, the residual mean, normalized to the calibrated model statistic, was used as a measure of the model's sensitivity to the changes in input parameters. The normalized residual mean is defined as the average value of the difference between calculated heads for the sensitivity run and heads simulated under calibrated model conditions. As such, the normalized residuals directly indicate the corresponding head difference due to the change implemented in the sensitivity run compared to the calibrated model.

Horizontal and vertical hydraulic conductivities of the Upper Glacial aquifer were increased and decreased by 100 ft/d and 30 ft/d, respectively. Horizontal hydraulic conductivity of the Magothy aquifer was increased and decreased by 20 ft/d and 10 ft/d, respectively. Vertical conductivity of the Magothy was increased and decreased by 2 and 1 ft/d, respectively. Where the Magothy aquifer exists under water-table conditions (northeast corner of the model area) horizontal conductivity was increased and decreased by 100 ft/d. The transitional zone (where reworked Magothy and Glacial material exists) was increased and decreased by 60 ft/d. Finally, groundwater recharge from precipitation was increased and decreased by two inches per year.

The sensitivity analysis indicated that the horizontal hydraulic conductivity values of the Magothy aquifer and recharge from precipitation are the most sensitive parameters. As shown in table 5-3, increases in Magothy horizontal conductivity and recharge resulted in a normalized residual mean of +0.485 and -0.380, respectively. Decreases in the same parameters yielded normalized residual means of -0.317 and +0.367, respectively.

5.4 MODEL VERIFICATION

The calibrated groundwater flow model was verified through simulation of an independent set of observed hydrologic conditions while aquifer stresses were different from those simulated in the calibrated case.

5.4.1 Verification Set-up

The groundwater model was verified to groundwater conditions observed in the Spring of 1993. Water levels measured in observations wells on or about April 1, 1993 were used as the verification target set. This target set included 125 of the 129 data point locations used in the calibrated model run, but is representative of a specific time under specific hydraulic conditions. The on-site demand for water was lowest during the March/April timeframe.

On-site groundwater pumpage data for Northrop Grumman supply wells for the month of March 1993 were applied to the model. Total on-site pumpage at this time was approximately 2.8 mgd and represents approximately 42 percent of the pumpage simulated in the calibration runs. Discharge to on-site recharge basins corresponds directly to on-site pumpage and was therefore adjusted accordingly. These conditions represent a significant change in hydraulic stresses imposed on the local aquifer system as compared to the calibration runs. Off-site pumpage (public water-supply wells) was not changed from the calibrated model.

In addition to on-site changes in pumpage and discharge to basins, groundwater recharge was increased over the entire model domain to simulate the natural increase in recharge to the groundwater system at this time of the year. Precipitation records indicate that March of 1993 was an extremely wet month with over 6 inches of precipitation measured. Because the verification run is a steady-state simulation, however, it would not be appropriate to increase the steady state recharge rate to one that is based on a monthly "event" of this magnitude (corresponding to over 72 inches per year of precipitation). Therefore, the groundwater recharge rate was increased by only 2 inches per year to be more representative of the increased seasonal recharge rate. Geraghty & Miller believes that considering the transient seasonal nature of groundwater recharge on Long Island, this increase is more representative for use in a steady-state application.

5.4.2 Verification Results

The same criteria used for model calibration (see section 5.2.2) were also used for model verification. All verification criteria were met. Simulated flow patterns match both local groundwater flow patterns in the areas of greatest concern (on-site and in areas downgradient to the south), and regional patterns over the entire model domain. In general, observed and simulated regional water levels (verification) are approximately one foot higher than those observed and simulated for the calibration run. In the immediate vicinity of the on-site recharge basins, however, observed water levels are similar in magnitude (verification and calibration). This is likely a function of the increase in the discharge to the basins under the calibration run hydraulic conditions. These trends are simulated by the model. The exceptions are near the Plant 3 basins, where simulated water levels (verification) are approximately 1 foot lower than observed, and at the lateral boundaries of the model, where water levels are influenced by constant head values (constant heads values set for this verification run were not modified from the calibration run). Minor discrepencies seen at the Plant 3 basins are likely a function of the daily fluctuations in discharge to the basins compared with the monthly average discharge rate applied in the model.

As discussed in the Calibration Targets section (section 5.2.1), the verification run also involves an evaluation of model-generated residuals. A residual was calculated for each head calibration target by subtracting the model-calculated water level from the observed water level (calibration target). A residual near zero signifies a close match between the model results and the observed field condition. Negative residuals occur where the model-calculated water levels are higher than observed. Conversely, positive residuals indicate that the model-generated water levels are lower than observed. The residual mean for the verification run was 0.42 ft, and is approximately one percent of the total change in head across the model area (more than 40 ft.) This value, which is close to zero, implies that positive residuals (areas where model-generated water levels are low) and negative residuals (areas where model-generated water levels are high) are relatively balanced within the model domain. The absolute residual mean for the verified model was 0.95 ft and is about two percent of the total change in head across the model area. The absolute residual mean is included as an additional measure to evaluate the quality of calibration without compensating errors from the addition of positive and negative residuals. In addition to a residual mean close to zero, the residual standard deviation should be low. The model residual standard deviation was 1.18 ft, which means that most model residuals are in error by no more than 1.18 ft.

6.0 SUMMARY AND CONCLUSIONS

Geraghty & Miller has completed a comprehensive modeling effort by developing a three-dimensional groundwater flow model for the Northrop Grumman site and the surrounding area. The modeling effort consisted of conceptual model development, model design and construction, model calibration, sensitivity analyses, and verification, and presentation of simulated results of the groundwater flow regime under calibrated, steady-state conditions.

The modeling effort and model design were structured to address critical groundwater issues at and around the Northrop Grumman site. A "systems approach," whereby the complexities of the groundwater system are evaluated as intricately related processes, was used in the modeling effort to allow for assessment of the effects of various potential remedial scenarios and water-supply alternatives on the groundwater resource. The modeling effort was intended to develop and construct a three-dimensional groundwater flow model that will be used as a tool for evaluation of these scenarios and alternatives at varying scales of interest.

The Upper Glacial aquifer has the highest and greatest range of estimated values for hydraulic conductivity due to the variation in deposits encountered (from lower permeability morainal deposits to outwash materials). The Magothy aquifer exhibits less variation in hydraulic characteristics than the Upper Glacial aquifer, but is less permeable and exhibits a higher degree of anisotropy due to stratification of the Magothy deposits.

Artificial stresses imposed on the aquifer system act as internal boundaries and include pumping wells and recharge basins. The horizontal direction of groundwater flow at Northrop Grumman is locally influenced by pumping supply wells and recharge basins. Pumping wells locally depress the water table, while recharge basins may produce local groundwater mounding.

The modular finite-difference groundwater flow code, known as MODFLOW, was selected for the groundwater flow model. The goal of model design and construction was to provide a consistent numerical representation of the conceptualized groundwater system. Model construction was accomplished by completing the following steps: discretization, definition of boundary conditions, parameter zonation, and representation of hydraulic stresses such as groundwater pumpage and recharge basins.

Discretization of the model domain into a finite-difference grid was conducted after careful consideration of project goals. The grid design also considered several additional factors, such as the level of detail of the data available to define the hydrogeologic framework and hydraulic characteristics, the ability to define and represent boundary conditions and stresses, and the amount and distribution of hydraulic head data for calibration. The grid design addressed all three dimensions by also including a vertical discretization scheme that resulted in eight model layers. Model Layers 1 and 2 represent the Upper Glacial aquifer; Model Layer 3 is representative of the Upper Glacial and Magothy (depending on local erosion); Model Layers 4, 5, 6, 7, and 8 represent the Magothy aquifer.

Appropriate mathematical boundary conditions, based on actual groundwater system boundaries where possible, were specified to define the lateral, upper, and lower boundaries of the flow model. In general, these boundary conditions include constant head and constant flux. Active pumping wells simulated in the calibrated model included industrial wells located on-site, and public water supply wells located off-site within the model domain. Sources of artificial recharge simulated in the calibrated model included on-site recharge basins, which return much of the supply water to the groundwater system.

The groundwater flow model was calibrated to steady-state groundwater conditions represented by average 1991 to 1993 flow conditions. Observed measurements considered as calibration targets included water levels from 129 on-site and off-site wells located within different portions of the aquifer system. In addition, specific water-level calibration criteria were considered, including reproducibility of observed flow patterns (i.e., water level contours) as well as several statistical measures (residual mean, absolute residual mean, residual standard deviation, and distribution of residuals). The residual mean for the calibrated model was -0.18 ft, which is close to zero, implying that positive residuals and negative residuals are relatively balanced within the model domain. Review of the distribution of residuals indicated that significant spatial bias was not exhibited. In addition, the model residual standard deviation was 1.15 ft, which means that most model residuals are in error by no more than 1.15 ft. The model was successfully calibrated to the specified criteria. The simulated groundwater flow patterns and features of the simulated flow field at the regional and site-wide scales are consistent with the conceptual model of the groundwater flow system. To increase the level of confidence in the models' ability to simulate the real system, a verification simulation was run. The model successfully simulated observed water levels under a set of hydraulic conditions that were different than those used in the calibration run.

In conclusion, the resultant model design provides a consistent numerical representation of the conceptualized groundwater system for evaluation of potential impacts on the aquifer system. In addition, because the model was constructed using MODFLOW, widely used transport codes can be readily implemented with additional input for evaluation of advective transport or general evaluations of solute transport.

7.0 REFERENCES

Bailey, B.H., K. Webster, R. Stewart. 1985. Long Island Precipitation Patterns and Drought Probability. State University of New York at Albany, Atmospheric Sciences Research Center, Publication No. 1000, 71 p.

Bear, J. 1972. Dynamics of Fluids in Porous Media, Dover Publications, Inc., New York.

Buxton, H.T., and E. Modica. 1992. Patterns and Rates of Groundwater Flow on Long Island, New York. Groundwater vol. 30, No. 6.

Buxton, H.T., and D.A. Smolensky. In Press. A Quantitative Analysis of the Development of the Groundwater Flow System of Long Island, New York. U.S. Geological Survey Water Supply Paper 2361-A.

Buxton, H.T., T.E. Reilly, D.W. Pollack, and D.A. Smolensky. 1991. Particle Tracking Analysis of Recharge Areas on Long Island, New York. Groundwater. Volume 29. No. 1.

Doriski, T.P., and F. Wilde-Katz. 1983. Geology of the 20-Foot Clay in Southern Nassau and Southwestern Suffolk Counties, Long Island, New York. Water-Resources Investigation 82-4056.

Doriski, T.P. 1986. Water-Table Altitude on Long Island, New York, March 1983 (Plate 1B) and Potentiometric Surface of the Magothy Aquifer, Long Island, New York, March 1983 (Plate 3B). U.S. Geological Survey Water-Resources Investigation Report 85-4321.

Feldman, S.M., D.A. Smolensky, and J.P. Masterson. 1992. Ground-Water Quality in the Bethpage-Hicksville-Levittown Area, Long Island, New York, With Emphasis on Volatile Organic Compounds, U.S. Geological Survey Water Resources Investigation Report 90-4182.

Franke, O.L., and P. Cohen. 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.

Franke, O.L., and R.T. Getzen. 1976. Evaluation of Hydrogeologic Properties of the Long Island Ground-Water Reservoir using Cross-Sectional Analog Models. U.S. Geological Survey Open-File Report 75-679, 80 p.

Getzen, R.T. 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.

Isbister, J. 1966. Geology and Hydrology of Northeastern Nassau County Long Island, New York. U.S. Geological Survey Water-Supply Paper 1825.

Linder, J.B., and T.E. Reilly. 1983. Analysis of Three Tests of the Unconfined Aquifer in Southern Nassau County, Long Island, New York, U.S. Geological Survey Water Resources Investigation Report 82-4021.

McClymonds, N.E., and O.L. Franke. 1972. Water-transmitting Properties of Aquifers on Long Island, New York. U.S. Geological Survey Professional Paper 627-E, 24 p.

McDonald, M.G., and A. W. Harbaugh. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Techniques of Water-Resources Investigations. U.S. Geological Survey, Reston, Virginia, Book 6, Chapter A1.

Miller, J.F., and R.H. Frederick. 1969. The Precipitation Regime of Long Island, New York. U.S. Geological Survey Professional Paper 627-A, 21 p.

Perlmutter, N.M., and J.J. Geraghty. 1963. Geology and Ground-Water Conditions in Southern Nassau and Southeastern Queens Counties, Long Island, New York. U.S. Geological Survey Water-Supply Paper 1613-A.

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.

Reilly, T.E., and H.T. Buxton. 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.

Reilly, T.E., H.T. Buxton, O.L. Franke, and R.L. Wait. 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 82-4045, 45 p.

Remson, I., G.M. Hornberger, F.J. Moly. 1971. Numerical Methods in Subsurface Hydrology with an Introduction to the Finite Element Method. Wiley-Interscience, New York.

Smolensky, D.A., H.T. Buxton, and P.K. Shernoff. 1989. Hydrogeologic Framework of Long Island, New York. U.S. Geological Survey, Hydrogeologic Investigations Atlas 709.

Smolensky, D.A. and S.M. Feldman 1990. Geohydrology of the Bethpage-Hicksville-Levittown area, Long Island, New York. U.S. Geological Survey Water-Resources Investigation Report 88-4135

Smolensky, D.A. and S.M. Feldman 1995. Three-Dimensional Advective Transport of Volatile Organic Compounds in Groundwater Beneath an Industrial-Residential Area of Nassau County, New York. U.S. Geological Survey Water-Resources Investigation Report 92-4148

Warren, M.A., W. de Laguna, and N.J. Lusczynski. 1968. Hydrology of Brookhaven National Laboratory and Vicinity, Suffolk County, New York. U.S. Geological Survey Bulletin 1156-C, 127 p.

\\gm_plain\data\aproject\grumman\ny0008.042\reports\regmod-f.doc

Table 2-1. Hydrogeologic units in the Vicinity of the Northrop Grumman Site, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Geologic Unit	Hydrogeologic Unit	Approximate Maximum Thickness (Feet)	Character Of Deposits And Water-Bearing Properties.
Recent deposits and fill	Recent deposits	10	Sand, gravel, clay, silt, organic mud, loam, and fill. Constitutes soil zone and fill area and is hydraulically connected to underlying Upper Glacial aquifer.
Upper Pleistocene deposits	Upper Glacial aquifer	75	Sand, fine to coarse, gravel, glacial outwash deposits, commonly brown or tan but may be yellow or orange. Some thin local lenses of clay or silty zones. Outwash deposits are moderately to highly permeable.
Magothy Formation-Matawan Group, undivided	Magothy Aquifer	650	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal zone. Sand and gravel are quartzose. Lignite, pyrite, and iron oxide concretions are common. Colors are gray, white, red, brown, and yellow. Most layers are poorly to moderately permeable; some are highly permeable locally. Water is unconfined in uppermost parts, elsewhere confined. Principle aquifer for public supply.
Raritan Formation	Raritan confining unit	175	Clay, solid and silty; few lenses and layers of sand. Lignite and pyrite are common. Colors are gray, red, and white, commonly variegated. Low to very low permeability; constitutes confining layer above Lloyd aquifer.
	Lloyd aquifer	300	Sand, fine to coarse, and gravel, commonly with clayey matric, some lenses and layers of solid and silty clay; locally contains thin lignite layers. Sand and most of gravel are quartzose. Colors are yellow, gray, and white; clay is red locally. Permeability low to moderate. Water is confined by overlying Raritan clay.
Bedrock	Bedrock		Crystalline and metamorphic and (or) igneous rocks; muscovite-biotite schist, gneiss, and granite. Contains a soft, clayey weathered zone more than 50 ft thick locally. Poorly permeable to relatively impermeable; forms lower boundary of ground-water system.

Modified from Smolensky and Feldman, 1995

\\gm_plain\data\aproject\grumman\ny0008.042\reports\table2-1.doc

Table 4-1. Hydrogeologic Units and Model Layering Scheme in the Vicinity of the Northrop Grumman Site, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Model Layer	Hydrogeologic Unit	Bottom Elevation (ft msl)
1	Upper Glacial (Magothy Aquifer northeast of site)	40
2	Upper Glacial (Magothy Aquifer northeast of site)	25
3	Upper Magothy Aquifer (locally Upper Glacial northwest of site)	-50
4	Magothy Aquifer	-140
5	Magothy Aquifer	-235
6	Magothy Aquifer	-365
7	Magothy Aquifer	-530
8	Magothy Aquifer	-600

ft msl feet relative to mean sea level.

Table 4-2. Summary of On-Site Pumpage for the Calibrated Flow Model, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Well Designation	NYSDEC Well Number	Location in Model Grid			Pumping Rate		
		I (row)	J (col)	K (layer)	(cfd)	(mgd)	(gpm)
GP-1	N8842	53	29	7	202,188	1.51	1,050
GP-2	N8154	43	30	6	14	0	0
		43	30	7	8	0	0
GP-3	N8124	48	27	7	9,479	0	49
GP-4	N1923	50	29	5	17	0	0
GP-5	N7635	37	27	5	106	0	1
GP-6	N7534	35	22	5	52,494	0	273
GP-8	N7535	26	30	5	1,755	0	9
GP-9	N7536	28	32	6	71,410	1	371
GP-10	N7636	27	35	5	121,202	1	630
GP-11	N7637	29	38	6	100,534	0.75	522
GP-13	N8454	22	34	7	113,188	0.85	588
GP-14	N8643	30	29	6	7,837	0	41
GP-15	N8816	26	40	6	58,192	0	302
GP-16	N7518	17	42	5	142,318	1.06	739
TOTALS					880,741	6.59	4,575

cfd Cubic feet per day.
mgd Million gallons per day.
gpm Gallons per minute.
NYSDEC New York State Department of Environmental Conservation.

Table 4-3. Summary of Off-Site Pumpage for the Calibrated Flow Model, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Water District Name	Local Well Number	NYSDEC Well Number	Location in Model Grid I (row)	J (col)	K (layer)	Pumping Rate (cfd)	Total Pumping Rate (mgd)	(gpm)
Bethpage Water District								
	5-1	N-8004	89	59	8	14,075	0.11	73
	6-1	N-3876	83	46	6	44,531	0.33	231
	6-2	N-8941	83	46	8	25,738	0.19	134
	7	N-8767	22	62	7	161,454	1.21	839
	8	N-8768	23	62	7	114,971	0.86	597
	9	N-6078	19	62	4	5	0.00	0
	10	N-6915	80	62	6	27,890	0.40	279
			80	62	7	25,745		
	11	N-6916	82	62	7	57,735	0.43	300
	BDG-1	N-09591	30	65	7	4,959	0.07	52
			30	65	8	4,959		
Hicksville Water District								
	1-4	N-7562	4	6	6	35,305	0.26	183
	1-6	N-09488	4	6	7	147,202	1.10	765
	3-2	N-8525	45	5	6	78	0.00	0
	4-2	N-8526	35	1	7	45,465	0.34	236
	7-1	N-6190	1	11	7	2,434	0.02	13
	8-1	N-6192	23	6	7	72,223	0.54	375
	8-3	N-9180	22	5	7	49,819	0.37	259
	9-1	N-8778	13	10	7	88,588	0.66	460
	9-2	N-8779	13	10	7	63,691	0.48	331
	9-3	N-10208	13	8	7	83,879	0.63	436
	10-1	N-09463	6	3	7	127,327	0.95	661
	11-1	N-10555	7	26	7	90,224	0.67	469

Table 4-3. Summary of Off-Site Pumpage for the Calibrated Flow Model, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Water District Name	Local Well Number	NYSDEC Well Number	Location in Model Grid I (row)	J (col)	K (layer)	Pumping Rate (cfd)	Total Pumping Rate (mgd)	(gpm)
Levittown Water District								
	6A	N-3618	85	5	6	23,260	0.17	121
	5A	N-7076	85	6	7	49,411	0.74	513
			85	6	8	49,411		
	14	N-5304	102	5	7	77,112	0.58	401
	13	N-5303	99	13	7	75,685	0.57	393
	12	N-5302	99	1	7	57,175	0.43	297
	8A	N-7523	97	7	8	105,838	0.79	550
	2A	N-8321	71	1	7	36,614	0.49	340
			71	1	8	28,768		
	7A	N-8279	97	7	6	21,727	0.51	353
			97	7	7	46,169		
	9	N-4450	90	2	6	101,858	1.09	756
			90	2	7	43,653		
	10	N-4451	57	5	6	5	0.00	0
Plainview Water District								
	1-1	N-4095	5	67	6	78,305	0.59	407
	1-2	N-4096	5	68	6	62,154	0.46	323
	2-1	N-7526	3	68	6	5,926	0.15	103
			3	68	7	13,828		
	3-1	N-4097	4	47	6	8,985	0.07	47
	3-2	N-6580	5	47	6	24,401	0.79	551
			5	47	7	81,691		
	4-1	N-6076	3	59	5	13,343	0.10	69
	4-2	N-6077	3	60	6	79,735	0.60	414

Table 4-3. Summary of Off-Site Pumpage for the Calibrated Flow Model, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Water District Name	Local Well Number	NYSDEC Well Number	Location in Model Grid I (row)	J (col)	K (layer)	Pumping Rate (cfd)	Total Pumping Rate (mgd)	(gpm)
South Farmingdale Water District								
	1-2	N-4043	100	66	6	56,131	0.42	292
	1-3	N-05184	99	66	6	21,701	0.16	113
	1-4	N-7377	99	66	7	42,244	0.57	399
			99	66	8	34,564		
	3-1	N-6150	101	44	7	104,979	0.79	545
	6-1	N-8664	104	41	7	53,108	0.40	276
	6-2	N-8665	104	40	7	48,749	0.36	253
New York Water Service Corporation								
	3-S	N-8480	102	27	7	171,009	1.28	888
	4-S	N-9338	102	26	7	260,946	1.95	1,356
TOTALS						3,166,781	24	16,451

cfd Cubic feet per day.
mgd Million gallons per day.
gpm Gallons per minute.
NYSDEC New York State Department of Environmental Conservation.

Table 4-4. Summary of On-Site Discharge to Basins for the Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Recharge	Location in Model Grid I (row)	J (col)	K (layer)	Cell Recharge Rate (cfd)	Total Recharge Rate (mgd)	(gpm)
Recharge Basins						
Plant 3	27	45	1	26,341	3.15	2,189
	27	46	1	26,341		
	28	41	1	26,341		
	28	42	1	26,341		
	28	45	1	26,341		
	28	46	1	26,341		
	29	41	1	26,341		
	29	42	1	26,341		
	29	43	1	26,341		
	30	43	1	26,341		
	30	44	1	26,341		
	30	45	1	26,341		
	30	46	1	26,341		
	31	45	1	26,341		
	31	46	1	26,341		
	29	44	1	26,341		
Plant 5	48	25	1	49,870	1.49	1,036
	49	26	1	49,870		
	50	26	1	49,870		
	51	27	1	49,870		
Plant 12	31	21	1	4,522	0.07	47
	31	22	1	4,522		
Southern Boundary	62	36	1	18,800	1.41	977
	63	38	1	18,800		
	63	40	1	18,800		
	64	41	1	18,800		
	64	43	1	18,800		
	62	35	1	18,800		
	63	37	1	18,800		
	63	39	1	18,800		
	64	42	1	18,800		
	64	44	1	18,800		
Total				817,979	6.12	4,249

cfd Cubic feet per day
mgd Million gallons per day.
gpm Gallons per minute.

Table 5-1. Summary of Observed and Simulated Water-Level Elevations, and Residuals, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Well Designation	Location in Model Grid I (row)	J (col)	K (layer)	Observed Head (ft msl)	Simulated Head (ft msl)	Residual (Observed minus Simulated) (ft)
gm-1s	10	35	1	72.42	71.69	0.73
gm-1i	10	35	3	72.37	71.62	0.75
gm-2s	13	42	1	72.39	70.82	1.57
gm-2i	14	43	3	71.43	70.54	0.89
gm-3s	14	24	2	71.4	70.53	0.87
gm-3i	16	24	3	70.78	70.12	0.66
gm-4s	17	24	1	73.1	70.03	3.07
gm-4i	17	24	3	70.75	69.95	0.8
gm-5s	21	27	1	70.53	69.3	1.23
gm-5i	21	27	3	70.29	69.2	1.09
gm-6i	21	35	3	64.92	69.29	-4.37
gm-7s	23	40	1	70.95	70.38	0.57
gm-7i	23	40	3	70.72	70.12	0.6
gm-7d	23	40	4	68.72	68.87	-0.15
gm-8s	26	45	1	73.37	73.32	0.05
gm-8i	26	45	3	73.28	72.18	1.1
gm-9s	25	24	1	69.85	68.83	1.02
gm-9i	25	24	3	69.69	68.76	0.93
gm-10i	31	20	3	68.93	68.29	0.64
gm-12s	35	30	1	68.78	68.04	0.74
gm-12i	35	30	3	68.22	67.93	0.29
gm-13s	40	38	1	68.53	68.19	0.34
gm-13i	40	38	3	68.64	68.1	0.54
gm-13d	43	36	4	66.66	67.2	-0.54
gm-14s	43	41	1	67.38	67.83	-0.45
gm-14i	45	39	3	67.27	67.35	-0.08
gm-15s	52	50	1	65.46	66.11	-0.65
gm-15i	59	53	3	64.69	64.5	0.19
gm-16i	46	33	3	67.67	67.26	0.41
gm-16s	46	33	1	67.77	67.36	0.41
gm17-s	49	26	1	70.73	69.87	0.86
gm-18s	58	30	1	65.66	65.42	0.24
gm-18i	57	30	3	66.2	65.52	0.68
gm-19s	59	46	1	65.64	65.09	0.55
gm-19i	59	46	3	65.51	65.02	0.49
gm-20s	64	36	1	65.48	64.99	0.49
gm-20i	64	36	3	64.86	64.62	0.24
gm-20d	64	36	4	63.88	63.97	-0.09
gm-21s	65	41	1	65.71	65.01	0.7
gm-21i	65	41	3	64.91	64.5	0.41
gm-22s	65	46	1	66.46	63.94	2.52
gm-22i	65	46	3	65.35	63.78	1.57
gm-22d	65	46	4	63.12	63.39	-0.27
gm-23s	37	23	1	67.83	67.78	0.05
gm-23i	37	23	3	67.82	67.65	0.17
gm-32s	49	34	1	66.71	66.96	-0.25
gm-33d2	60	31	7	60.07	61.94	-1.87
gm-35d2	76	40	7	57.06	57.97	-0.91
gm-36d2	79	54	7	54.61	55.87	-1.26
gm-36d	79	54	4	56.5	56.96	-0.46
gm-38d2	84	59	7	51.37	53.24	-1.87

Table 5-1. Summary of Observed and Simulated Water-Level Elevations, and Residuals, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Well Designation	Location in Model Grid I (row)	J (col)	K (layer)	Observed Head (ft msl)	Simulated Head (ft msl)	Residual (Observed minus Simulated) (ft)
gm-37d	73	60	5	58.2	59.19	-0.99
gm-37d2	73	60	6	57.82	58.88	-1.06
gm-38d	84	59	6	52.56	53.74	-1.18
hn-8d	28	47	4	68.81	70.87	-2.06
hn-24s	32	31	1	69.49	68.26	1.23
hn-24i	32	31	3	68.12	68.11	0.01
hn-25s	28	36	1	69.91	69.36	0.55
hn-25i	28	36	3	69.51	69	0.51
hn-25d	28	36	4	67.05	66.68	0.37
hn-26s	28	40	1	73.57	72.23	1.34
hn-26i	28	40	3	71.49	71.07	0.42
hn-27i	31	41	3	71.83	71.17	0.66
hn-28s	33	41	1	70.56	70.7	-0.14
hn-28i	33	42	3	68.52	70.69	-2.17
hn-29s	35	39	1	70.51	69.32	1.19
hn-29i	35	39	3	68.88	69.18	-0.3
hn-29D	35	39	4	66.67	68.43	-1.76
hn-30s	31	46	1	71.6	74.13	-2.53
hn-30i	31	46	3	70.19	72.24	-2.05
gm-34d	81	30	6	56.59	56.17	0.42
gm-34d2	81	30	7	55.01	55.97	-0.96
hn-40s	45	48	1	66.39	67.52	-1.13
hn-40i	45	48	3	66.31	67.46	-1.15
hn-41s	54	53	1	64.47	65.6	-1.13
hn-41i	54	53	3	63.85	65.57	-1.72
hn-42s	37	49	1	68.47	69.44	-0.97
hn-42i	37	49	3	68.07	69.34	-1.27
1231	5	65	1	74.93	76.46	-1.53
1232	17	65	1	71.1	71.92	-0.82
1234	73	65	1	58.62	59.58	-0.96
1236	101	66	2	41.72	40.84	0.88
8888	1	10	1	80.29	82.92	-2.63
9079	32	15	1	67.97	68.44	-0.47
9654	92	21	2	51.99	51.6	0.39
9658	104	27	2	36	36.41	-0.41
9660	104	66	2	35.03	35.91	-0.88
9661	93	65	2	51.19	49.75	1.44
9918	52	6	2	64.13	65.88	-1.75
9919	10	3	1	72.1	74.36	-2.26
9920	7	19	1	74.48	74.13	0.35
9921	73	31	1	60.17	60.43	-0.26
9922	4	1	1	78.22	79.92	-1.7
9928	87	25	1	53.1	54.02	-0.92
9930	92	68	1	48.87	49.92	-1.05
9931	41	49	1	67.14	68.39	-1.25
9932	8	54	2	73.9	73.55	0.35
9981	4	39	2	77.8	77.03	0.77
10591	17	54	1	71.58	71.09	0.49
10592	32	64	2	68.96	69.41	-0.45
10593	24	22	1	69.84	69.04	0.8
10594	29	25	1	69.57	68.41	1.16

Table 5-1. Summary of Observed and Simulated Water-Level Elevations, and Residuals, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Well Designation	Location in Model Grid I (row)	J (col)	K (layer)	Observed Head (ft msl)	Simulated Head (ft msl)	Residual (Observed minus Simulated) (ft)
10597	44	15	1	67.04	67.16	-0.12
10600	63	23	1	62.76	63.65	-0.89
10602	77	34	1	60.59	58.62	1.97
10603	78	23	1	57.89	58.05	-0.16
10627	71	32	5	60.86	60.8	0.06
10628	70	55	1	60.33	61.26	-0.93
10631	62	31	1	63.55	64.5	-0.95
10633	68	45	1	62.36	62.91	-0.55
10634	69	41	1	60.36	62.68	-2.32
10635	77	31	1	58.9	58.6	0.3
10636	62	13	1	63.26	63.55	-0.29
10813	70	20	1	61.21	61.36	-0.15
10814	82	50	2	56.26	55.91	0.35
10815	80	13	1	57.3	57.04	0.26
10816	90	39	1	52.5	52.57	-0.07
10818	85	41	1	54.65	54.7	-0.05
10820	81	30	3	57.44	56.7	0.74
10821	80	53	1	56.81	56.78	0.03
10822	80	13	3	57.46	57	0.46
10977	73	65	8	56.75	58.3	-1.55
10999	92	29	6	51.83	51.06	0.77
11000	92	29	3	51.92	51.61	0.31
11067	73	65	3	57.07	59.53	-2.46
11722	101	5	5	40.1	41.19	-1.09
11723	101	5	8	37.47	40.05	-2.58
11724	10	66	3	72.1	73.66	-1.56
11731	10	66	7	70.78	72.25	-1.47

ft msl Elevation in feet above mean sea level

Table 5-2. Summary of Head Calibration Statistics, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

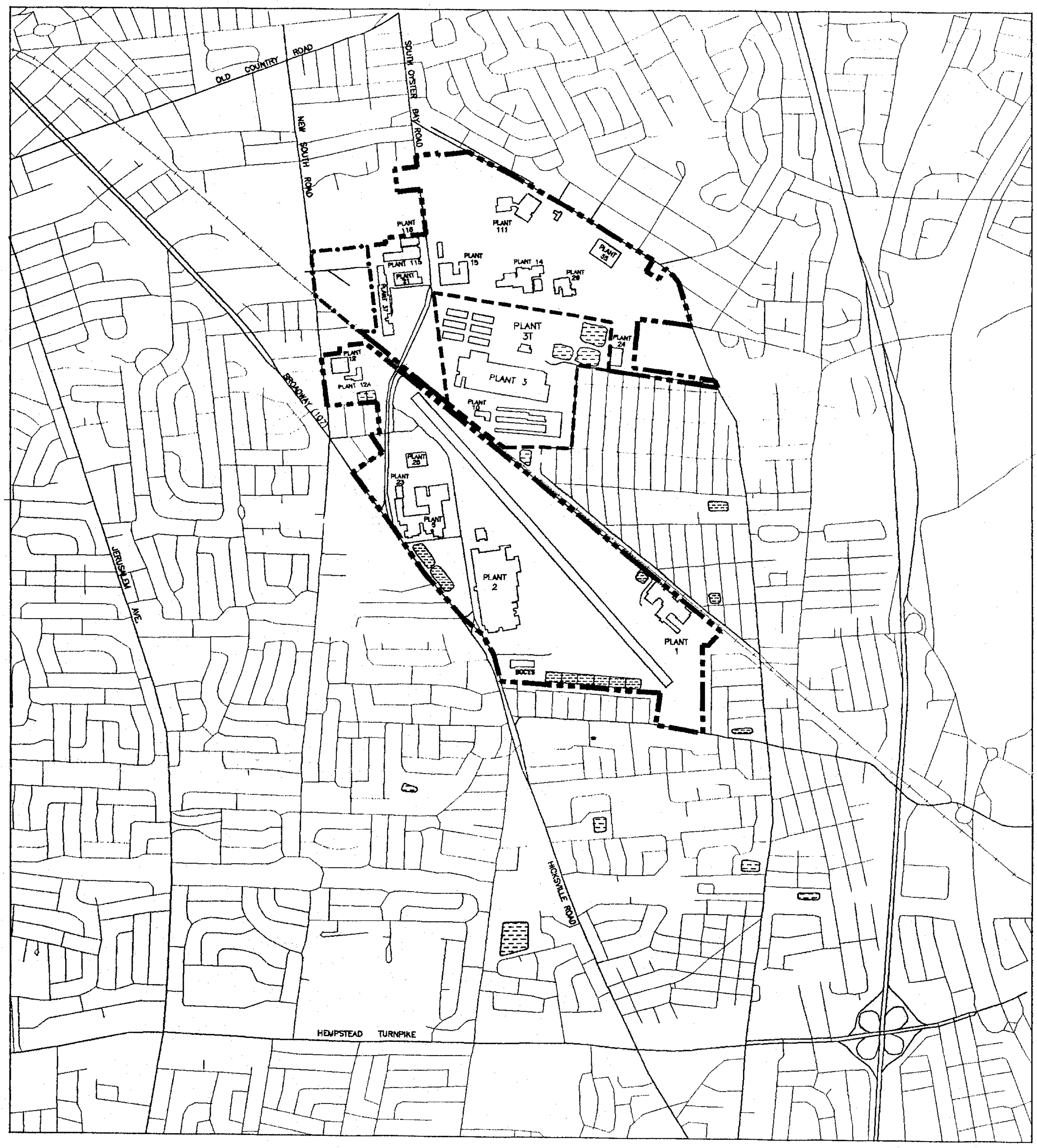
Layer	Number of Targets	Residual Mean	Residual Standard Deviation	Absolute Residual Mean
1	59	-0.047321	1.144789	0.888437
2	11	0.141799	0.883136	0.776525
3	36	-0.043084	1.230547	0.907337
4	8	-0.620859	0.790201	0.713014
5	3	-0.674157	0.519758	0.713133
6	4	-0.262039	0.868422	0.858083
7	6	-1.388095	0.388341	1.388095
8	2	-2.065014	0.511937	2.065014
Total Model	129	-0.18	1.15	0.909753

Table 5-3. Summary of Sensitivity Analysis Statistics, Groundwater Flow Model, Northrop Grumman Corporation, Bethpage, New York.

Parameter Tested	Calibrated Value	Type of Change	Parameter Changed to	Normalized Residual Mean
Upper Glacial K(h)	300 ft/d	Increase	400 ft/d	+ 0.264
		Decrease	200 ft/d	- 0.294
Shallow Magothy K(h)	200 ft/d	Increase	300 ft/d	- 0.156
		Decrease	100 ft/d	+ 0.166
Magothy K(h)	30 ft/d	Increase	50 ft/d	+ 0.485
		Decrease	20 ft/d	- 0.317
Transitional Zone K(h)	120 ft/d	Increase	180 ft/d	+ 0.017
		Decrease	60 ft/d	- 0.049
Upper Glacial K(v)	60 ft/d	Increase	90 ft/d	- 0.004
		Decrease	30 ft/d	- 0.008
Magothy K(v)	2 ft/d	Increase	4 ft/d	+ 0.23
		Decrease	1 ft/d	- 0.43
Groundwater Recharge	22.36 in/yr	Increase	24.36 in/yr	- 0.380
		Decrease	20.36 in/yr	+ 0.367

ft/d feet per day
in/yr inches per year
K(h) Horizontal hydraulic conductivity
K(v) Vertical hydraulic conductivity

DWG DATE: 08OCT97	PRJCT NO.NY0008.068-2	HARD FILE: GRUM	DRAWING: SITEB	CHECKED: JS	APPROVED: CSG	DRAFTER: A.WARREN



EXPLANATION

RECHARGE BASIN

PROPERTY BOUNDARY OF NORTHROP GRUMMAN CORPORATION

PROPERTY BOUNDARY OF THE U.S. NAVY SITE

PROPERTY BOUNDARY OF THE OCC/RUCO SITE

N

NOTE:
WELL INVENTORY REVISED BETWEEN AUGUST 4 AND AUGUST 23, 1995; WELL DATA OBTAINED FROM UNITED STATES GEOLOGICAL SURVEY, NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS, NASSAU COUNTY DEPARTMENT OF HEALTH, AND THE NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION.

0 2000 FT

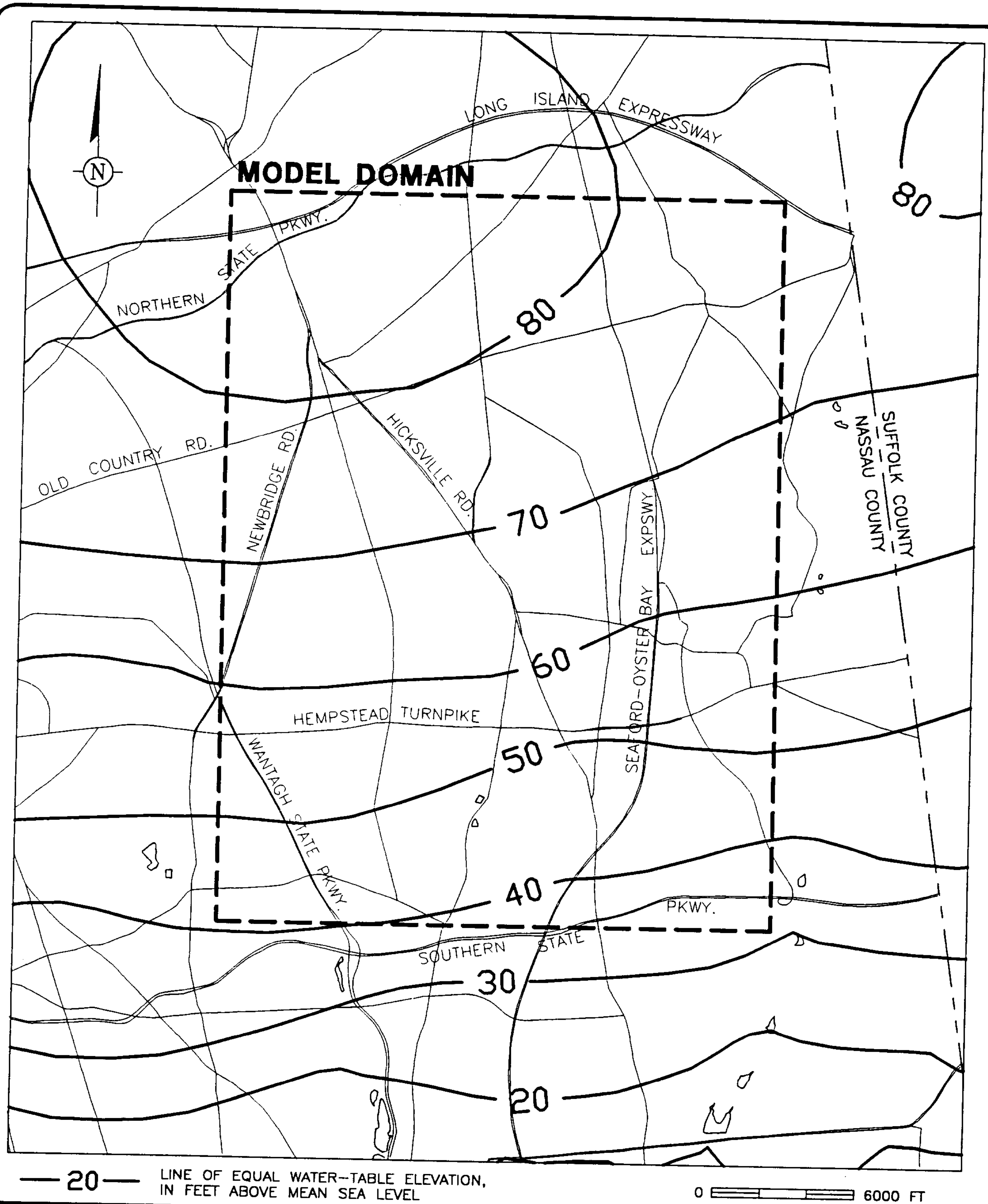
GERAGHTY & MILLER, INC.
Environmental Services
A Heidemij Company

REGIONAL SITE LOCATION

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE
2-1

0057A01Z



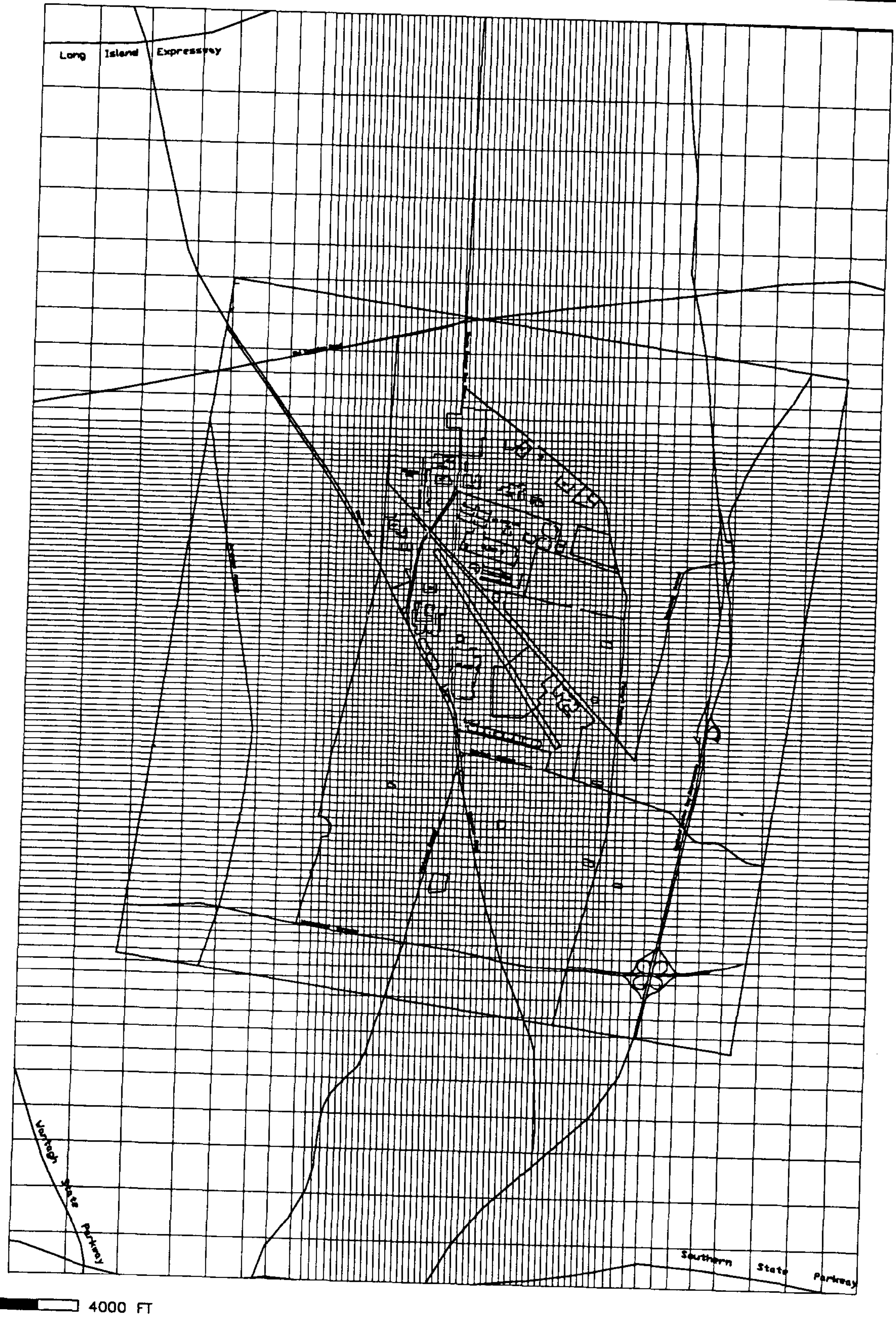
DRAFTER: W.H.CICIO | APPROVED: C.S.G. | CHECKED: R.P. | DRAWING: WT-CONFG | HARD FILE: | PRJCT NO.: NY0008.123T2 | DWG DATE: 29OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

GENERALIZED WATER-TABLE CONFIGURATION AND EXTENT OF MODEL DOMAIN

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 2-2



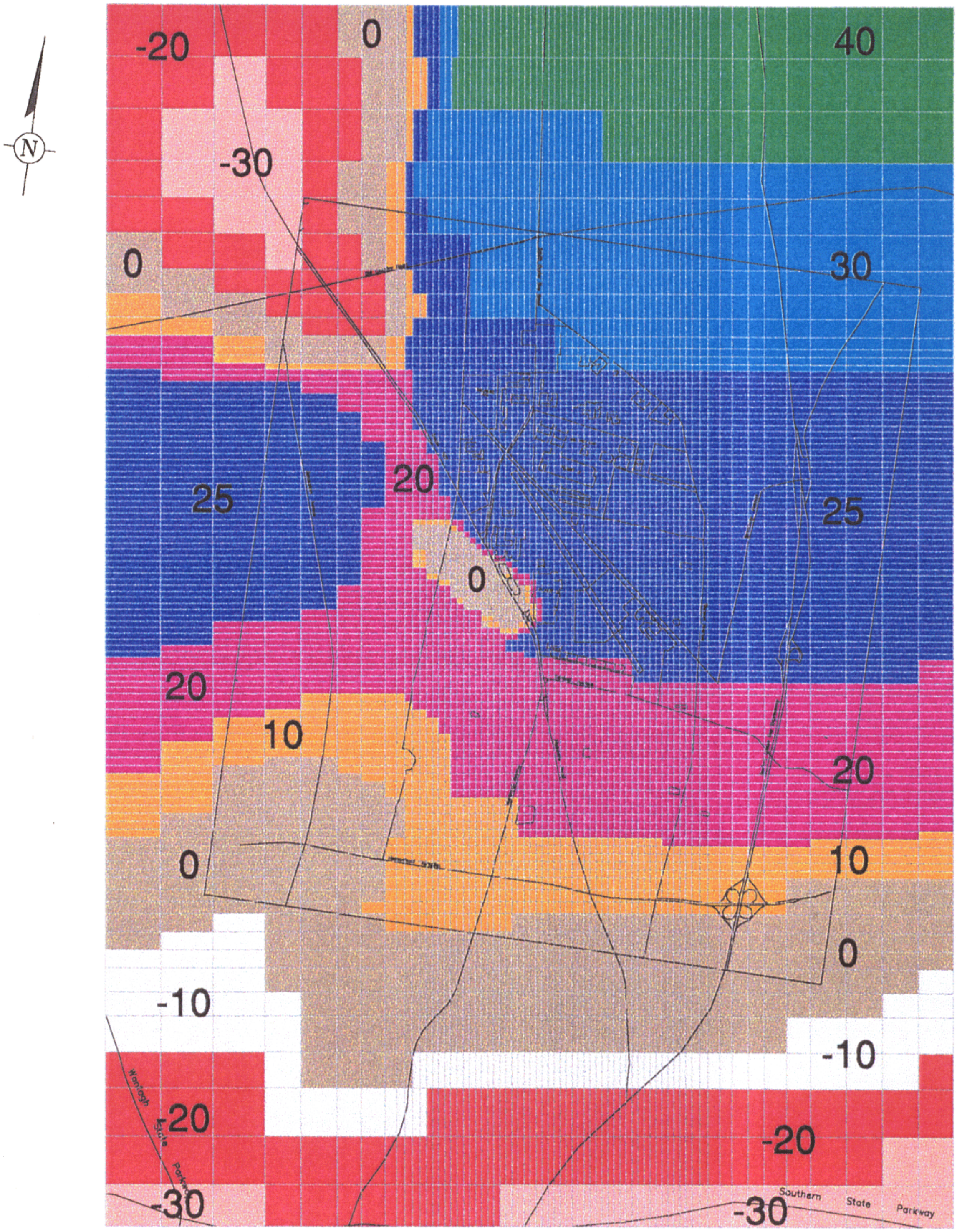
DRAFTER: B.CICIO | APPROVED: CSG | CHECKED: RP | DRAWING: FIG4-1 | PRJCT NO.: NY0008.068-2 | FILE NO.: | DWG DATE: 30OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

MODEL GRID

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-1



LEGEND

-30	BOTTOM SURFACE OF UPPER GLACIAL AQUIFER UNIT (FT MEAN SEA LEVEL)

0 4000 FT

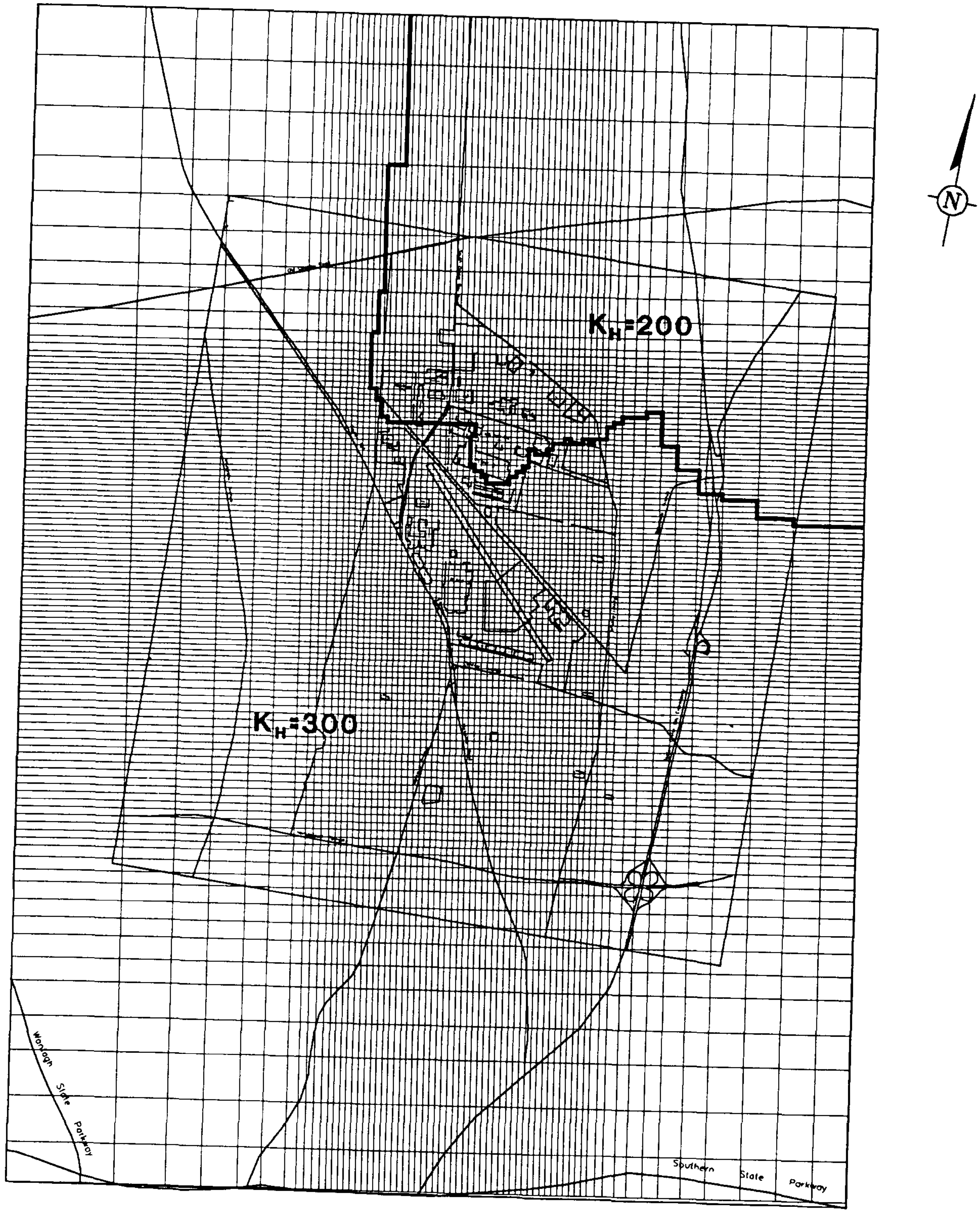
GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

BOTTOM SURFACE OF UPPER GLACIAL AQUIFER MODEL LAYER 2 GROUNDWATER FLOW MODEL

NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-2

DWG DATE: 09OCT97 | PRJCT NO.: NY0008.068-2 | FILE NO.: GRUM | DRAWING: FIG4-2 | CHECKED: JS | APPROVED: CSG | DRAFTER: -



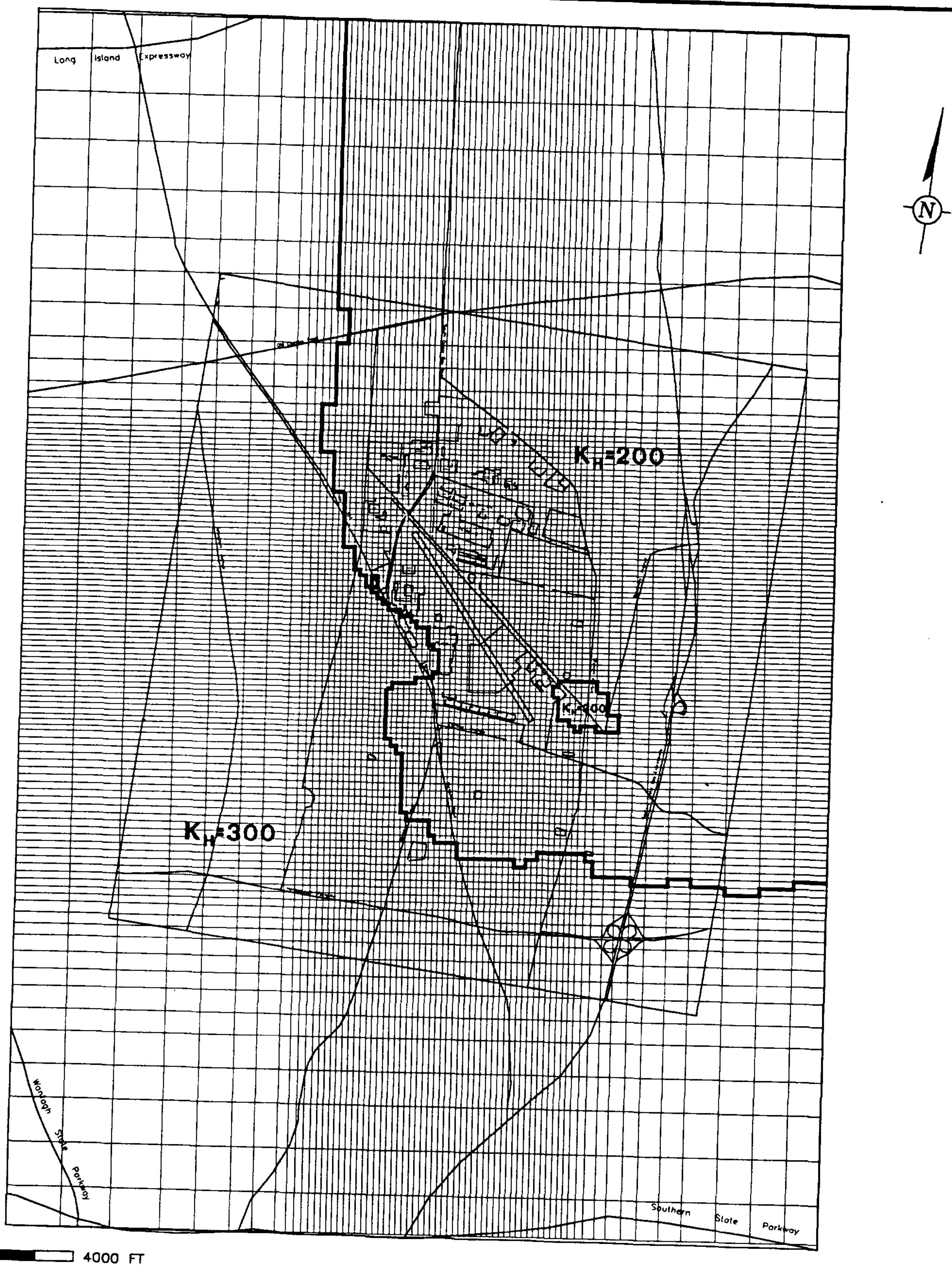
DRAFTER: A.WARREN | APPROVED: CSG | CHECKED: JS | DRAWING: FIG4-4 | FILE NO.: GRUM | PRJCT NO.: NY0008.068-2 | DWG DATE: 09OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

HYDRAULIC CONDUCTIVITY ZONES FOR MODEL LAYER 1

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-3



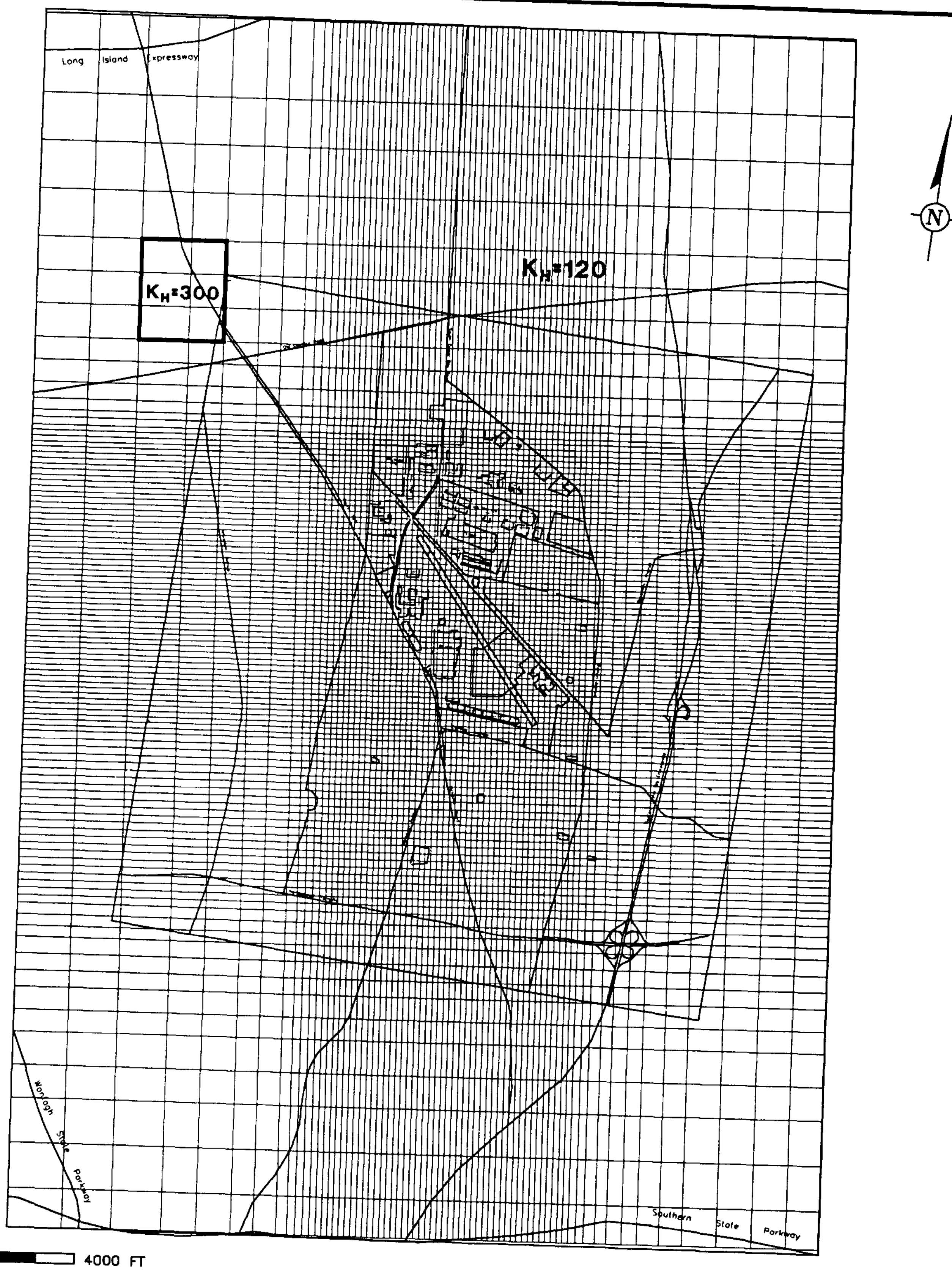
DRAFTER: A.WARREN
APPROVED: CSG
CHECKED: JS
DRAWING: FIG4-5
PRJCT NO.: NY0008.068-2 FILE NO.: GRUM
DWG DATE: 09OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

HYDRAULIC CONDUCTIVITY ZONES FOR MODEL LAYER 2

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-4



GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

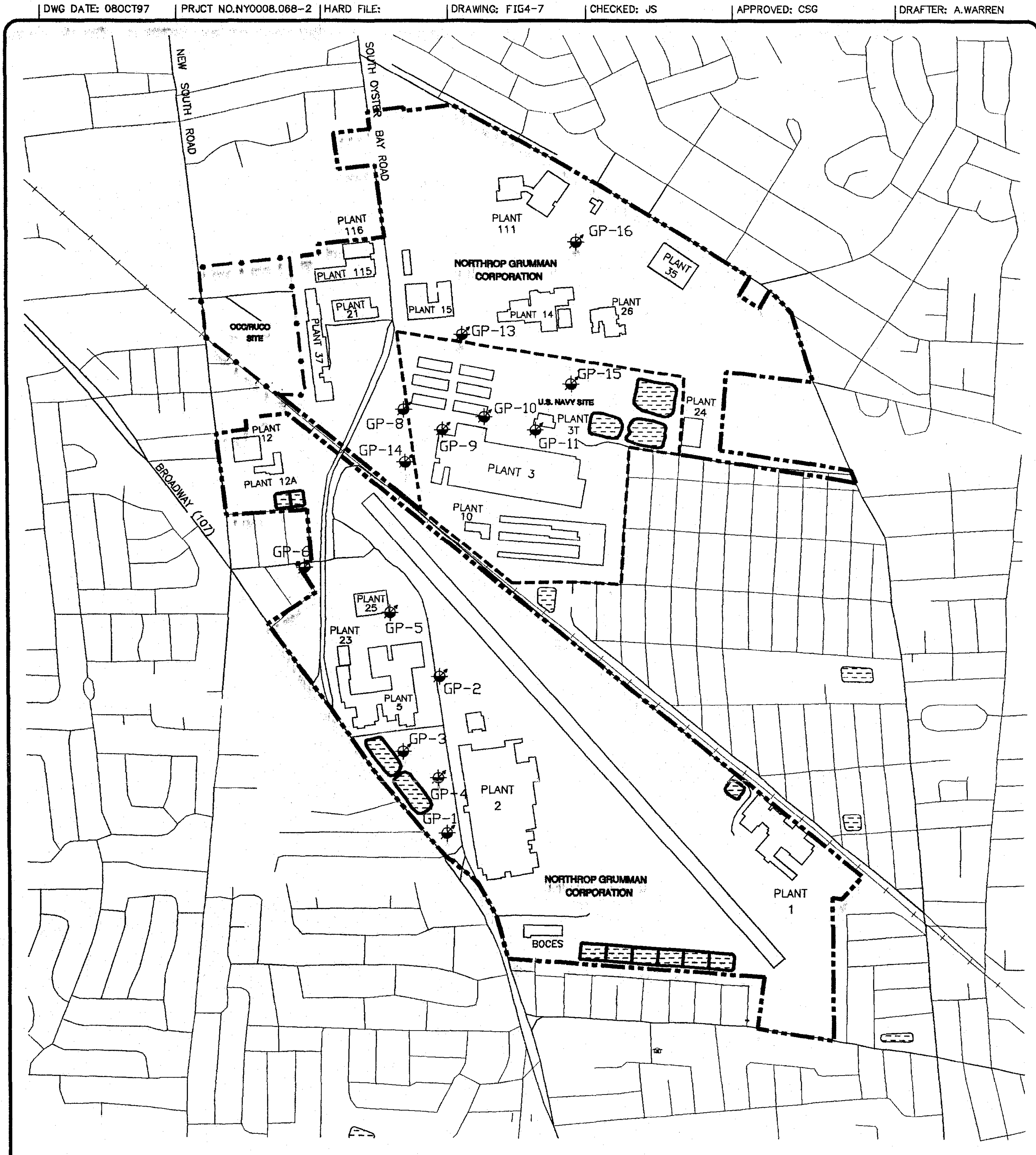
HYDRAULIC CONDUCTIVITY ZONES FOR MODEL LAYER 3

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-5

DWG DATE: 29OCT97 | PRJCT NO.: NY0008.068-2 | FILE NO.: | DRAWING: FIG4-6 | CHECKED: JS | APPROVED: CSG | DRAFTER: A.WARREN

DWG DATE: 08OCT97	PRJCT NO.NY0008.068-2	HARD FILE:	DRAWING: FIG4-7	CHECKED: JS	APPROVED: CSG	DRAFTER: A.WARREN



EXPLANATION

RECHARGE BASIN

PROPERTY BOUNDARY OF NORTHROP GRUMMAN CORPORATION

PROPERTY BOUNDARY OF THE U.S. NAVY SITE

PROPERTY BOUNDARY OF THE OCC/RUCO SITE

GP-16 — LOCATION AND DESIGNATION OF DEEP GRUMMAN PRODUCTION WELL

0 1000 FT

N

NOTE:
WELL INVENTORY REVISED BETWEEN AUGUST 4 AND AUGUST 23, 1995; WELL DATA OBTAINED FROM UNITED STATES GEOLOGICAL SURVEY, NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS, NASSAU COUNTY DEPARTMENT OF HEALTH, AND THE NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION.

GERAGHTY & MILLER, INC.
Environmental Services
A Heidemij Company

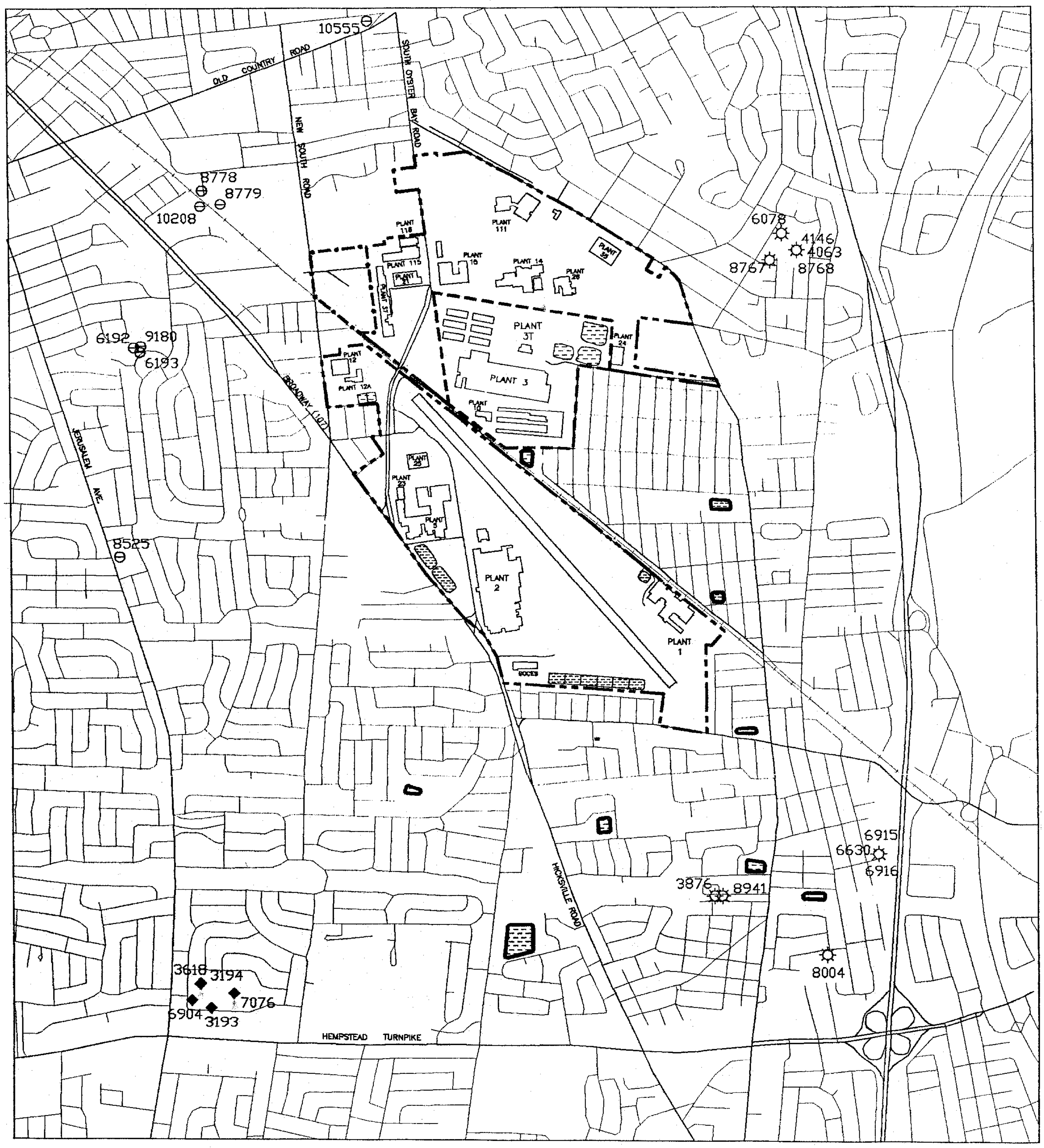
LOCATIONS OF ON-SITE SUPPLY WELLS AND RECHARGE BASINS

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-6

0057AB3Z

DWG DATE: 08OCT97 | PRJCT NO.NY0008.068-2 | HARD FILE: GRUM | DRAWING: FIG4-8 | CHECKED: JS | APPROVED: CSG | DRAFTER: A.WARREN



EXPLANATION

RECHARGE BASIN

PROPERTY BOUNDARY OF NORTHROP GRUMMAN CORPORATION

PROPERTY BOUNDARY OF THE U.S. NAVY SITE

PROPERTY BOUNDARY OF THE OCC/RUCO SITE

3876 — LOCATION AND DESIGNATION OF BETHPAGE WATER DISTRICT PUBLIC SUPPLY WELL

8525 — LOCATION AND DESIGNATION OF HICKSVILLE WATER DISTRICT PUBLIC SUPPLY WELL

3193 — LOCATION AND DESIGNATION OF LEVITTOWN WATER DISTRICT PUBLIC SUPPLY WELL

0 2000 FT

NOTE 1:

IN ADDITION TO THE 24 PUBLIC SUPPLY WELLS SHOWN ABOVE, 29 ADDITIONAL SUPPLY WELLS WERE SIMULATED IN THE MODEL BUT WERE BEYOND THE EXTENT OF THE MAP.

N

NOTE 2:

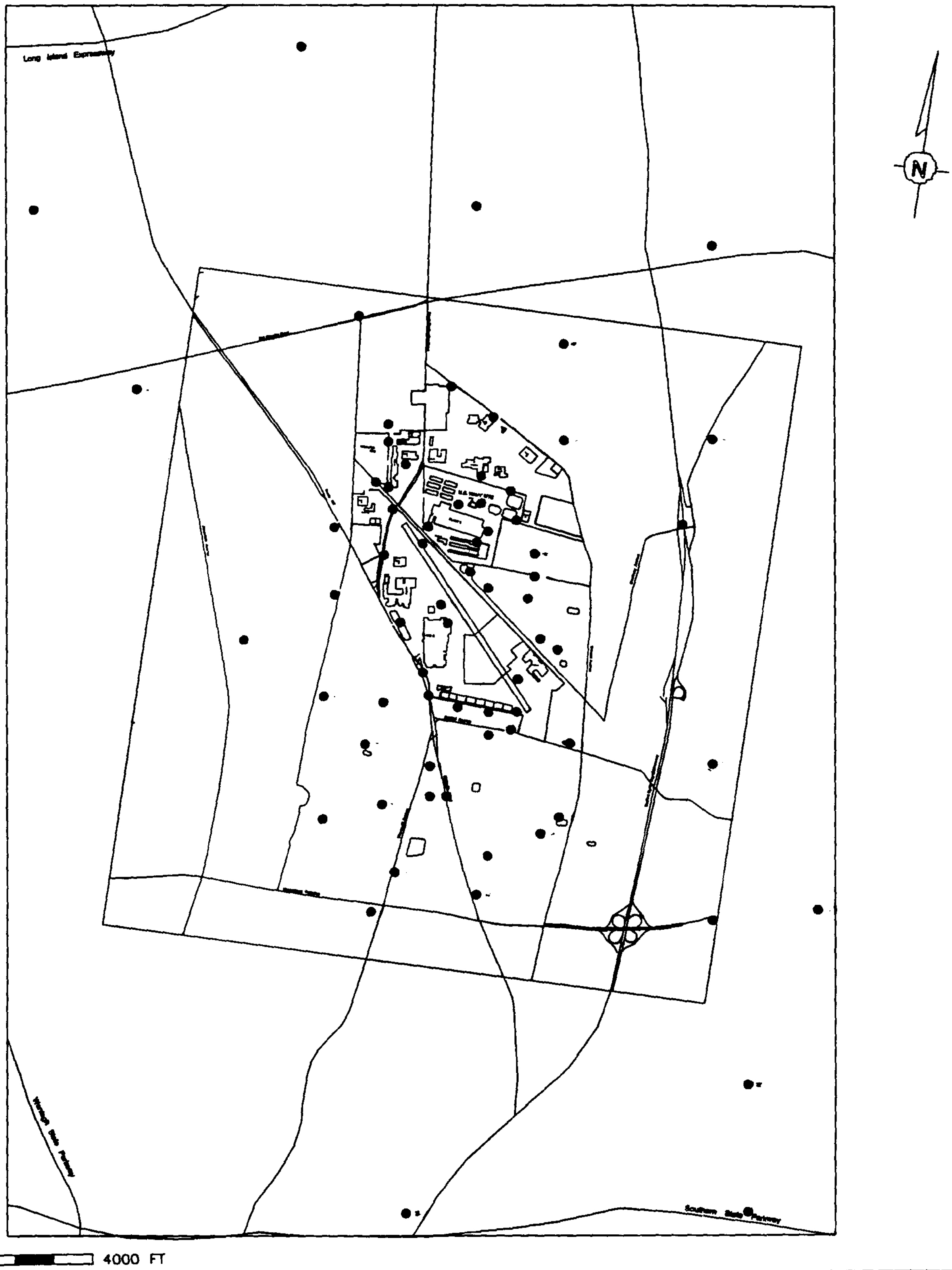
WELL INVENTORY REVISED BETWEEN AUGUST 4 AND AUGUST 23, 1995; WELL DATA OBTAINED FROM UNITED STATES GEOLOGICAL SURVEY, NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS, NASSAU COUNTY DEPARTMENT OF HEALTH, AND THE NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION.

GERAGHTY & MILLER, INC.
Environmental Services
A Heidemij Company

LOCATIONS OF OFF-SITE SUPPLY WELLS AND RECHARGE BASINS

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 4-7



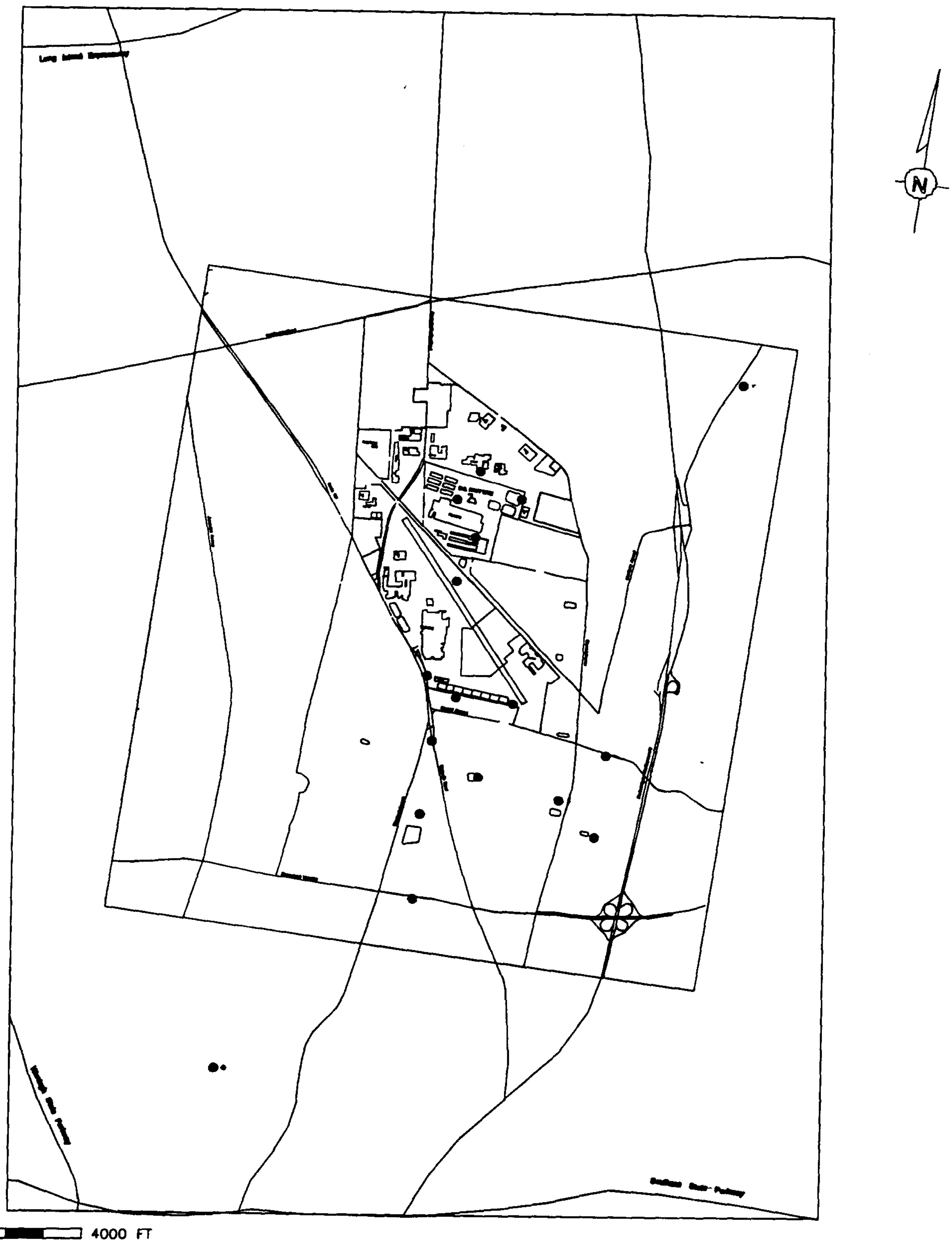
DRAFTER: -
APPROVED: CSG
CHECKED: JS
DRAWING: FIG5-1
PRJCT NO.: NY0008.068-2 FILE NO.: GRUM
DWG DATE: 13OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

LOCATIONS OF HEAD CALIBRATION TARGETS IN THE UPPER GLACIAL AQUIFER GROUNDWATER FLOW MODEL

NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 5-1



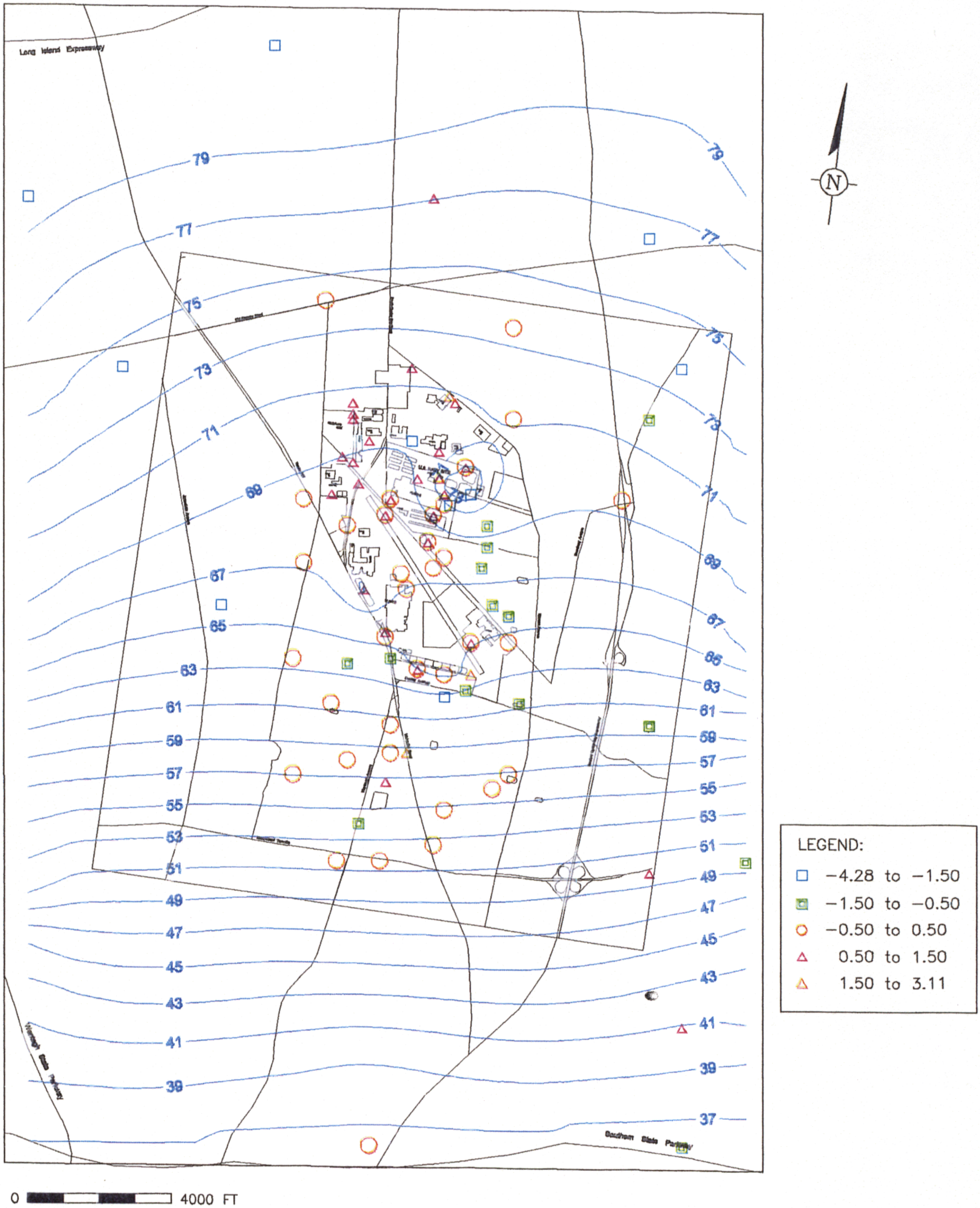
GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

LOCATIONS OF HEAD CALIBRATION TARGETS IN THE MAGOTHY AQUIFER GROUNDWATER FLOW MODEL

NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 5-2

DWG DATE: 13OCT97 | PRJCT NO.: NY0008.123-2 | FILE NO.: GRUM | DRAWING: FIG5-2 | CHECKED: JS | APPROVED: CSG | DRAFTER: -



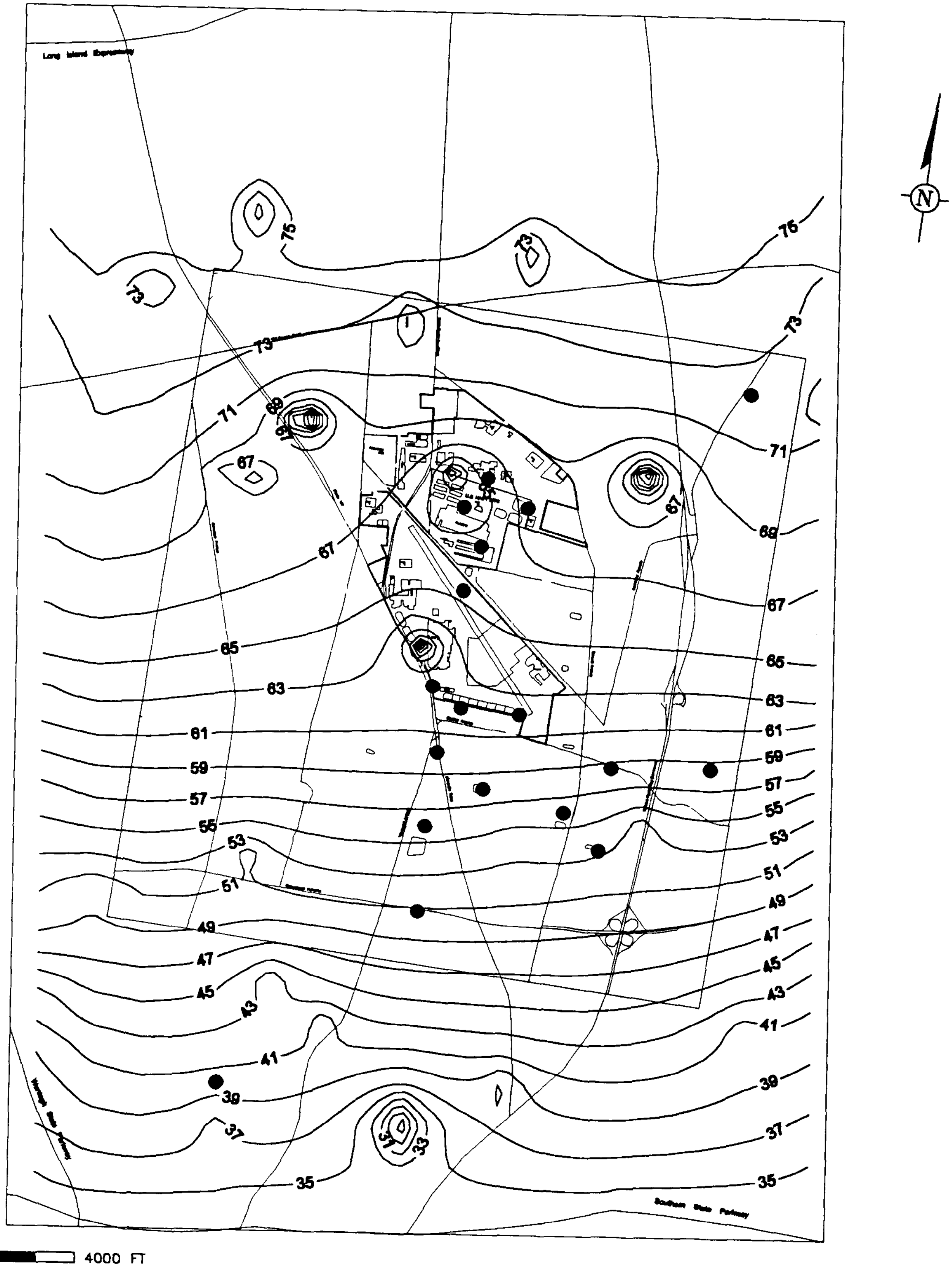
DRAFTER: W.H.CICIO | APPROVED: CSG | CHECKED: JS | DRAWING: FIG5-3 | FILE NO.: | PRJCT NO.: NY0008.068-2 | DWG DATE: 29OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

SIMULATED REGIONAL WATER-TABLE CONFIGURATION AND RESIDUALS FOR THE UPPER GLACIAL AQUIFER

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE 5-3



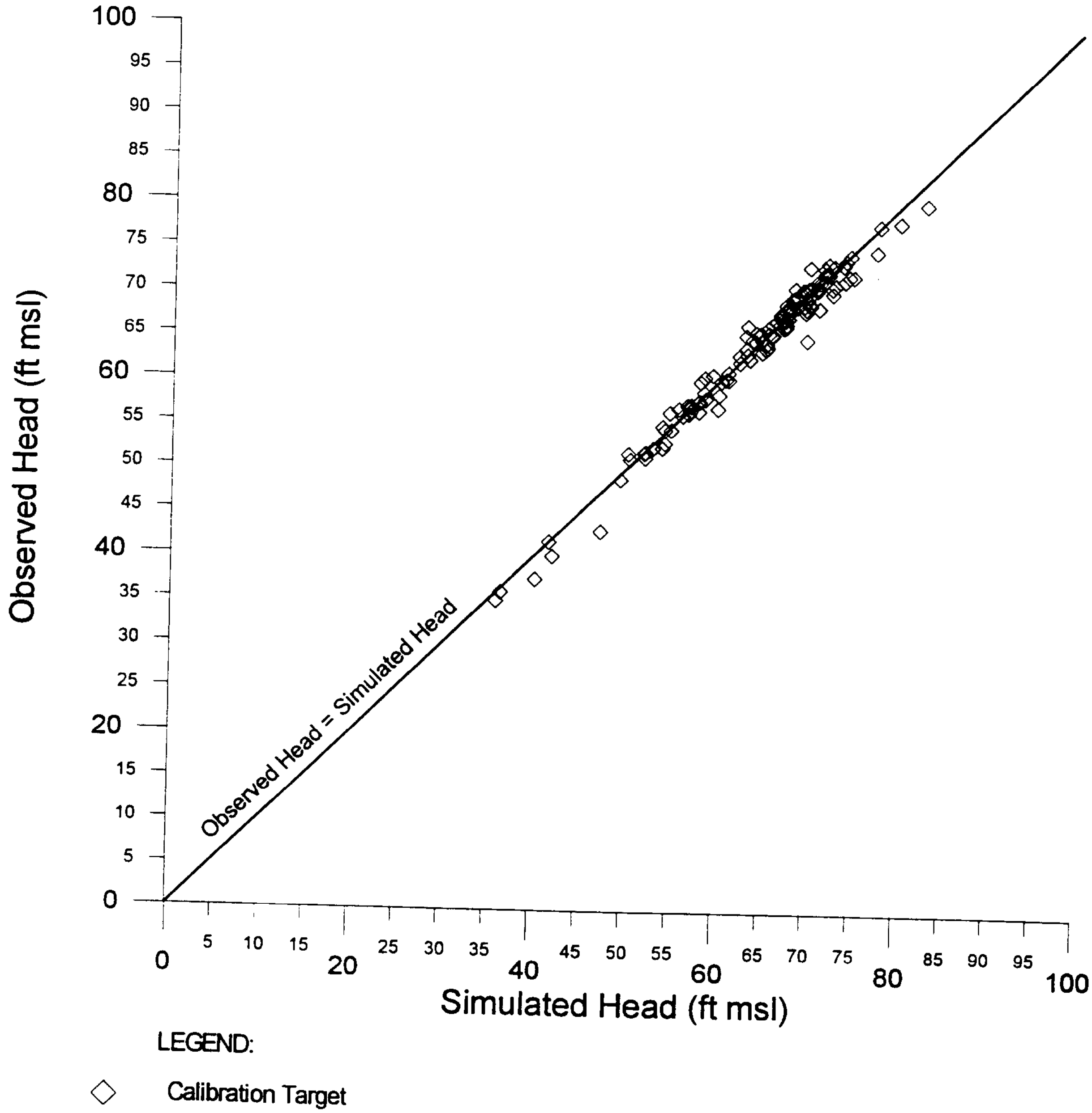
DRAFTER: B.CICIO | APPROVED: CSG | CHECKED: JS | DRAWING: FIG5-4 | PRJCT NO.: NY0008.068-2 FILE NO.: | DWG DATE: 29OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

SIMULATED REGIONAL POTENTIOMETRIC SURFACE MODEL LAYER 7 AND TARGET LOCATIONS

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE
5-4



DRAFTER: W.H.CICIO | APPROVED: M.WOLFERT | CHECKED: R.PORSHE | DRAWING: NON-CAD | FILE: | PRJCT NO.: NY0008.123T2 | DWG DATE: 30OCT97

GERAGHTY & MILLER, INC.
Environment and Infrastructure
a heidemij company

SCATTERPLOT OF HEAD CALIBRATION TARGETS

GROUNDWATER FLOW MODEL
NORTHROP GRUMMAN CORPORATION
BETHPAGE, NEW YORK

FIGURE

5-5