A GIS-BASED APPROACH FOR CALCULATING GROUNDWATER FLOW INTO THE TIVOLI BAYS

John D. Albertson, P.E.

Polgar Fellow

Yale University
School of Forestry and Environmental Studies
New Haven, CT

Project Advisor:

Paul K. Barten, Ph.D.
Associate Professor of Water Resources
Yale University

ABSTRACT

A method was developed that uses a geographic information system (GIS) and a FORTRAN program to site well transects optimally and compute groundwater flow into lake and wetland systems such as the Tivoli Bays. The GIS is used to manage the elevation and soils data. The program generates potential well transects, computes slope gradient from digital elevation data, and identifies representative slopes for monitoring. An algorithm for calculating flow into the bays, based upon the radial nature of local groundwater flow, is described. Surface slope around the Tivoli Bays varies greatly, ranging from 4 to 31 percent. The hydraulic conductivity of soil along the transects is lowest at the upland-bay interface. Flow is isolated from the regional groundwater system by glacial lake sediments. This method is presently being employed to compute the groundwater term in a comprehensive water balance study of the Tivoli Bays. Wells will be installed, groundwater gradient data collected, and flow into the bays calculated as a part of this project. This method can be applied to most wetland or lake systems where relatively shallow local flow is the primary pathway of groundwater into the system.

TABLE OF CONTENTS

Abstract I-3

List of Figures. I-6

List of Tables I-6

Introduction I-7

Methods. I-15

Results. I-20

Discussion I-24

Acknowledgements I-25

References I-26

LIST OF FIGURES

1. Relationship between two and three dimensional flow systems I-9
2. Transect monitoring and gradient calculation . . I-18
3. Mean transect slopes I-21
4. Transect slope distribution. I-22
5. Locations of selected transects. I-23

LIST OF TABLES

1. Slope values selected for monitoring I-22

INTRODUCTION

Much debate surrounds the issue of wetland preservation. Many argue for wetland protection on the basis of the unique functions and finite supply of wetlands. Proponents of development contend that protectionists have failed to accurately quantify the benefits of wetland functions and demonstrate how they outweigh the costs of preservation. The basic scientific information needed to help resolve this controversy is, at present, incomplete.

Many wetland functions are dependent upon, or a direct result of, the wetland's hydrologic regime. However, there is a paucity of published research on the subject (Mitsch and Gosselink 1986; Carter 1986). An understanding of the sources, volumes, composition, and timing of the various inflows and outflows of water is basic to an understanding of wetland functions. It is in pursuit of this understanding that we address the water balance of the Tivoli Bays, a part of the Hudson River National Estuarine Research Reserve (HRNERR). The work reported in this paper is a portion of an ongoing water balance study being conducted at the Tivoli Bays (Barten in prep.).

The water balance will provide a comprehensive accounting of the volume and timing of the inflows and outflows for Tivoli North and South Bays. For each bay, the inflow terms include precipitation, streamflow from the uplands, tidal exchange with the river and the adjacent bay, and groundwater inflow from the uplands. The outflow terms include evapotranspiration, and tidal exchange with the river and the adjacent bay. In addition to the measurement of flows, the water balance will support the development of a microcomputer-based water balance model that can be used to help quantify the transport of nutrients and to calculate chemical budgets.

Of all the terms in the water balance of surface water bodies, groundwater is perhaps the least understood (Winter 1976). It is often ignored or simply taken as the residual term needed to balance the measured inflows with the outflows. The often unique chemistry of groundwater coupled with the need for accurate wetland water balances warrants a more deliberate approach.

The objective of the work described in this paper was to develop a physically-based method of calculating the groundwater flow into the Tivoli Bays. The method was intended for immediate use in the Tivoli Bays water balance study and future application to studies of similar systems. A balance was sought between comprehensiveness and ease of use. The method described in this paper uses a FORTRAN program to expand and tailor the data management and analysis capabilities of a Geographic Information System (GIS) to the specific problem of calculating radial groundwater flow into lakes and wetlands. This approach reduces a complex three-dimensional heterogeneous groundwater system into a fan of two-dimensional quasi-homogeneous systems (Figure 1). Each two-dimensional system is a vertical slice of land, parallel to the flow (radial to the bay). The third dimension, that is essentially orthogonal to the flow, can be removed from consideration. The total flow calculation for each bay is produced by a summation of these two-dimensional flow calculations.

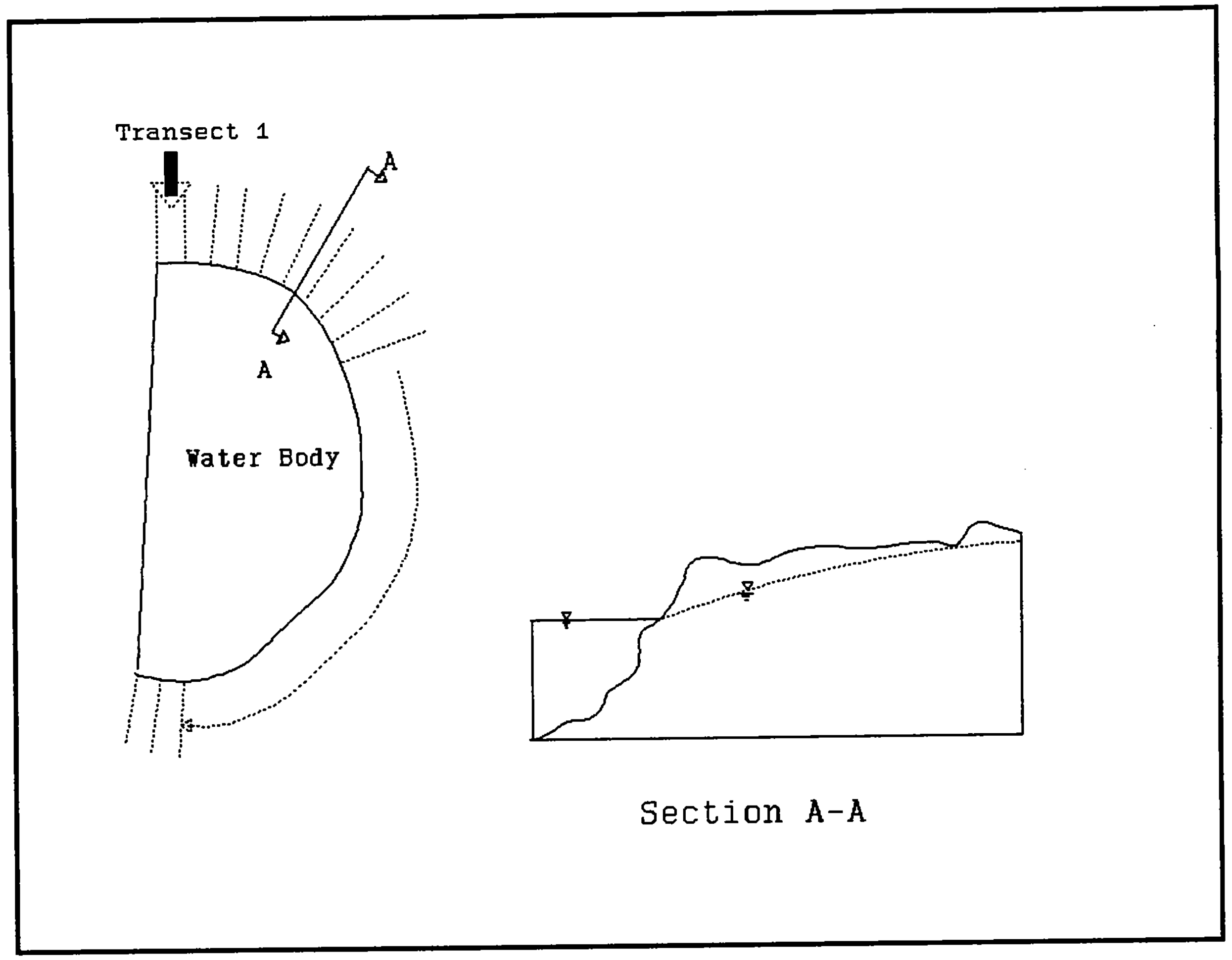

Figure 1: Relationship between two and three dimensional flow systems

The symmetry of local groundwater flow into lakes or wetlands provides the justification for this simplification. The GIS helps to manage the large amount of spatially distributed data associated with such an approach.

Description of groundwater flow into wetlands

Groundwater flow is affected by geologic and topographic features and gravity. It may also be affected by temperature and chemical concentration gradients; these gradients are negligible for the site under consideration. The geologic characteristics and history of the site influence the porosity and permeability of the media (soil and rock), which are in turn responsible for the volume of water and the relative ease with which it can move through the media. A combination of the geologic and topographic features define the boundaries of the flow field and strongly influence the form and location of the water table. The form of the water table represents the distribution of the hydraulic potential -- the energy that moves the water through the media.

Henry Darcy, while working on the sand filtration of the city of Dijon's water supply in 1856, developed a law relating these parameters to the volumetric flow rate of water (Domenico and Schwartz 1990 after Darcy 1856). His work revealed the proportionality of flow to both the hydraulic gradient and the hydraulic conductivity[1].

The simple one-dimensional form of Darcy's law can be expressed as:

$$Q=-K*A*dh/dl$$

Q = Groundwater discharge (L^3/T)
K = Hydraulic conductivity of the media ($(L^3/T)/L^2$)
A = Cross-sectional area of flow field (L^2)
dh/dl = Hydraulic gradient (L/L).

The geometry of the groundwater table is known to be a subdued representation of the surface topography (Domenico and Schwartz 1990 after King 1899). Although a qualitative description such as the term "subdued" is insufficient for quantitative groundwater computations, it is helpful in suggesting the general direction of flow and boundary conditions of the flow field. For example, wetlands such as the Tivoli Bays are at regional minimum elevations (low points in the groundwater system) and generally receive flow from the surrounding uplands. This hydrogeologic setting is common to most intertidal wetlands (Carter 1986).

Methods of calculating flow into wetlands

In a review of wetland studies, LaBaugh (1986) focused on seven projects that presented the most complete water balances. Of these, one study neglected to consider the groundwater component, two studies estimated it as a residual of the measured

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[1] Permeability explains the media's capacity to conduct a general fluid. Hydraulic conductivity, a joint property of the media and the water, explains the media's capacity to conduct water.

terms, two others computed it from occasional measurements, one solved for the amount of groundwater that would be required to dilute the salinity measured in a tidal marsh, and one provided a flow net analysis with data from a nest of wells and piezometers. This review demonstrates the lack of a definitive set of methods in current wetland water balance research.

There are four general classes of methods that may be used for calculating groundwater flow into lakes and wetlands: *water balance*, where the groundwater flow is taken as the residual of measured terms; *direct measurement*, using devices such as seepage meters; *analytical methods*; and *numerical methods* (Dowd 1984).

The water balance approach often leads to significant misunderstandings about the interaction of groundwater and surface water bodies (Winter 1976). The residual difference between measured inputs and measured outputs is not simply the unmeasured net groundwater flow; it is the sum of the errors from each measured term, the unmeasured groundwater inflow minus any groundwater outflow, and the unmeasured overland flow into the water body. Therefore, the assignment of this residual to the groundwater term is misleading and would be an unacceptable approach for the water balance study of the Tivoli Bays as well as other systems.

The direct measurement approach typically employs seepage meters, as pioneered by Lee (1977). There are two major shortcomings to the use of this method at the Tivoli Bays: the meters require frequent tending below the water surface,

rendering them inefficient and expensive for long-term studies; and, an accurate integration of these point measurements over the entire seepage interface is elusive. The areal distribution of seepage can be quite irregular with considerable differences within distances of a few meters (McBride and Pfannkuch 1975).

In contrast to the first two methods, analytical and numerical methods are based directly upon the mechanism causing the flow, thus limiting the inferential biases. They incorporate a site's hydrogeologic properties directly into the calculation of groundwater flow. In their most complete form, analytical and numerical solutions produce a hydraulic potential distribution and a subsequent calculation of groundwater flow. The mathematical development of a hydraulic potential distribution is of great value in scenario analyses, where there are no actual distributions to measure. However, water balances, such as the present project, seek to calculate actual flows -- not to predict hypothetical flows. Therefore, the analytical and numerical solutions are useful to this study to the extent they can relate measured values of potential to estimates of actual groundwater flow.

Three-dimensional analytical solutions are exceedingly complex for sites such as the Tivoli Bays. They are typically used only for cases with simple geometry with defensible assumptions of homogeneity and isotropy (Wang and Anderson 1982). Since the advent of digital computers, numerical techniques have displaced analytical techniques for complex systems.

Numerical approaches model the continuous flow domain as a mesh of nodes or cells and solve the governing equations between these discrete elements. While robust and powerful, this approach is mathematically intensive. It is typically reserved for rigorous scenario analyses of groundwater systems, and in most cases is technically beyond the reach of the non-hydrogeologist.

In consideration of the specific objectives of this work, an approach was developed that applies GIS technology to the problem of managing and processing a large amount of spatially distributed data. As shown by Darcy's law, the data of interest are hydraulic conductivity, hydraulic gradient, and the cross-sectional area of the flow. The GIS is used to provide and manage spatially distributed soils data. Estimates of the hydraulic gradient must be developed through point measurements of the height of the water table. Wells can be installed along flow lines and the hydraulic gradient calculated as the vertical difference in the water level between wells divided by the longitudinal distance along the flow path between wells. It would be prohibitively expensive to install and monitor wells placed along each potential transect, as defined in the context of this work as the width of a GIS grid cell (30 by 30 meters), at a study site. Therefore, some method must be used to interpolate gradient values between the well transects.

If we accept that the water table is a subdued representation of the surface topography, so too must the slope of the water table (hydraulic gradient) relate to the slope of the surface topography. By developing a site-specific relationship between the slopes of the monitored transects and their hydraulic gradients, we can make reliable estimates of the hydraulic gradient at unmeasured transects, as a direct function of land slope.

METHODS

A 30-meter resolution GIS database was developed for the upland areas surrounding the Tivoli Bays with the raster-based IDRISI software package (Eastman 1992). Primary layers were developed for elevation, from USGS digital elevation model (DEM) data, and for soil type, from Dutchess County soil survey information (USDA SCS, in press). Secondary layers were created for surface slope percent through the use of the IDRISI slope function on the elevation layer, and for hydraulic conductivity from a cross referencing of the soil type layer and a soils attribute file.

Since the hydraulic gradients for non-monitored flow lines will be inferred from the hydraulic gradients of monitored flow lines on the basis of slope, the monitored transects should be representative of the slope distribution of all the possible transects. Therefore, a selection process was developed that involves a non-parametric statistical analysis of the slopes in the population of possible transects. Transects are defined for the purpose of this study as vectors with a width of one GIS grid cell (30 meters) directed radially from the bays 150 meters into the uplands (Figure 1). This transect length is sufficient to capture the influence of groundwater flow to the bays on the form of the water table.

Generation of transects

A wetland GIS layer was created by assigning values of one to all cells covering the bays and values of zero to all upland cells. A distance layer was generated through the use of the IDRISI distance function on the wetland layer. Each cell on the distance layer contains a value representing its distance from the nearest bay in meters. A layer containing an arc representing the upper boundary of all the transects was generated by reclassifying the distance layer such that all cell values equal to 150 meters were reclassified to one, and all others were reclassified to zero. The resulting upper boundary arc layer contains values of one for each cell along the upper boundary of the transects and values of zero for all other cells.

A FORTRAN program I_QUERY was developed to query the upper boundary arc layer and record the row and column address of each cell located on the arc. These cells define the upper boundary coordinates for each potential transect around the bays.

A second FORTRAN program GWTRANS was developed to generate the cell addresses (row and column numbers) along each possible transect, which connects an upper boundary cell to the nearest bay. The user supplies the upper boundary coordinate data file and the original distance layer and the program generates transects that provide the shortest distance path from each upper boundary cell to the appropriate bay (approaching the bay radially). This is accomplished by seeking the steepest descent down the distance surface from the upper boundary cell. The cell addresses are recorded for each cell along each transect.

Analysis of transect slopes

The program GWTRANS queries the slope layer and records slope values for each cell along each transect. It then calculates the arithmetic mean slope along each transect and generates a sorted array of mean transect slopes, arranged from minimum to maximum slope values.

Given a user-specified number of transects to be monitored, n, the program partitions the sorted array of transect slopes into n blocks of equal size and selects the median element from each block. These representative slope values are used to select n actual transects. The actual selection involves a process of identifying n transects that: (1) have slope values within some user-specified tolerance of the selected slope values; and, (2) are reasonably equally spaced around the bays.

Hydraulic gradient data

The field work associated with the remainder of the methods section will be performed during the ongoing water balance study. The n selected transects are to be monitored, with two wells each

(Figure 2). The hydraulic gradient for each transect will be computed as:

$$Gradient=\frac{H_1-H_2}{L}$$

Gradient = Hydraulic gradient (L/L)

H_1 = Elevation of water table at well 1 (L)

H_2 = Elevation of water table at well 2 (L)

L = Distance between wells, along flow line (L)

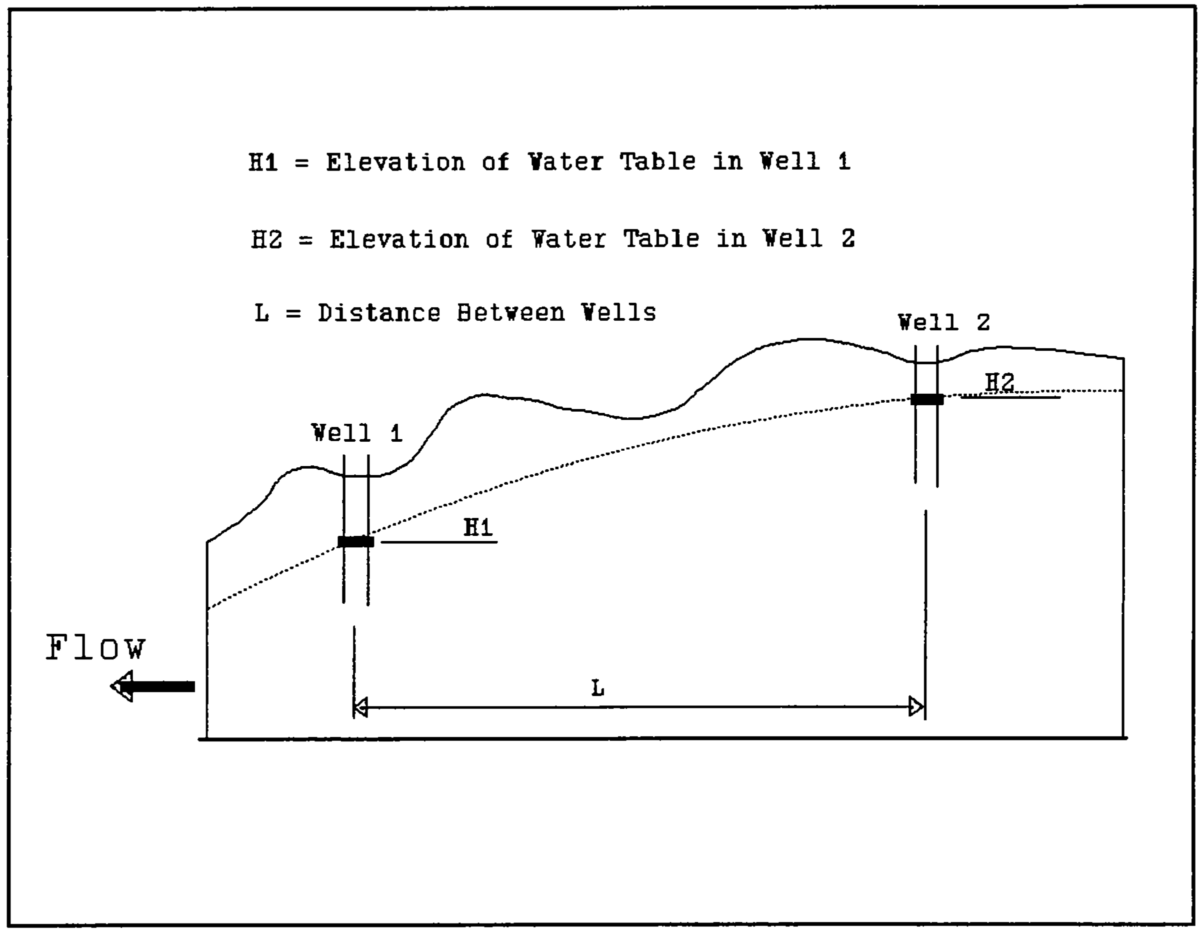

Figure 2: Transect monitoring and gradient calculation

Data from the monitored transects will be used to develop a regression equation that relates transect slope to hydraulic gradient for the monitored transects. The expected form of the equation is:

$$Gradient_i=C*slope_i$$

$Gradient_i$ = Gradient for transect i

C = Regression coefficient

$Slope_i$ = Slope of transect i (percent)

Soil data

The soils of the Tivoli Bays riparian area rest upon relatively impermeable deposits of silt and clay that were deposited by Glacial Lake Albany (Central Hudson Gas & Electric Corp. 1960; Carey and Waines 1987). These deposits hydraulically separate the local groundwater flow and the Tivoli Bays from the deeper regional groundwater flow. The thickness of the surface deposits varies. Initial estimates of this parameter will be collected during the installation of the wells.

The flow rate into the bays is, for the most part, limited by the low hydraulic conductivity of the lacustrine and fluvial deposits located at the upland-bay interface. Therefore, the hydraulic conductivity of each grid cell at the upland-bay interface will be assigned to the corresponding transect. These less permeable soils at the outflow end of each two-dimensional flow system limit the flow rate to the bays.

Calculation of groundwater flow

The elevation of the head in each well will be monitored periodically to account for the temporal variation in the hydraulic gradient due to variations in recharge and evapotranspiration. A FORTRAN program based on Darcy's law is being developed to calculate the flow over the period between measurements for each transect. The program will sum these flows around each bay to estimate total groundwater inflow for each bay.

RESULTS

The upper boundary arc was generated and yielded a total of 214 cells. These cells were used to generate 214 transects. Transect slopes range from 4 to 31 percent, with a mean of 14 percent and a standard deviation of 4.6 percent (Figure 3).

The transect slopes approach a normal distribution (Figure 4). Seventy-three percent of the transects have slopes within one standard deviation of the mean. A total of five slope values were selected from the sorted array for monitoring with wells. The selected slopes are listed in the left column of Table 1.

Actual transect sites were selected that balanced the criteria of meeting the required slope values and being roughly equally spaced around the bays. The selected transects and their slopes are listed in the right two columns of Table 1 and shown in Figure 5.

The hydraulic conductivity values selected for the 214 transects range from 6 to 400 cm/day, with over 95% of the transects having values less than 10 cm/day.

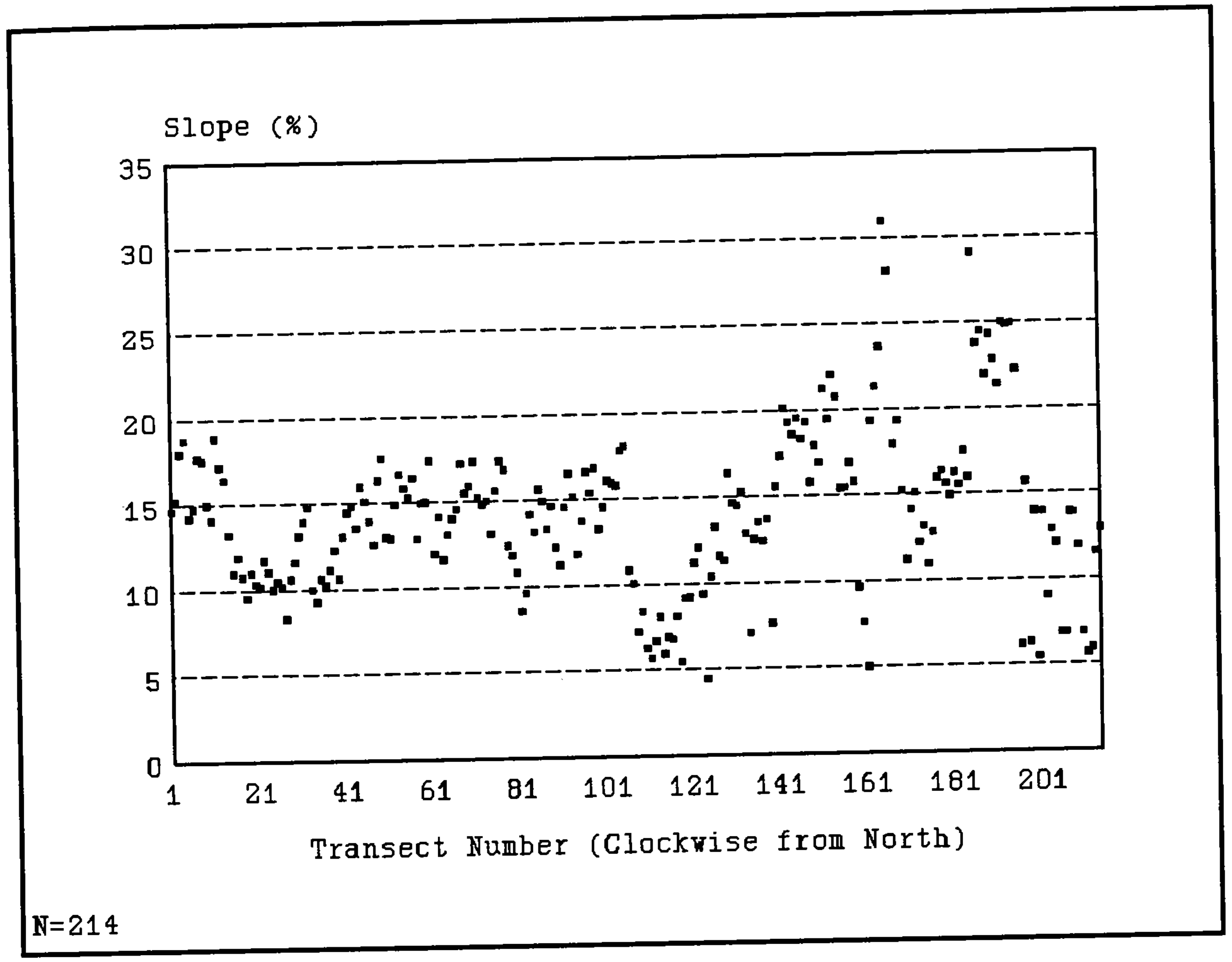

Figure 3: Mean transect slopes

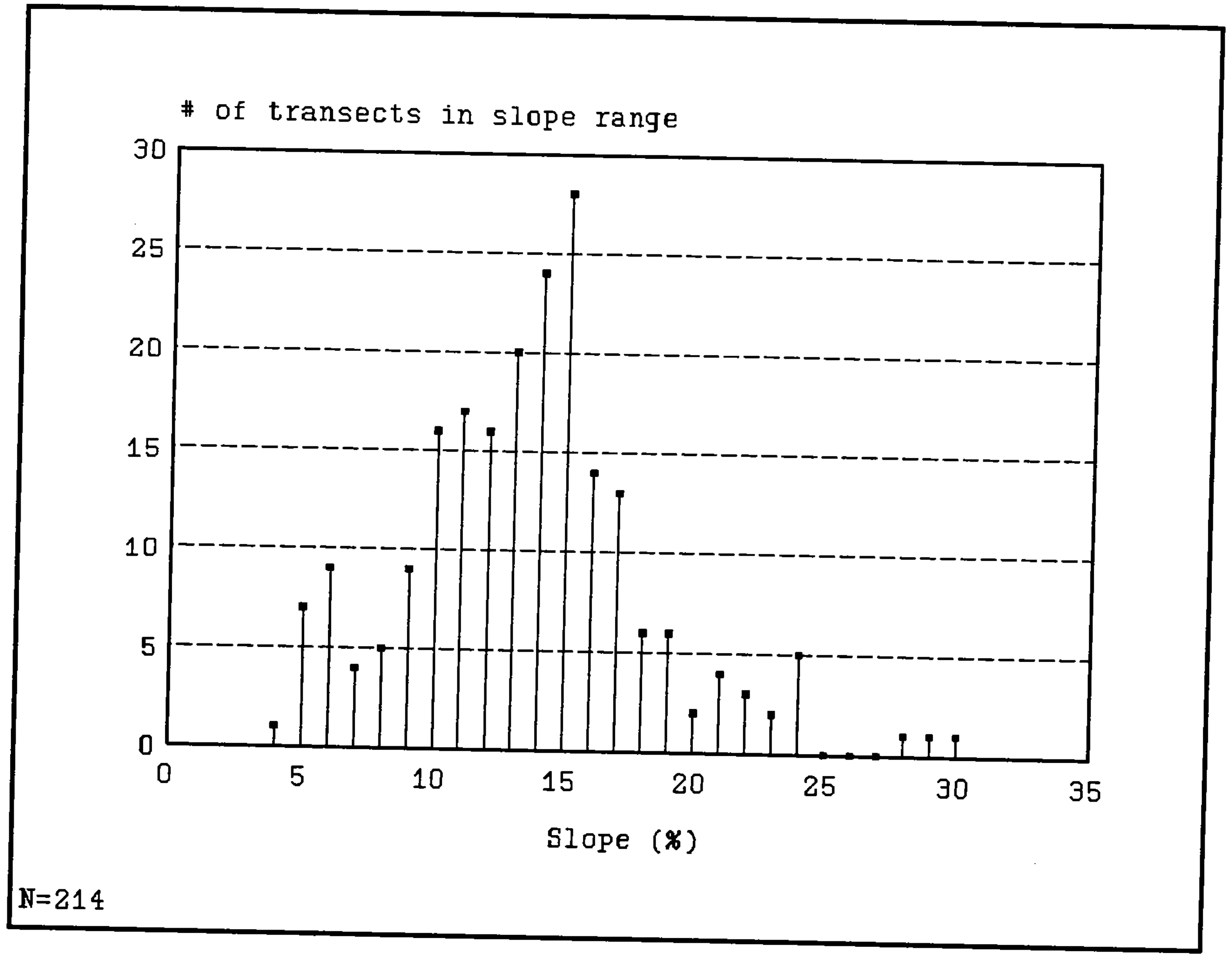

Figure 4: Transect slope distribution

Table 1: Slope values selected for monitoring

Representative Slope (%)	Selected Transect Number	Slope of Selected Transect (%)
8	109	8
12	22	12
14	62	14
16	156	16
19	191	21

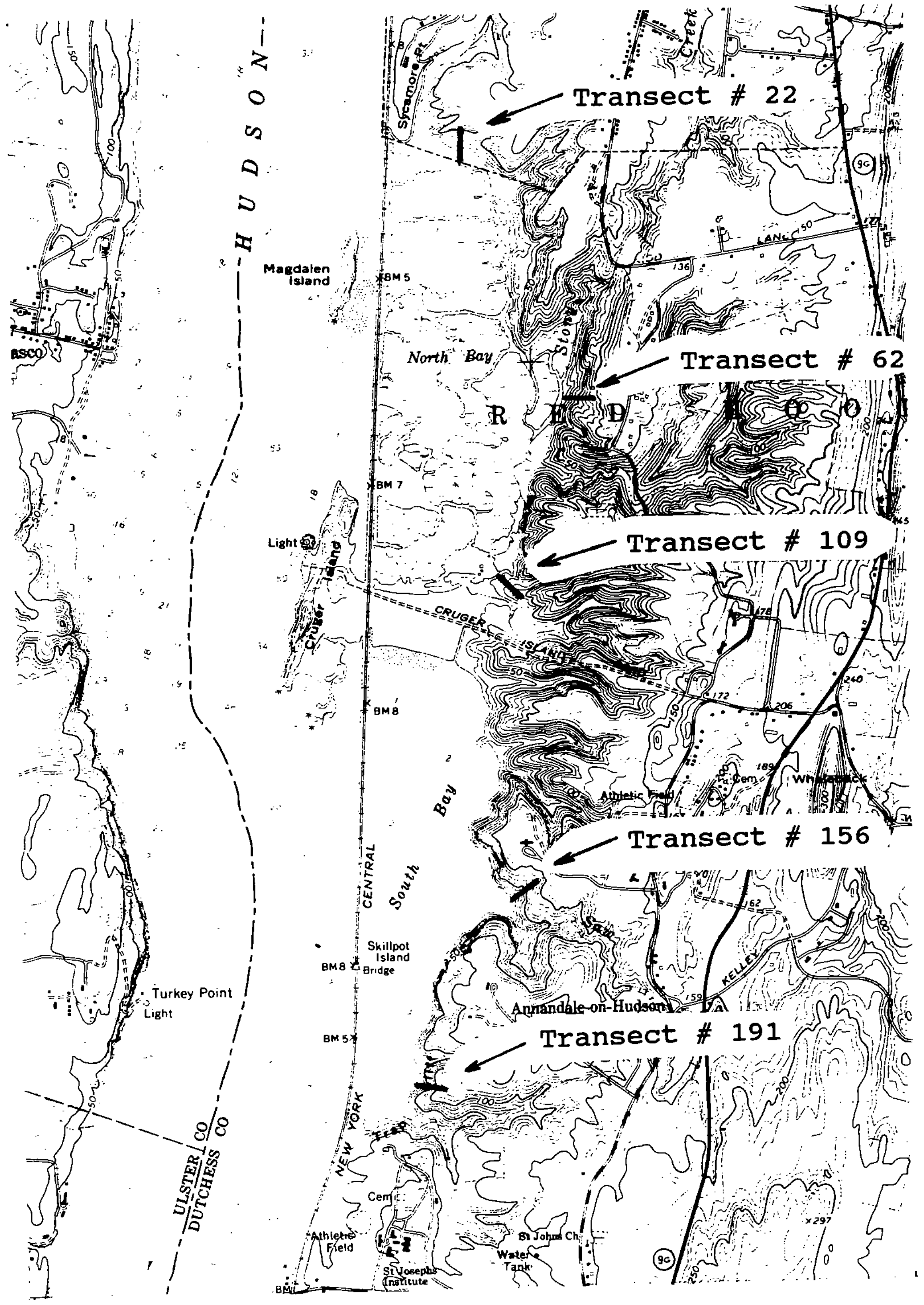

Figure 5: Locations of selected transects
(USGS 7.5 minute quadrangle, Saugerties, NY)

DISCUSSION

The slope of the riparian zone surrounding the Tivoli Bays is quite varied, which suggests that the site may not be suited well to a simple spatial interpolation of hydraulic gradient values between a limited number of monitored transects (Figure 3). By linking the hydraulic gradient to land slope, through a site-specific regression equation, we capture this variation in slope and use it to yield an improved representation of the unmeasured portions of the hydraulic potential distribution. If the original number of transects proves insufficient to accurately represent the relation of hydraulic gradient to land slope, the sample size can be systematically expanded to improve the spatial coverage and reduce the error in groundwater flow predictions.

Field measurements of the hydraulic conductivity and flow field thickness are required to refine the model estimates of the Tivoli Bays groundwater component.

This method can be applied to most wetland or lake systems where relatively shallow local flow is the primary path of groundwater into the system. In non-tidal wetlands, the magnitude, and therefore the importance, of the groundwater flow can be substantial. This method can leverage relatively limited field observations with readily available elevation and soils data to greatly enhance the accuracy of water balance estimates and subsequent ecological work.

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