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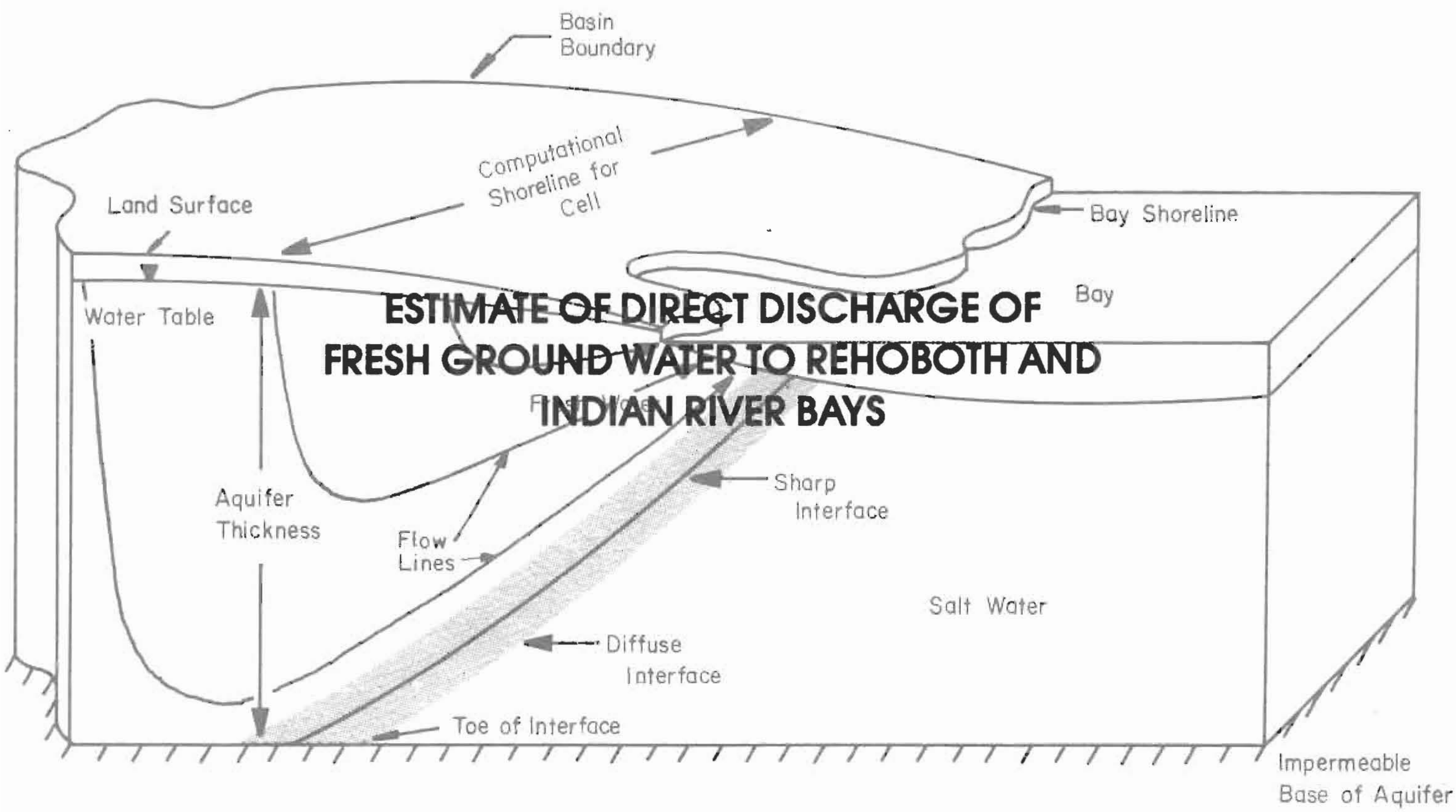

ESTIMATE OF DIRECT DISCHARGE OF FRESH GROUND WATER TO REHOBOTH AND INDIAN RIVER BAYS

BY

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NEWARK, DELAWARE

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ABSTRACT

The results of water-budget and flow-net model calculations indicate that the rate of fresh ground-water discharge into Rehoboth and Indian River bays is in the range of 21 to 43 million gallons per day. The estimates should be used only as gross indicators of actual conditions because of data gaps and the simplifying assumptions used in the models. However, the estimated discharge rates are significant and useful studies of the water budget of the Bays.

Two models were used in order to have a basis to evaluate the validity of the results. The models produced similar results in a majority of the sub-basins that drain into the Bays. However, the models produced different results in some sub-basins. It was not possible to determine which model produced the better results because of a lack of field data with which to calibrate the models or check the validity of the underlying assumptions.

This investigation was a first cut at modeling the flow of fresh ground water into the Bays. Because of limited resources the study used existing data and relied on simple analytic equation based models for the calculations. A systematic data collection effort is needed to improve the accuracy of any ground-water models to be used in the Inland Bays area. The findings of this investigation can serve as a guide to future field and modeling studies.

Purpose and Scope

This report focuses on Rehoboth and Indian River bays. These bays are part of the Inland Bays area of Sussex County, Delaware. The location of the study area is shown in Figure 1.

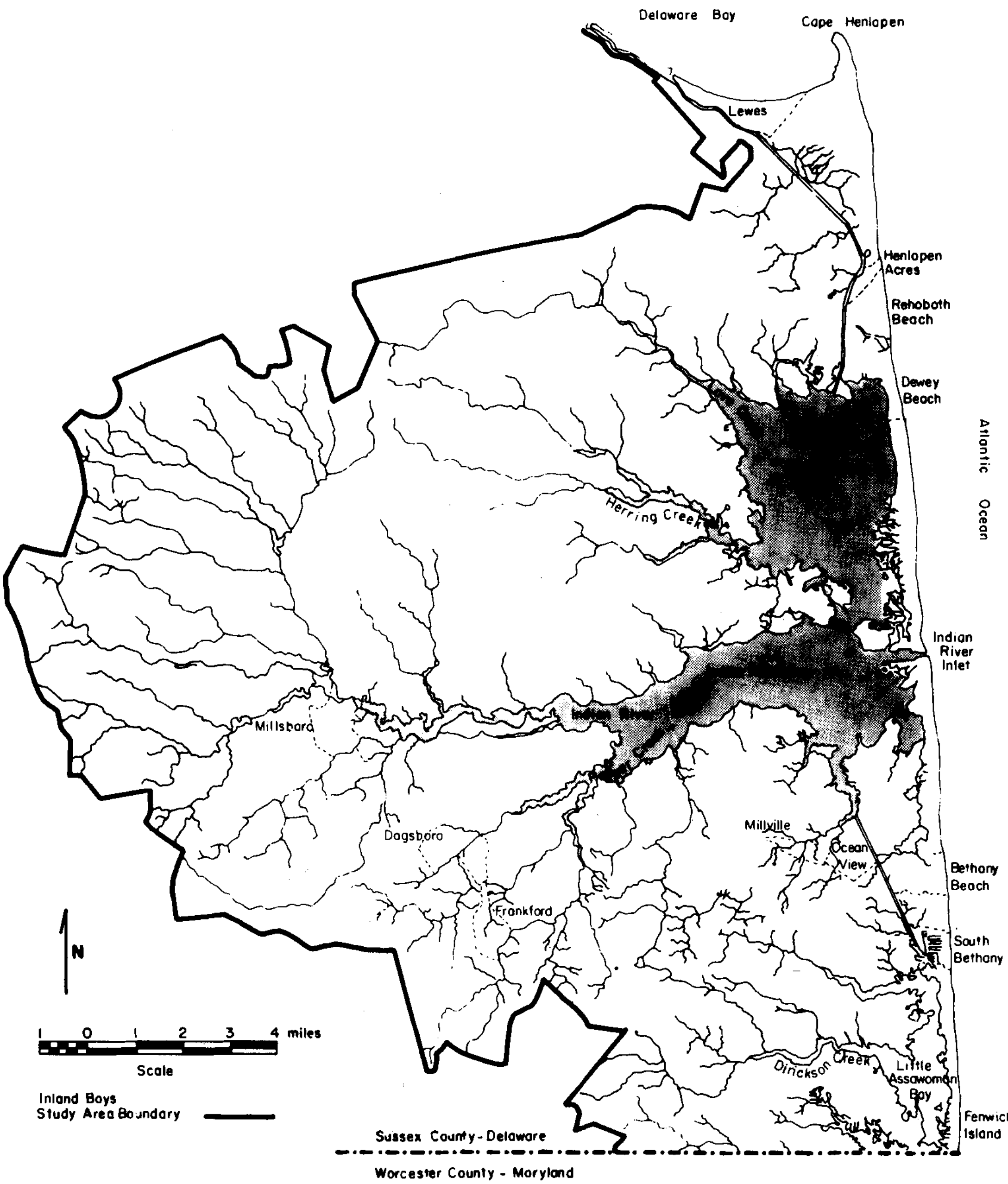


Figure 1. Location of study area.

Fresh water flowing into Rehoboth and Indian River bays, of which direct ground-water discharge is a part, has a significant effect on the environmental health of the Bays. This ground water is derived from infiltration of precipitation in drainage basins immediately adjacent to the Bays. It is these areas that have and are currently experiencing intensive residential development. The effects of development on the Bays need to be systematically investigated. An estimate of the discharge rate can be used to help assess the impacts of development on the environmental health of the Bays.

Much of the basic research for this report was completed under a contract from the Water Supply Branch, Department of Natural Resources and Environmental Control (WSB-DNREC). This report is a refinement of the contract report prepared for the DNREC. The differences between this report and the contract report involve re-interpretations of several of the drainage basin boundaries and cell shorelines.

Acknowledgments

Thanks are expressed to Matthew J. Paejerowski for his assistance in the preparation of this report. Alexander H.-D. Cheng (University of Delaware, Department of Civil Engineering), Kenneth D. Woodruff, and Robert R. Jordan, Delaware Geological Survey (DGS) are thanked for critically reviewing the manuscript. William S. Schenck (DGS) drafted many of the figures for this report.

METHODS

Two independent methods, a flow-net model and a water-budget model, were used to estimate the rate of direct ground-water discharge. The hydrogeological framework and hydrologic conditions used as input to the models were defined from available published and unpublished data. The data base included lithologic and geophysical logs, cross sections, isopachous and structure contour maps (DGS files; Denver, 1983; Andres, 1986b, in prep.; Chrzastowski, 1986; Johnston, 1973, 1977), aquifer test results (DGS files; Johnston, 1973, 1977), water-table elevation contour maps of Adams et al. (1964), Boggess et al. (1964), Boggess and Adams (1964, 1965), and water-budget figures from Johnston (1973, 1976, 1977).

Flow-net Analysis

A flow net is a graphical representation of a flow field. A flow net is composed of flow lines, which show flow directions, and equipotentials, which are locations of equal hydraulic head (i.e., equal water-table elevations). Flow nets are commonly used for evaluating ground-water flow velocities and discharge rates.

The assumptions used in the flow-net model are:

- Steady state flow conditions exist in the aquifer.

- The water-table contours shown on the Hydrologic Atlas maps are representative of the steady state flow field in the Columbia aquifer. The hydrologic effects of modifications to the shoreline (e.g., man-made canals and lagoons) made after these maps were completed could not be addressed and probably are significant.

- Only water from the Columbia aquifer discharges to the Bays and the aquifer discharges all of its water to the Bays (e.g., no underflow). Stegner's (1972) analog model study of ground-water flow in the vicinity of Rehoboth Bay found that almost all of the flow in the Columbia aquifer discharges to the Rehoboth Bay.

- The ground-water flow system can be represented by a series of boxes or cells. The aquifer is homogeneous and isotropic within each cell. Complex aquifer geometry was represented by a complex set of simple geometries. Selection of cell boundaries minimized aquifer inhomogeneities and anisotropy. Intracell inhomogeneities were smoothed by using an average hydraulic conductivity and gradient for a particular cell.

- There is an impervious, horizontal, and infinite lower boundary to each cell. Deviations from the impervious lower boundary were not considered by the model.

- No pumping or on-site wastewater disposal occurrs within the area. These activities affect the flow field and, therefore, the discharge rate. Cases where water pumped from the aquifer is discharged elsewhere (i.e., a sewage treatment plant with a surface water outfall) could not be modeled. This reduces the amount of water that is discharged from the aquifer directly to the Rehoboth and Indian River bays.

- Water in the Bays has an average composition similar to sea water. This assumption affected the modeled configuration of the fresh water-salt water interface but did not significantly affect the computed discharge.

The study area was divided into a series of cells that have similar hydrogeologic characteristics and spatial proximity. The cells are roughly equivalent to the ground-water drainage basins used in the water-budget model. For each cell, ground-water discharge (Q) was calculated from the Darcy flux (V):

$$V = K\,i; \text{ and,}$$

the cross-sectional area of the cell (A).

$$Q = V\,A$$

The average and range of hydraulic conductivity (K), aquifer thickness (b) (excluding the thickness of any included confining beds), and hydraulic gradient (i) values used as input are listed in the Appendix. Gradient (i) was measured in areas away from streams and the Bays. These gradients were thought to be representative of the average water flow through the aquifer and therefore the total amount of water flowing under the bayshore. Cross-sectional area was calculated from the product of average aquifer thickness and shore length (refer to the Appendix for specific data). Shore length refers to the length of the bayside boundary of a cell. Shore length was measured along a smoothed line oriented approximately parallel to the actual shoreline and located inland of the toe of the salt-water wedge. Assuming steady state ground-water flow, the flow rate at the toe is equal to the flow rate at the shore (Kasheff, 1983). The position of the toe was estimated by the method described in Kasheff (1983). An illustration of the measurement methods is shown in Figure 2a.

Two shorelines were defined for the Indian River Bay South Shore area. The first included the large tidal stream shorelines (type a). The second excluded the large tidal stream shorelines (type b).

In some areas, the geometries of the basin and shoreline are such that the fresh-water aquifer probably is more lens-shaped than wedge-shaped (e.g., Long Neck east, Dumpling Neck, and part of Long Neck north, see Figures 2b, 3a-3g). Figure 2b illustrates how this geometry was simplified to a wedge shape to facilitate flow-net construction and discharge rate calculations. One result of this simplification was to exclude part of the tidal creek shoreline from the length of the computational shoreline.

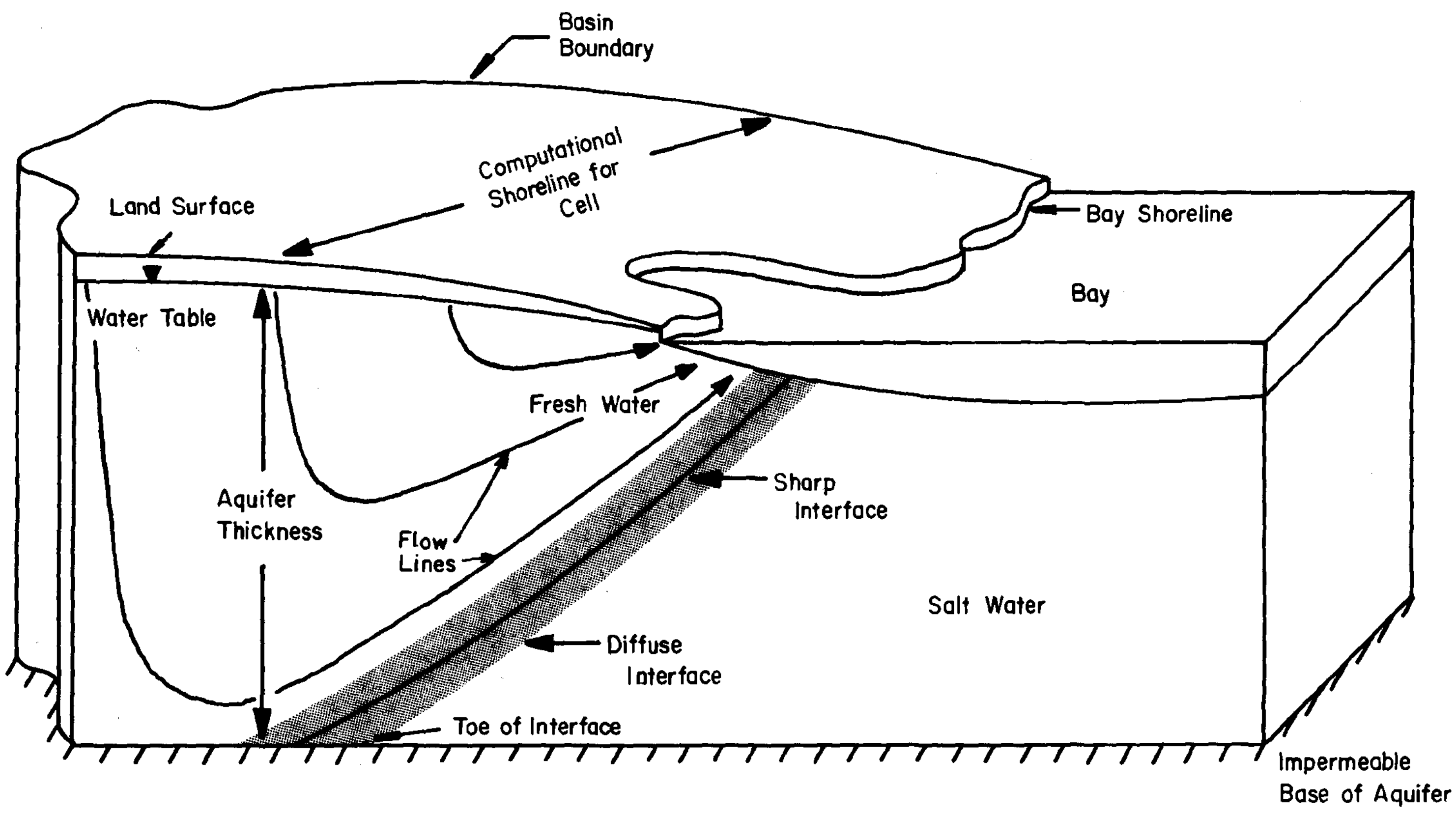


Figure 2a. Generalized hydrogeologic setting and measurement methods.

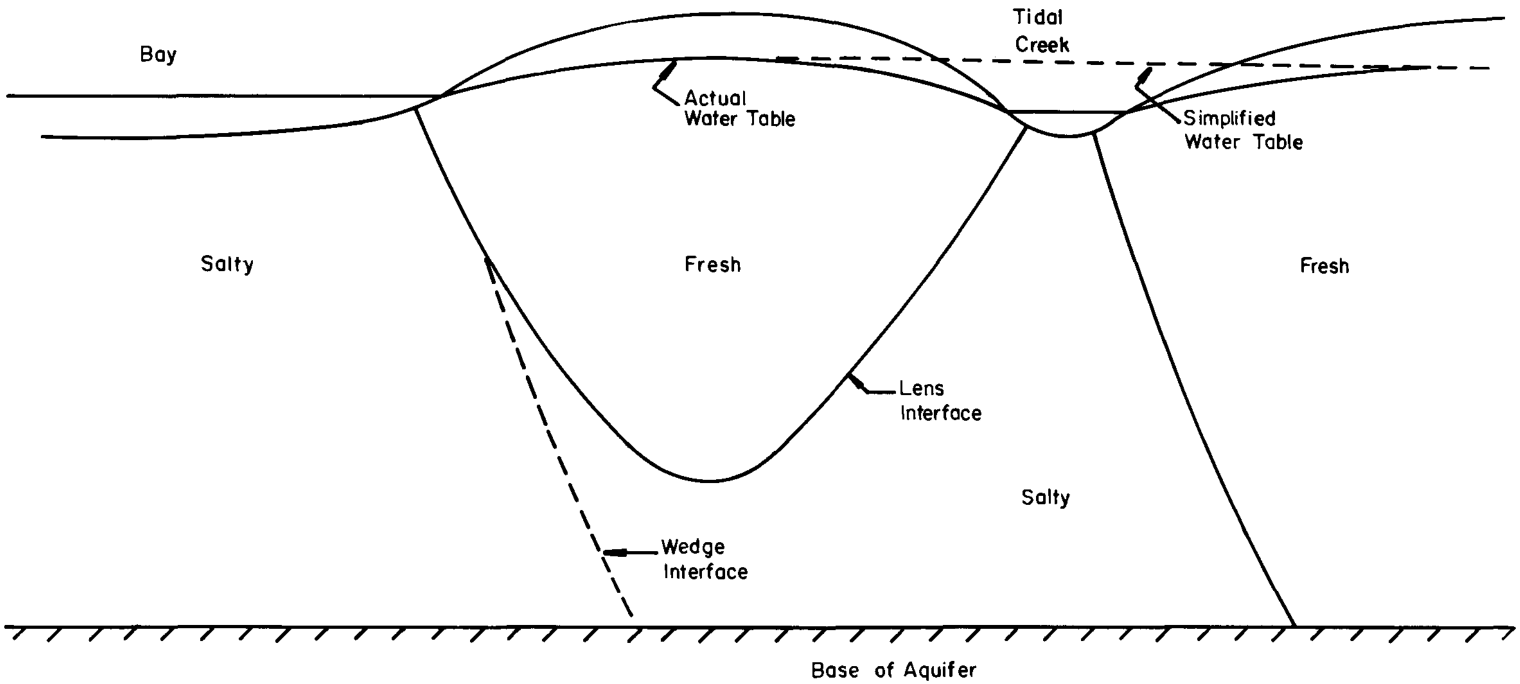


Figure 2b. Simplification of fresh-water lens for fresh-water wedge.

Another result was to increase the aquifer thickness. Because these two results have opposite effects on the computed discharge they tend to cancel out. The eastern end of Long Neck is the most extreme example of a lens-shaped fresh-water aquifer. Because a tidal ditch cuts Long Neck, the fresh-water aquifer to the east of the ditch may function as a separate aquifer (i.e., an island aquifer). There are virtually no water-table elevation data for this area so that a flow net could not be constructed and a discharge rate based on flow-net analysis could not be calculated.

Water-budget Analysis

In general, a water budget (water balance) is an accounting of the volumes of water contained in, or flowing through aquifers, streams, ponds, and other systems of the hydrologic cycle.

The assumptions used in the water-budget model are:

- Steady state flow conditions exist in the aquifer. The water-table contours shown on the Hydrologic Atlas maps are representative of the steady state flow field in the Columbia aquifer.

- The ground-water discharge and recharge rates presented in Johnston (1973, 1976, 1977) are applicable to the area. The extent of ground-water drainage basins can be defined utilizing available water-table elevation contour maps (Hydrologic Atlas maps).

- Only the Columbia aquifer discharges to the Bays. Within a ground-water drainage basin the aquifer discharges all of its water to the Bays.

The ground-water drainage basins that discharge directly into Rehoboth and Indian River bays and adjacent tidal marshes were defined on the Hydrologic Atlas maps and their areas were measured with an electronic graphics calculator (digitizer). The drainage basins are shown in Figures 3a-3g. Basin boundaries were approximated by a series of straight line segments. The areas were multiplied by the unit ground-water discharge rate (500,000 to 600,000 gallons per day per square mile (gpd/mi^2), Johnston, 1973, 1976, 1977) to obtain a range of ground-water discharge rates for the basin.

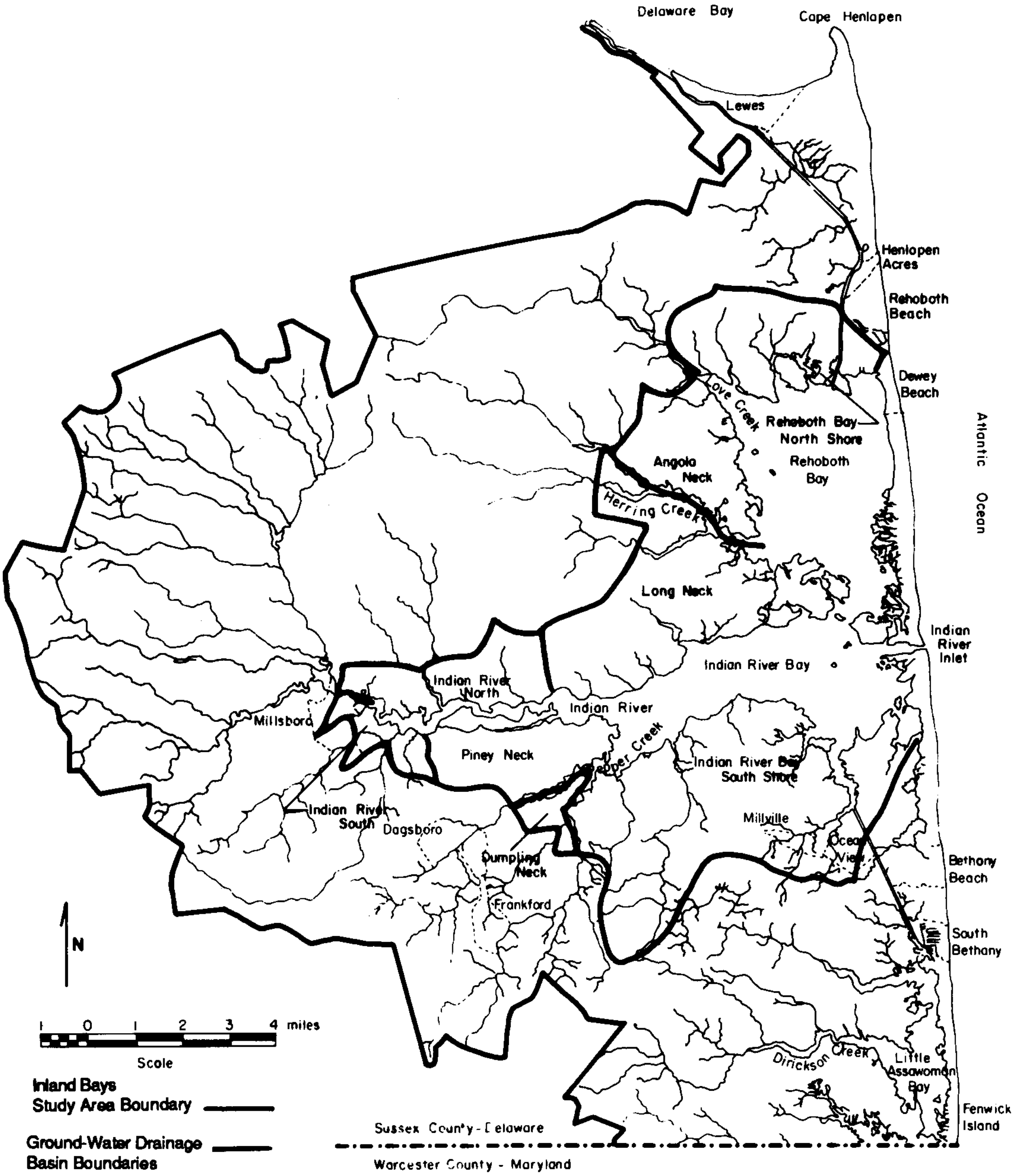


Figure 3a. Index map showing areas that drain directly into Rehoboth and Indian River bays.

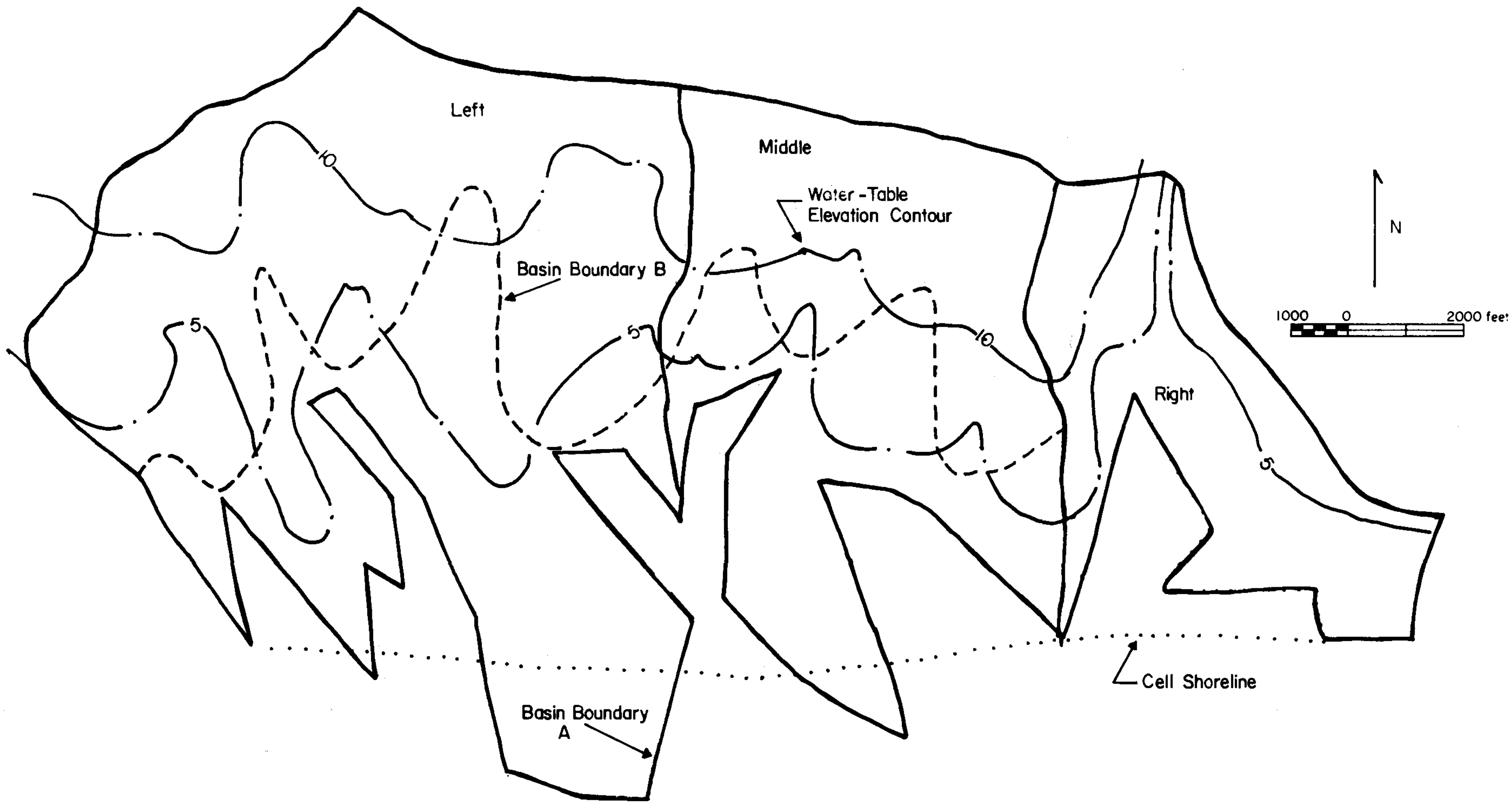


Figure 3b. Rehoboth Bay North Shore areas. Location shown on Figure 3a.

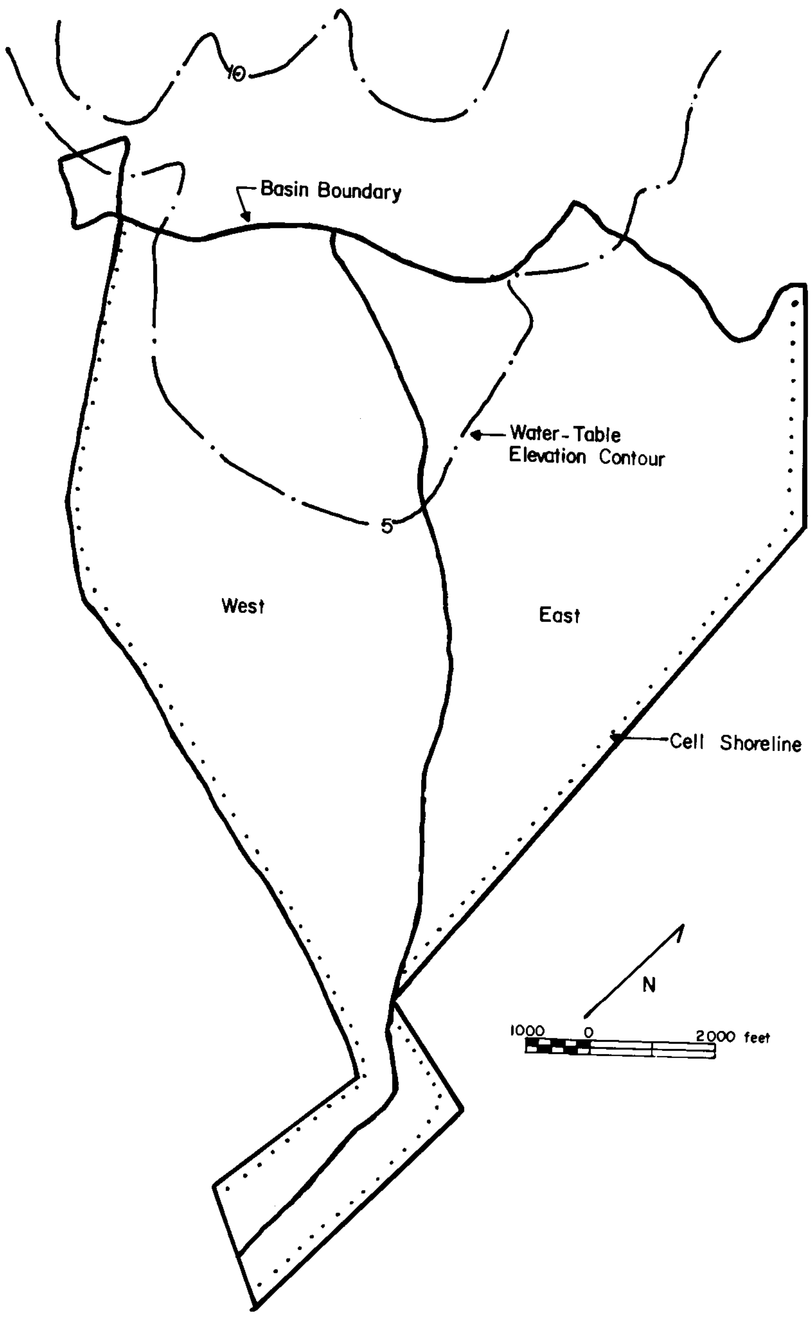


Figure 3c. Angola Neck areas. Location shown on Figure 3a.

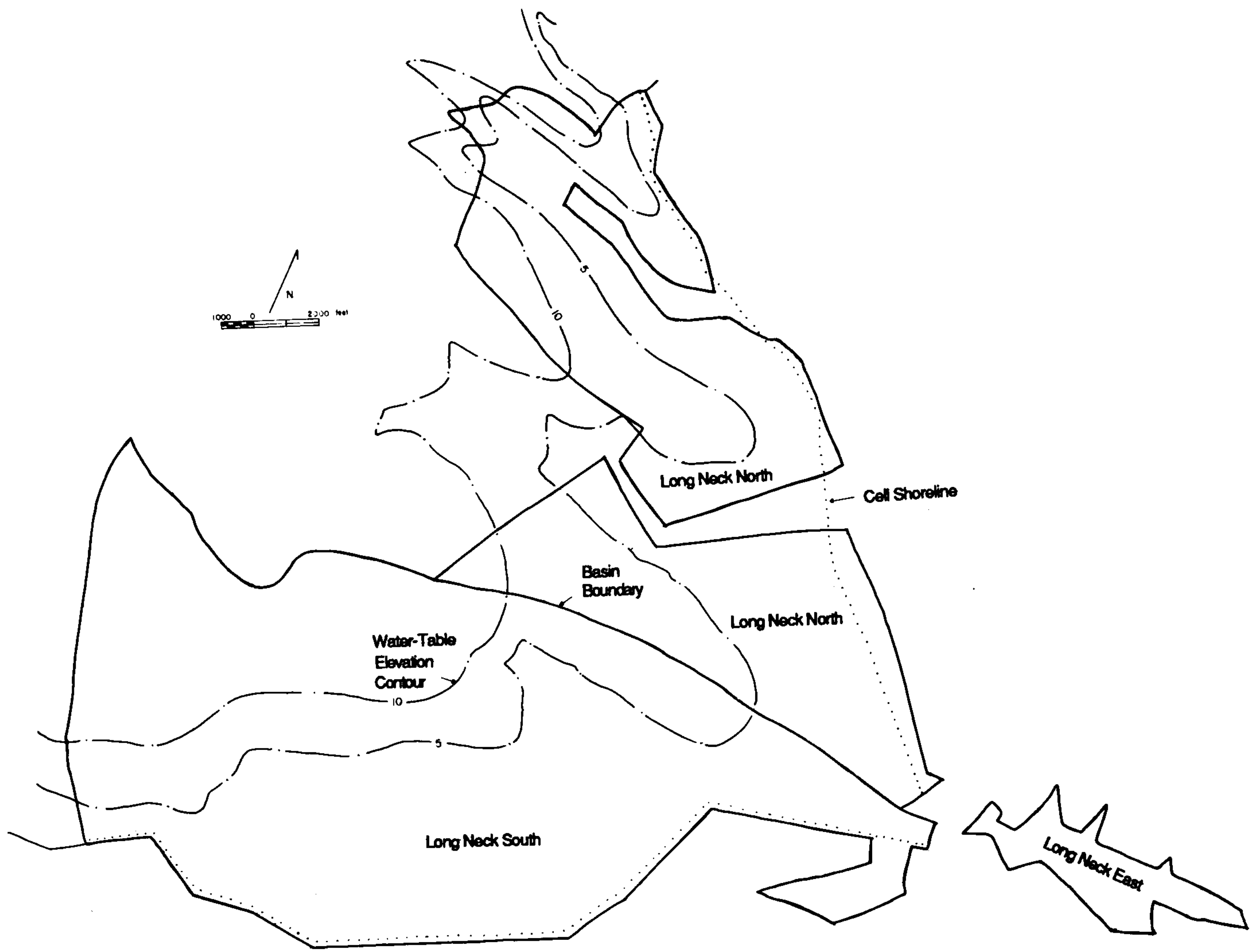


Figure 3d. Long Neck areas. Location shown on Figure 3a.

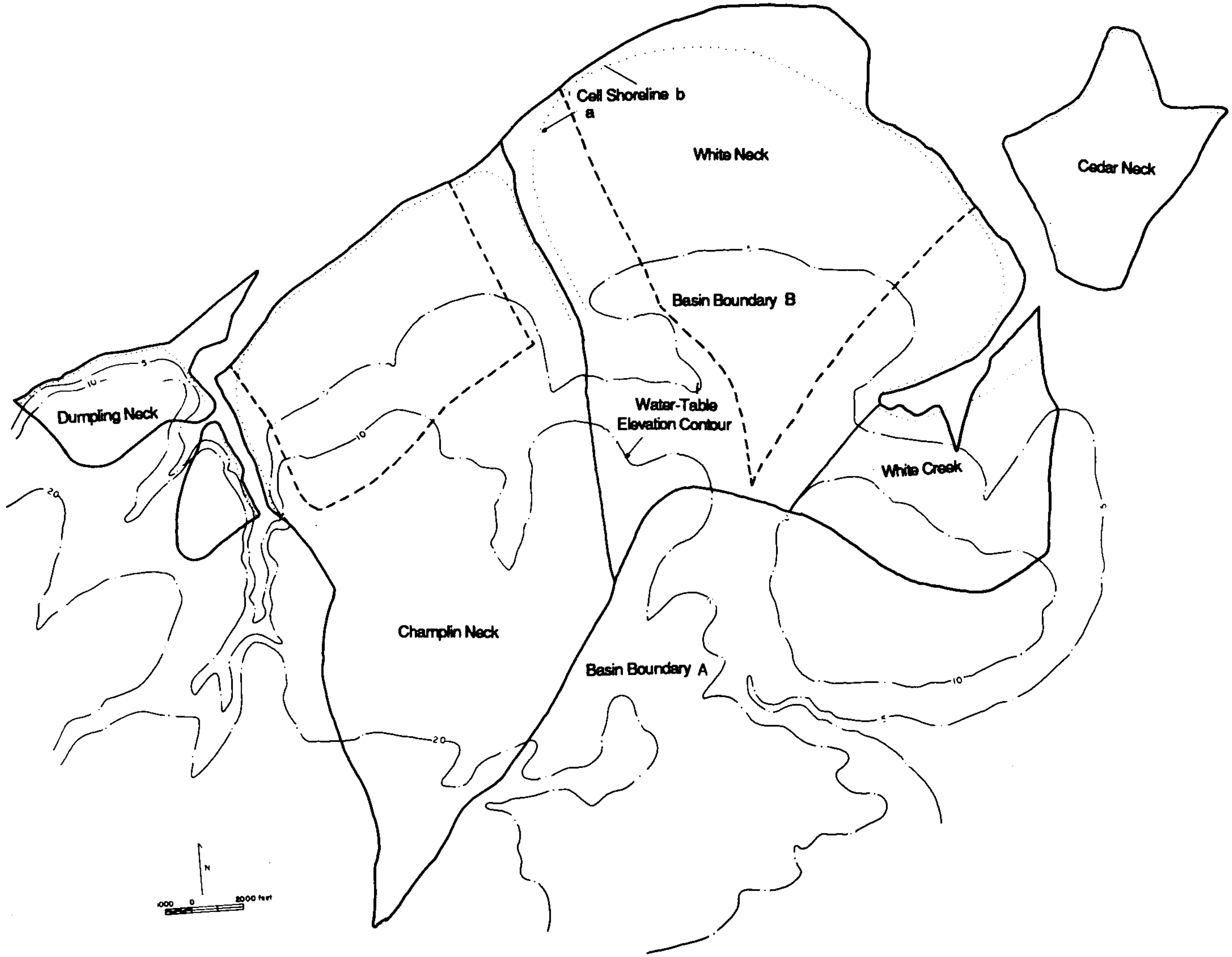


Figure 3e. Indian River Bay South Shore and Dumpling Neck areas. Location shown on Figure 3a.

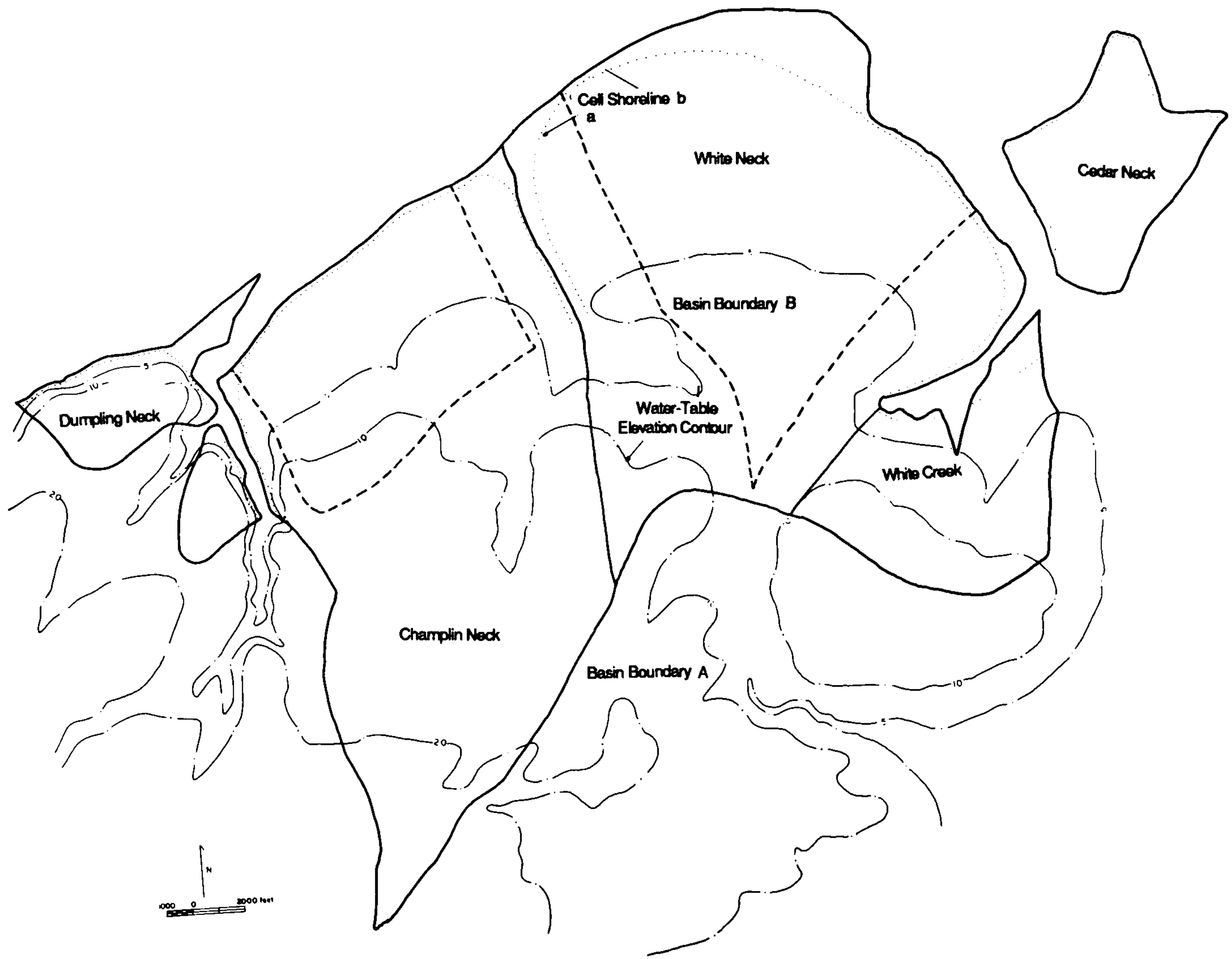


Figure 3e. Indian River Bay South Shore and Dumpling Neck areas. Location shown on Figure 3a.

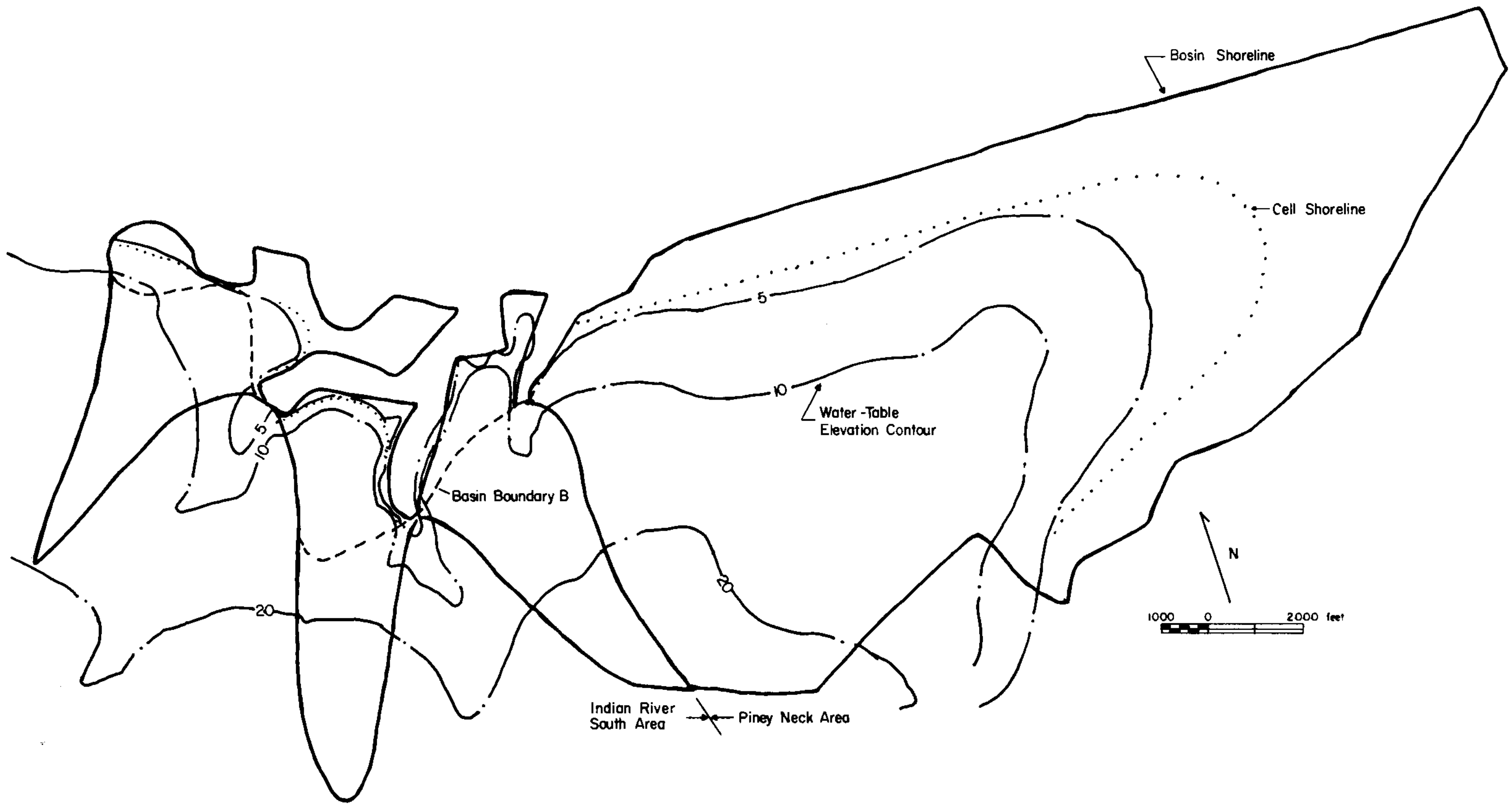


Figure 3f. Piney Neck and Indian River south areas. Location shown on Figure 3a.

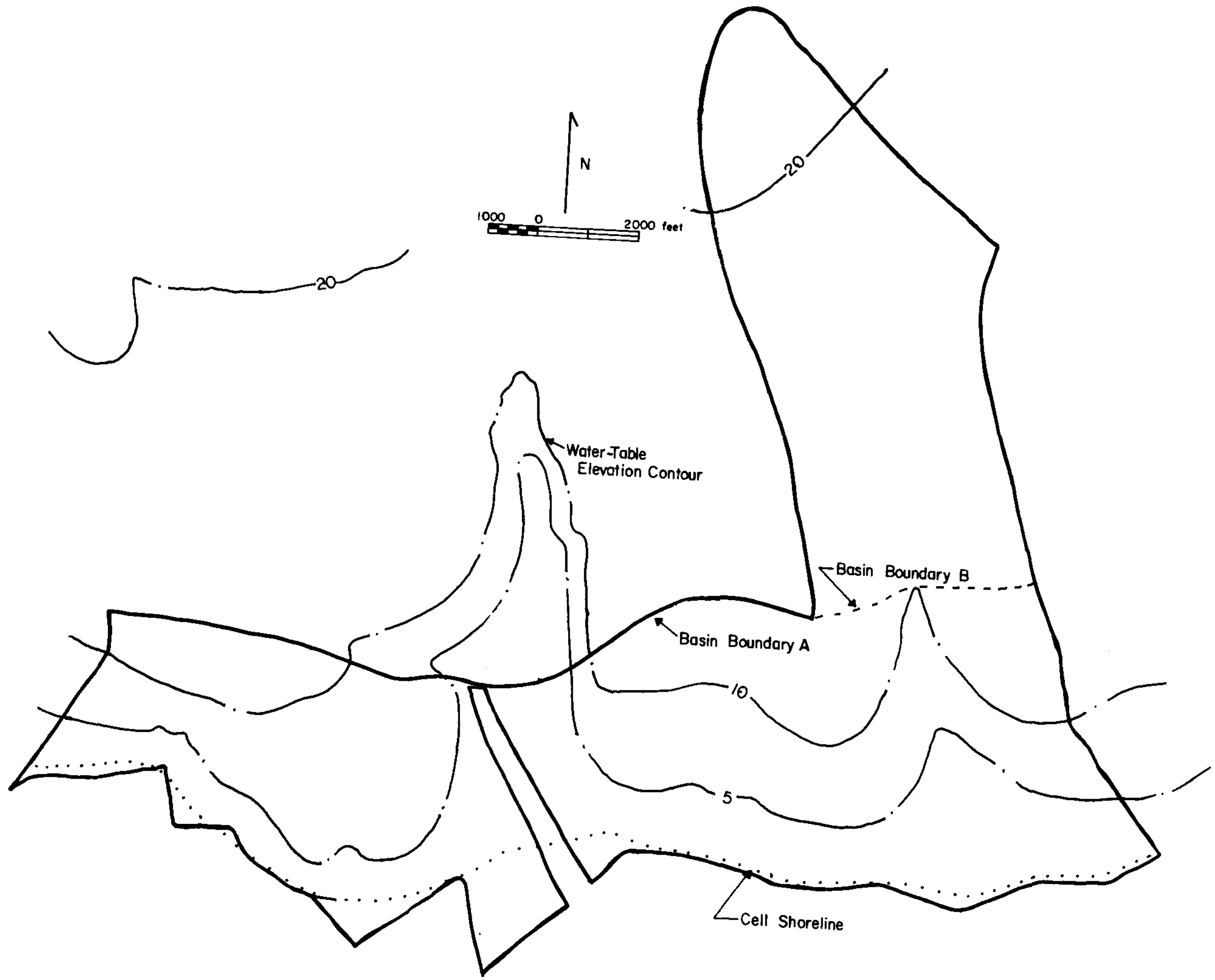


Figure 3g. Indian River north area. Location shown on Figure 3a.

Two types of basin areas were defined for the Rehoboth Bay North Shore, Indian River Bay South Shore, Indian River north, and Indian River south areas. The first type (type a) included areas drained by fresh-water swamps, ephemeral streams (as denoted on the Hydrologic Atlas maps), tax ditches, and large tidal streams. The second type (type b) excluded most of these areas.

Lauffer (1982) found that there is a net downward flux of bay water into an area of tidal marsh on Angola Neck. For this reason, tidal marshlands were excluded from the area measurements.

Model Sensitivity

In both models, discharge was calculated as the simple product of the input parameters. As a result, the calculated discharge rates were affected equally by the same relative changes of any of the input parameters. For example, doubling the aquifer thickness or basin area doubled the calculated discharge rate. This was important in the evaluation of the model results.

RESULTS AND DISCUSSION

Basin Maps

Figures 3a-3g show the ground-water basins, shorelines, and water-table elevation contours. The water-table elevation contours were either taken from the Hydrologic Atlas maps or derived from data shown on the maps.

Definition of the ground-water discharge basins that discharge directly to the Bays proved to be difficult for several reasons:

1. The water-table elevation contour maps are not very detailed. Only the 5-foot elevation contour could be interpolated with any confidence. Detailed basin definition would require contour intervals of one foot or less.

2. Much of the study area south of Indian River Bay is drained by tax (drainage) ditches. There also are many ephemeral streams that drain directly into the

Bays. Some of these streams are tidal along their lower reaches and are inland extensions of the Bays. The portion of the aquifer drained by the ephemeral streams and tax ditches is not certain. If any portion of ground-water flow is bypassing tax ditches and ephemeral streams, then using these small streams to define ground-water drainage basins will result in underestimation of the sizes of ground-water basins.

At one extreme, in which almost all areas draining to any stream were excluded (type b), approximately 40 square miles drain to the Bays. At the other extreme, in which areas drained by ephemeral and tidal streams were included, approximately 57 square miles drain to the Bays (type a). Comparison of the results generated by the water-budget and flow-net models did not indicate the correct method of calculating basin size.

General Geology

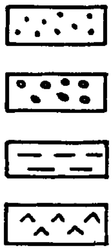
Both models used the assumption that only the Columbia aquifer discharges fresh ground water to the Inland Bays. The Columbia aquifer occurs within the Columbia Group as defined by Jordan (1962), and in some areas, includes sands of the underlying Bethany formation as defined by Andres (1986a), and sandy beds of overlying unnamed Holocene deposits. In the study area, the Columbia Group is a lithologically heterogeneous unit that consists of medium to coarse sand with variable amounts of gravel and areally discontinuous lenses and layers of fine sand, silt and/or clay. Sands of the Bethany formation are an important part of the Columbia aquifer in the area south of Indian River Bay. In general, Holocene deposits are comprised of organic-rich sandy silt that underlies present streams and the Bays, or sand that makes up the Atlantic shore beaches.

Hydrogeologic Characteristics

The results of the hydrogeologic evaluations are presented as cross-sections (Figures 6-9) and table (Appendix). The cross-sections were chosen to show the widest range of geologic conditions. Explanation of symbols and locations of cross-sections are shown in Figures 4 and 5.

Comparison of unit flux values (herein defined as discharge through a one-foot wide section of aquifer) indicated significant differences in hydrologic conditions

Lithology



Sand

Gravel

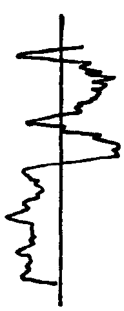
Silt/Clay/Organic

Shell

NGVD 1929-National Geodetic
Vertical Datum of 1929

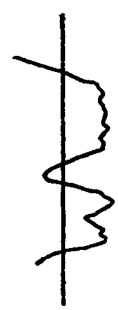
Oh55-5 - DGS well number

Natural gamma log,
radiation increasing
to right.



Spontaneous potential log,
voltage increasing
to right.

SP



On figures 5-8 sub-bay bottom geology inferred from Chrzastowski (1986).

Figure 4. Explanation of cross-section symbols.

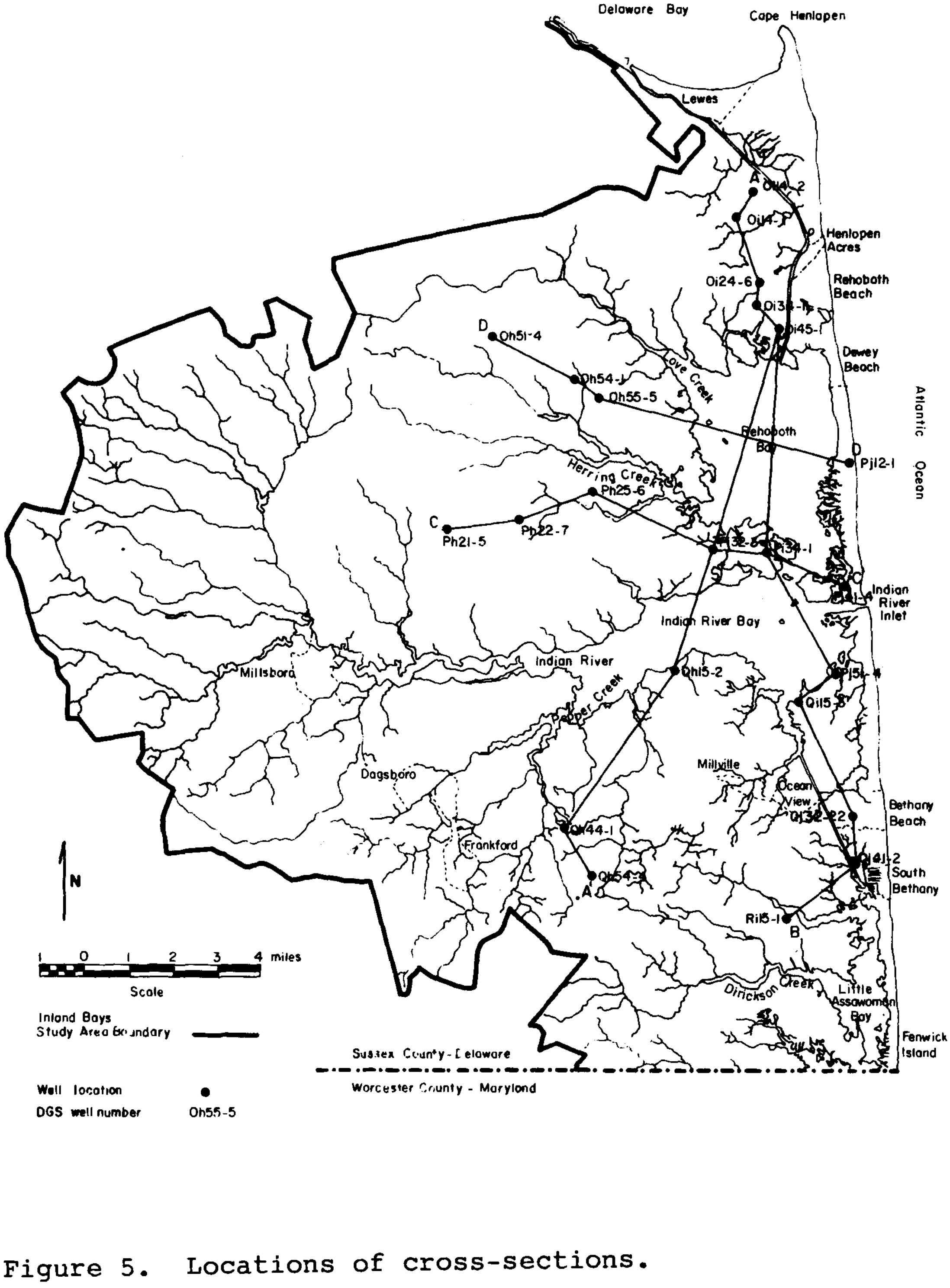


Figure 5. Locations of cross-sections.

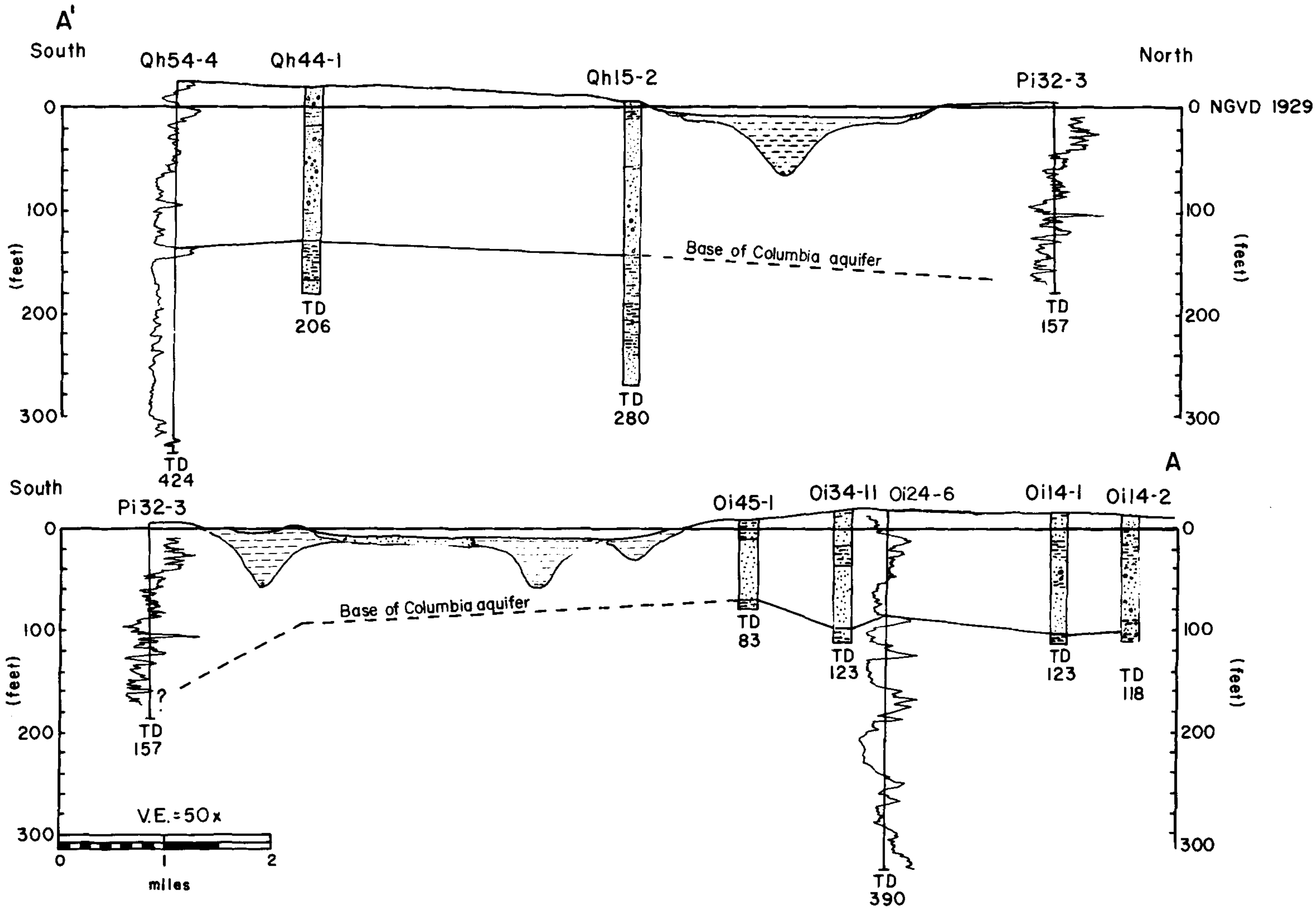


Figure 6. Cross-section A-A'.

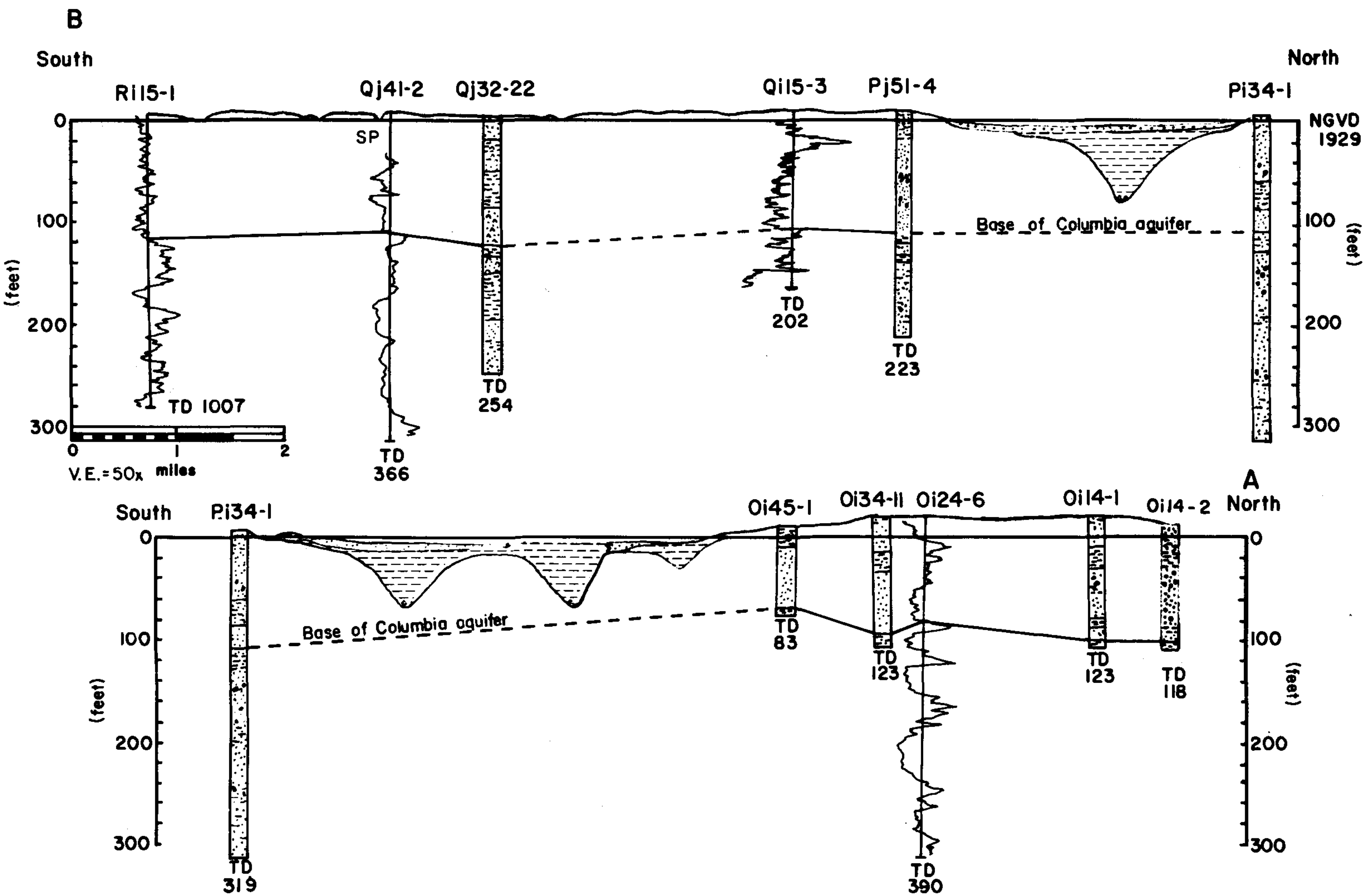


Figure 7. Cross-section A-B .

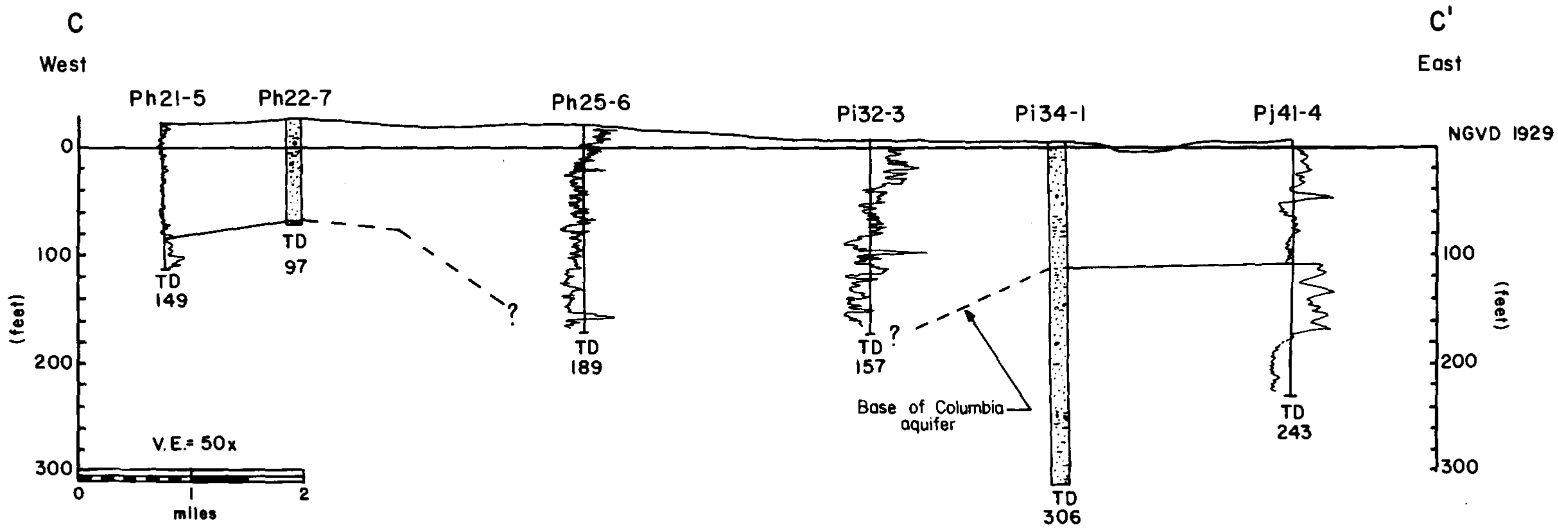


Figure 8. Cross-section C-C'.

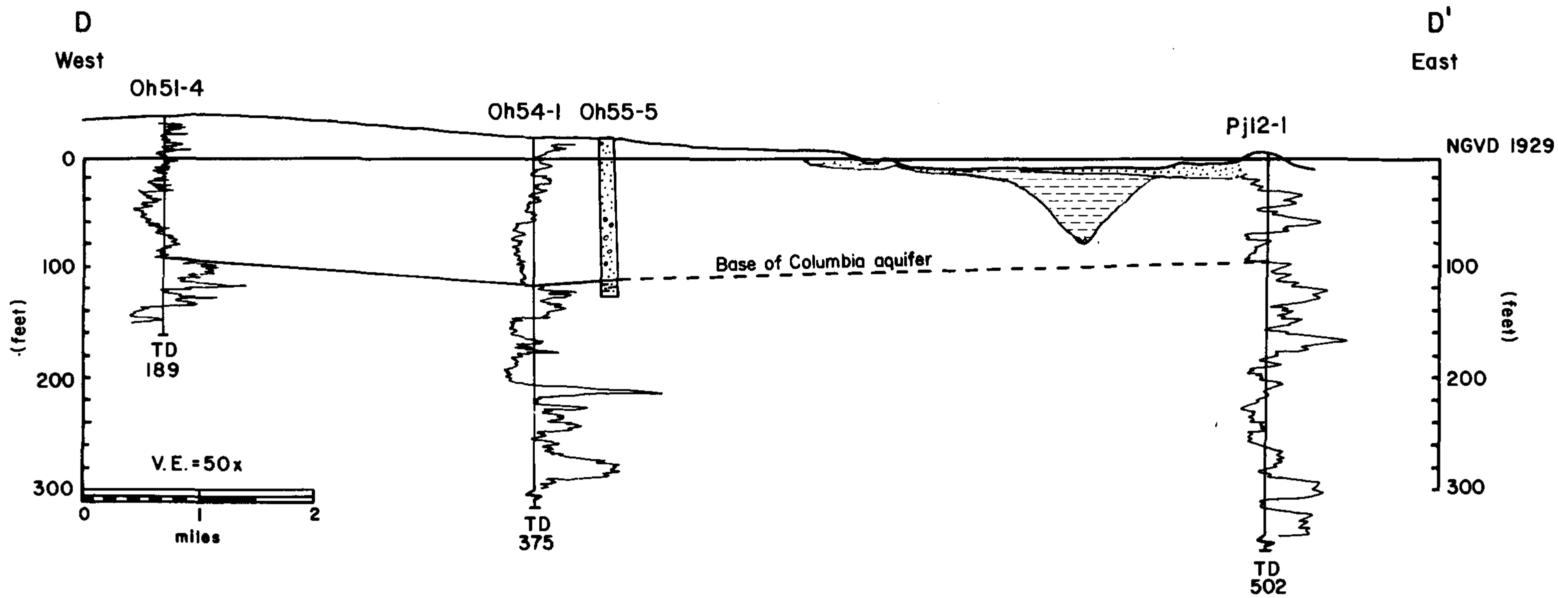


Figure 9. Cross-section D-D'.

between basins (Appendix). In the Long Neck South and Rehoboth Bay North Shore areas, it appears that the high flux values are due to greater than average gradients. In the Piney Neck and Dumpling Neck areas, it appears that the high flux values are due to greater than average hydraulic conductivities and aquifer thicknesses. Chrzastowski (1986) conducted an extensive study of the subbottom geology of Rehoboth and Indian River bays. He found that in most areas, the Bays are underlain by a thin (<10 feet) layer of silt and clay. However, there are significant inhomogeneities such as deep, mud filled antecedent channels (paleochannels) of the present streams, and sandy beach and nearshore areas. It should be noted that the sandy baybottom sediments contain a significant amount of silt and, therefore, are less permeable than the Columbia Group sediments that comprise the Columbia aquifer.

The low hydraulic conductivity, fine-grained sediments tend to reduce the average hydraulic conductivity of the aquifer and may act as a local barrier to ground-water discharge. If the water can not discharge from the aquifer at another location, then gradients in onshore portions of the aquifer would have to increase to allow the water to flow through the low hydraulic conductivity material. This phenomenon, which is evident adjacent to Love Creek and several other streams underlain by thick mud-filled paleochannels, usually is only local in nature. However, it is possible that this is the mechanism causing the higher than average gradients in the Long Neck south and Rehoboth Bay North Shore areas.

MODEL EVALUATIONS

The models were evaluated by comparing the results generated by each model. If the models generated similar results (difference less than twenty-percent of larger value), no further evaluation was done. The twenty percent difference value is reasonable considering the methods used to estimate the input data. If there was a significant difference between the results generated by the models, the input data were reevaluated and other explanations for the difference were investigated.

Model Results

Table 1. Estimates of Direct Ground-Water Discharge to Rehoboth Bay

Drainage basin	Water-Budget estimates (500,000 to 600,000 gpd/mi^2)	Based on Johnston (1977) transmissivity values	Based on best estimates of hydraulic conductivity
Rehoboth Bay North Shore			
total (a)	3.00 to 3.60	7.22	4.30
left	1.64 to 1.96	3.08	1.71
middle	0.90 to 1.07	1.78	1.18
right	0.48 to 0.57	2.36	1.41
total (b)	1.60 to 1.91		
left	0.68 to 0.82		
middle	0.44 to 0.52		
right	0.48 to 0.57		
Angola Neck			
east	0.89 to 1.07	1.31	1.12
west	1.03 to 1.24	0.82	1.10
Long Neck			
north	2.47 to 2.96	2.26	2.76
east	0.12 to 0.14	----	0.14
Total (a)	7.39 to 8.87	11.61	9.42
Total (b)	5.99 to 7.18		

Notes: 1. See text for description of area types a and b.
2. Total flow values designated (c) are based on a discharge rate of 600,000 gpd/mi^2. Total flows are the sums of subarea flows. Small differences are due to rounding off. Drainage basins are shown in Figures 3a-3g.

Table 2. Estimate of Direct Ground-Water Discharge to Indian River and Indian River Bay

Drainage basin	Water-budget estimate 500,000 to 600,000 gpd/mi²)	Based on Johnston (1977) transmissivity values	Based on best estimates of hydraulic conductivity
Long Neck			
south	3.95 to 4.74	5.33	5.60
east	0.12 to 0.14		0.14
Indian River Bay South Shore			
total (a)	10.58 to 12.70		12.17
Cedar Neck	0.80 to 0.96		2.34
White Neck	4.61 to 5.54		4.59
Champlin Neck	4.12 to 4.94		4.02
White Creek	1.05 to 1.26		1.22
total (b)	4.88 to 5.85		6.07
Cedar Neck	0.80 to 0.96		1.93
White Neck	2.70 to 3.24		2.26
Champlin Neck	1.38 to 1.65		1.88
Indian River (a)			
north	2.84 to 3.40	4.08	3.41
south	0.74 to 0.88		1.42
(b)			
north	1.82 to 2.19		
south	0.64 to 0.77		
Piney Neck	2.13 to 2.56		8.22
Dumpling Neck	0.64 to 0.77		2.64
Total (a)	20.99 to 25.19		33.60
Total (b)	15.29 to 16.70		27.50

Notes: 1. See text for description of area types a and b.
2. Total flow values designated (c) are based on a discharge rate of 600,000 gpd/mi². Total flows are the sums of subarea flows. Small differences are due to rounding off. Drainage basins are shown in Figures 3a-3g.

There are several nonexclusive reasons why the results of the two models could be different. If the discharge calculated by the water budget was much greater than discharge calculated by flow-net analysis, then: hydraulic conductivity was too low; the cell size was too small (e.g., thickness or shore length); the basin size was too large; and/or, Johnston's (1973, 1976, 1977) discharge rates are too high. If the discharge calculated by flow-net analysis was much greater than discharge calculated by water budget, then: hydraulic conductivity was too high; some flow is derived from deeper aquifers or from other basins (the basin size is too small); the cell shape was distorted (this causes the flow net to be distorted so that flow lines and equipotentials are not perpendicular); and/or the excess water is not discharging to the Bays.

One measure of cell shape distortion (a cause for larger flow-net model results) is the shore length to basin area ratio (Appendix). In most cases where the flow-net model results are much greater than the water-budget model results, the shore length to basin area ratio is greater than the average ratio.

Johnston (1977) Digital Model

Johnston's (1977) transmissivity values were derived from the calibration of a two-dimensional, finite difference ground-water flow model. For the part of the present study area covered by the Johnston (1977) model the calibration was based only on the comparison of observed and calculated water-table elevations. This technique resulted in the model calibrated transmissivities being significantly larger than transmissivities estimated from well log and specific capacity data. Johnston (1977) considered the model-calibrated transmissivity data to be more accurate than transmissivities estimated from well log and specific capacity data.

In general, discharge rates based on Johnston's (1977) transmissivity data were higher than discharge rates based on the estimated hydraulic conductivity values used in this study. The primary reasons for this are the difference between model application methodologies and the availability of data. The Johnston (1977) model generated a rough approximation of the observed ground-water flow field by adjusting the value of aquifer coefficients. The analytical models used in this study were based on the observed groundwater flow field and estimated aquifer coefficients. Additional data for estimating aquifer thickness and aquifer coefficients also were available for this study.

Rehoboth Bay North Shore

The Columbia aquifer in the Rehoboth Bay North Shore area drains into Rehoboth Bay, the Lewes and Rehoboth Canal, and several small streams (Arnell Creek, White Oak Creek, and Bald Eagle Creek) that flow into the Bay. The difference between the total discharge rates generated by the two models is less than twenty percent for the type a basins. The flow-net model results are up to 2.7 times greater than the water-budget model results for the type b basins both on the whole and for each subarea.

The flow-net model results are approximately 2.5 times greater than the water-budget model results for the right subarea This is probably due to a distorted cell shape (greater than average shoreline to basin area ratio, Appendix). The right subarea (Figure 3b) could be eliminated from the study because the water-table contours indicate that the Columbia aquifer in this area drains into the Lewes and Rehoboth Canal.

Reevaluation of the hydrogeologic data indicates that the thick, low hydraulic conductivity underlying Rehoboth Bay may lower the average hydraulic conductivity of the aquifer (resulting in the observed high gradients) and/or force some flow paths toward a more distant discharge area. If this is true, then the flow-net model generated results are too high. Alternatively, the observed high gradients may be due to the relatively greater land surface slopes (U. S. Department of Agriculture, 1984). If this is true, then the observed gradients may not be representative of the entire aquifer. It is also possible that some flow is coming from outside the basin. If this is true, then the models do not accurately represent field conditions.

Angola Neck

The Columbia aquifer in the Angola Neck east area drains into Rehoboth Bay. The Angola Neck west area drains into the tidal portion of Herring Creek. The two models generated similar results for this area. It appears that subbay floor geology could influence the location of the discharge area.

One likely discharge area is the sandy bottom located just offshore. Another is located west of the confluence of the Herring Creek and Love Creek paleochannels. This latter feature could focus ground-water flow.

Long Neck

The Columbia aquifer in the Long Neck area drains into the tidal portions of Herring Creek and Guinea Creek and into Rehoboth and Indian River bays. The two models generated similar results for this area. It appears that subbay floor geology could influence the location of the discharge area. One likely discharge area is the adjacent sandy bay floor. A possible discharge area is located west of the confluence of the Herring Creek and Love Creek paleochannels. If fresh ground water extends out under Rehoboth Bay this feature could focus ground-water flow.

Indian River Bay South Shore

The Columbia aquifer in this area drains into several large tidal streams (Vines Creek, Blackwater Creek, and White Creek), the Assawoman Canal, and numerous small streams and tax ditches. The flow-net model results for the entire area are nearly equal to the maximum water-budget model results for both area types a and b. However, the flow-net model results are significantly greater for the Cedar Neck subarea (two to three times greater). The difference appears to be due to a distorted cell shape (e.g., the shoreline is too long). The flow-net model results for the White Neck subarea are less than the minimum water-budget model results for this area suggesting that one or more of the input parameters was not correct. One possible explanation is that ephemeral streams and tax ditches are capturing a significant amount of ground-water flow (e.g., the basin is too large). Another plausible explanation is that the average ground-water discharge rates determined by Johnston (1973, 1976, 1977) are not valid for this area. A factor contributing to a lower ground-water discharge is a higher ground-water evapotranspiration rate due to a lesser depth to ground water.

Piney Neck

The Columbia aquifer in the Piney Neck area drains into Pepper Creek and Indian River. The flow-net model results are approximately 2.5 times greater than the water-budget model results. Some of the difference appears to be due to a high hydraulic conductivity value (160 ft/day, estimated from aquifer test data from the Indian River power plant). It is possible that some flow is recharging the subcropping Pocomoke aquifer. Additionally, some of the difference may be due to a distorted cell shape (because of the long shoreline), or flow coming from outside the basin. The observed gradients do not indicate that the fine-grained sediments underlying Pepper Creek and Indian River are effectively lowering the average hydraulic conductivity of the aquifer.

Dumpling Neck

The Columbia aquifer in the Dumpling Neck area drains into Pepper Creek, Vines Creek (tidal streams) and Herring Branch. The flow-net model results are approximately 3.5 times greater than the water-budget model rates. The difference may be due to a distorted cell shape (caused by along shoreline). It is also possible that some flow paths are diverted to a more distant discharge area (i.e., the hydraulically-connected, underlying Pocomoke aquifer); or, that some flow is coming from outside the basin. The observed gradients do not indicate the fine-grained sediments underlying Pepper Creek and Vines Creek are effectively lowering the average hydraulic conductivity of the aquifer.

Indian River North

The Columbia aquifer in the Indian River north drains into Indian River and Swann Creek. The two models generated nearly identical discharge rates when the larger basin size was used as input to the water-budget model. However, a difference of greater than twenty percent occurs when the smaller basin size was used in the water-budget model. If the smaller discharge rate is correct, then it is likely that some of the water in the Columbia aquifer is recharging the hydraulically-connected, underlying Pocomoke aquifer. Alternatively, the fine-grained subriver bottom sediments may effectively lower the average hydraulic conductivity of the aquifer.

Indian River South

The Columbia aquifer in the Indian River south area drains into Indian River and several small streams (Iron Branch, Wharton's Branch, and unnamed streams). Flow-net model results are approximately 1.5 to 3 times greater than the water-budget model results. The greater difference occurred when the smaller basin size was used as input to the water-budget model. The difference appears to be due to a distorted cell shape (caused by a long shoreline). It is also possible that some flow may come from outside the basin or that some flow is recharging deeper aquifers. The observed gradients do not indicate that the fine-grained sediments underlying Indian River are effectively lowering the average hydraulic conductivity of the aquifer.

Summary

There are several plausible reasons for the differences between the results generated by the two models. In the cases where the flow-net model results nearly equal to the minimum water-budget model results (Indian River Bay South Shore), a smaller basin size (created by excluding areas that drain into ephemeral streams), or a lower ground-water discharge rate (due to a higher rate of evapotranspiration) may have been responsible for the results. In the cases where the flow-net model results exceeded the water-budget results, a smaller cell size (shorter shoreline) and/or a lower hydraulic conductivity value were necessary to bring the results in line. It is also possible that some or all of the excess water is flowing to a more distant discharge area and/or deeper aquifers; or, that some flow comes from outside the basin.

Overall, the total discharges generated by the two models are generally in agreement considering the number of assumptions used in the models. There are however, significant differences in some of the individual areas or subareas, indicating that one or both of the models is not valid for these areas. At present, there are no data that conclusively demonstrate which model produces the better results. Field measurements of streamflow, ground-water levels, and ground-water quality on land and beneath the Bays are needed to better understand what is happening.

POSSIBLE IMPROVEMENTS

Data Needed to Improve Model Accuracy

As with many simulations, accuracy is improved by more exactly representing field conditions. Additional estimates of hydraulic conductivity, and more control points for determining aquifer thickness are needed to improve the accuracy of the model. The model also needs to be calibrated with field data. Calibration requires knowledge of the position and character of the fresh water-salt water interface, a more detailed evaluation of the water-table configuration, and data on the three-dimensional aspects of the flow field.

Other Models

Stegner (1972) constructed a Hele-Shaw model to simulate the fresh water-salt water interface for a cross-section extending through Rehoboth Bay to the ocean. He found that the results of the simulations were not reproducible and quantitative estimates of discharge generated by the model could not be rigorously calibrated.

A digital model will be more accurate than the flow-net model used in this study only if it can more accurately simulate the flow field. This would require small scale aquifer inhomogeneities and geometrical complexity to be incorporated in the model. Furthermore, the Columbia aquifer is part of a larger three-dimensional aquifer system characterized by a three-dimensional flow field.

At present, there are very few available and documented digital models that will directly simulate a fresh water-salt water flow system. SUTRA and AQUIFEM-SALT are two readily available, well documented models. SUTRA (Voss, 1984a) can simulate such a flow system as a two-dimensional cross-section with either a sharp or a diffuse interface. AQUIFEM-SALT (Voss, 1984b) can simulate such a flow system in two dimensions with a sharp interface. At present, three-dimensional models that simulate the fresh water-salt water interface are in the development stages. Reilly and Goodman (1985) and Essaid (1986) summarize the status of modeling of the fresh water-salt water flow problem.

An intensive search and study of available models should be completed before any digital modeling is attempted. Besides documentation and availability, some other necessary considerations for choosing a digital model are: how does the model treat solute transport, transient conditions, pumping wells, and areally variable recharge; are program files easily altered; and, can the model be coupled to an optimization model for water resources management purposes?

CONCLUSIONS

The results of water-budget and flow-net models predict that fresh ground water is flowing into Rehoboth and Indian River bays at an average rate of 21 to 43 million gallons per day. The models used the best available data to calculate the discharge rate. However, the accuracy of model calculations is uncertain because of a number of simplifying assumptions inherent in the models and deficiencies in the input data. In any case, the predicted rate of ground-water discharge is significant and useful in application to study of the water budget of Rehoboth and Indian River bays.

The models predicted different discharge rates in some areas. Overall, the total discharges generated by the two models are not too different considering the number of assumptions used in the models. There are however, significant differences due to the way in which the models represent field conditions and the underlying assumptions of the models. It is not always possible to determine which model produces the better results because of a lack of field data with which to calibrate the models or check the validity of the underlying assumptions. A systematic data collection effort is needed to improve the accuracy of any ground-water model to be used in the Inland Bays area.

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Appendix

Aquifer Characteristics.

Area	K range (ft/day)	K average (ft/day)	i range	i average	b range (ft)	b average (ft)	Unit Flux (ft^3/s)	Shorelength (ft)	Basin Area ($miles^2$)	Shorelength/ Basin Area (1/ft)
Rehoboth Bay Basin										
Rehoboth Bay									(a)	(a)
North Shore	50-125	87.5	.0091-.00096	.0045	46-96	68	25.8	23,471	6.01	1.35×10^{-4}
left			.0063-.0022	.0036	46-80	63	20.0	11,405	3.27	1.25×10^{-4}
middle			.0063-.0022	.0042	57-96	76	27.9	5,673	1.79	1.14×10^{-4}
right			.0091-.00096	.0050	55-79	67	29.5	6,393	0.95	2.41×10^{-4}
Rehoboth Bay									(b)	(b)
North Shore									3.19	2.52×10^{-4}
left									1.37	2.98×10^{-4}
middle									0.87	2.34×10^{-4}
right									0.95	2.41×10^{-4}
Angola Neck										
east	75-85	80	.0019-.00077	.0013	100-115	107	11.1	13,440	1.78	2.71×10^{-4}
west	75-140	115	.0009-.0007	.0008	100-130	115	10.8	13,693	2.06	2.38×10^{-4}
Long Neck										
north	75-150	100	.0018-.0008	.0014	80-140	110	15.4	23,970	4.94	1.74×10^{-4}
east										
Rehoboth Bay Basin		95.6 (c)		.0028 (c)		89 (c)	19.1 (c)	74,574 (total)	15.02 (a) 12.20 (b)	2.04×10^{-4}(a,c) 2.34×10^{-4}(b,c)
Indian River Bay Basin								(a)	(a)	(a)
Long Neck										
south	80-105	80	.0057-.0006	.0031	95-115	105	26.0	28,788	7.90	1.31×10^{-4}
east	50-100	75							0.23	
Indian River Bay South Shore										
total	75-125	109	.0040-.00032	.0019	85-125	105	20.6	76,798	21.17	1.30×10^{-4}
Cedar Neck	100-125	112	.0031-.00089	.002	85-95	90	20.2	15,486	1.61	3.45×10^{-4}
White Neck	50-125	87.5	.0026-.00032	.0015	100-120	110	16.5	37,197	9.23	1.44×10^{-4}
Champlin Neck	100-125	112	.0029-.0008	.0019	85-125	105	22.3	24,115	8.23	1.05×10^{-4}
White Creek	100-125	112	.0026-.0017	.0022	90-100	95	23.4	6,992	2.10	1.20×10^{-4}
								(b)	(b)	(b)
total								44,904	9.77	1.69×10^{-4}
Cedar Neck								12,800	1.61	2.85×10^{-4}
White Neck								18,350	5.41	1.22×10^{-4}
Champlin Neck								11,284	2.75	1.47×10^{-4}
Piney Neck	140-190	160	.0036-.0012	.0022	105-130	115	40.5	27,153	4.26	2.28×10^{-4}
Dumpling Neck	90-125		.0016.-0028	.002	110-140	125	27.5	12,829	1.28	3.59×10^{-4}
Indian River									(a)	(a)
north	105-150	125	.0019-.001	.0015	90-110	100	18.8	24,254	5.67	1.53×10^{-4}
south	80-120	100	.0018-.001	.0014	100-120	110	15.4	12,363	1.47	3.02×10^{-4}
									(b)	(b)
north									3.65	2.38×10^{-4}
south									0.75	5.91×10^{-4}
Indian River Bay Basin		116 (c)		.0020 (c)		106 (c)	23.1 (c)	182,185 (a) 150,291	41.98 (a) 27.84 (b)	1.96×10^{-4} 2.55×10^{-4}
Average:										
Rehoboth Bay and Indian River Bay basins		105 (c)		.0024 (c)		99 (c)	21.4 (c)			
Total (a)								256,759(a)	57.0(a)	1.99×10^{-4}(a,c)
Total (b)								224,865(b)	40.0(b)	2.46×10^{-4}(b,c)

Notes:

b (thickness) determined from total thickness of unconfine dequifer minus thickness of included clay layers. i (gradient) determined from 20-foot, 10-foot, and 5-foot water-table elevation contours in areas away from streams. See text for discussion.

See methods section for descriptions of types (a) and (b).

(c) Denotes average value.