

Report on Groundwater Flow Beneath
Coastal Salt Marshes

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Submitted to:
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This report concerns the results of the study of groundwater beneath salt marshes only. Therefore, it is not to be taken as a complete report on the Truro Groundwater Study. It is intended to be integrated into the Truro Groundwater Report as a portion of the overall study.

PREFACE

The following is a final progress report on the study of the fresh-salt ground water transition zone beneath coastal marshes. The study has been funded sequentially through the University of Massachusetts National Park Service Cooperative Studies Unit via funds from the National Park Service and by the Water Resources Center of the U.S. Geologic Survey. Funding from the National Park Service commenced in June of 1974 and continued through the end of July, 1974. These funds were intended as seed money to get the project initiated and were supplemented by funds from the U.S. Geologic Survey from the period August 1974 through December 1974. Therefore, the project was in an intermediate stage at the time of transition from funding by the National Park Service to funding from the U.S. Geologic Survey. The results presented in the following report are identified in terms of their funding source. However, it would be exceedingly foolhardy to ignore the results of the U.S. Geologic Survey portion of this project in formulating the results and conclusions of this study. Therefore, information and results obtained during the period of research funded by the U.S. Geologic Survey are incorporated within the following report. Finally, additional data analysis was carried (at no expense to either the National Park Service or to the Geologic Survey) which yielded the equipotential and flow diagrams which are critical to the overall understanding of the problem. These results have been reported at a Northeastern meeting of the Geological Society of America in March of 1975 at Syracuse and at the June meeting of the American Geophysical Union. In that these results

have been published and are important to the overall conclusions of the study, they too are included in this report.

ACKNOWLEDGMENTS

The authors of this report wish to express their appreciation to the following individuals for their assistance and advice to this study. Mr. Tom Rice of the Department of Geology and Geography, University of Massachusetts, provided stimulating discussions and was extremely kind in assisting in much of the field work in this project. Mr. Harry Pegg of the University of Massachusetts gave invaluable assistance in constructing the special well points needed for this study. Mr. Peter Johnson and Mr. Clyde Beatty provided great assistance in the field work. Dr. M. Frimpter of the U.S. Geologic Survey provided valuable discussions and suggestions during this study. Dr. P. Godfrey, of the University of Massachusetts National Park Service Cooperative Studies Unit was instrumental in initiating the funding of this project and arranging for the use of critical instruments. Superintendent L. Hadley and Mr. James Killian of the Cape Cod National Seashore provided critical logistical support for this research, including the use of a field laboratory. Dr. Peter Mangarella of the Ocean Engineering Program and the Civil Engineering Department of the University of Massachusetts worked closely with the authors of this report and contributed most heavily to the determinations of the instantaneous flow diagrams and their understanding, which are presented in this report. Dr. George E. McGill, Acting Chairman of the Department of Geology and Geography at the University of Massachusetts during the time of this study kindly permitted the use of the Wang 2200 programmable computer used in reducing some of the data.

INTRODUCTION

As population densities increase within coastal areas, the problem of limited ground water resources becomes a significant factor in planning the growth and management of coastal lands. The outer portions of Cape Cod, Massachusetts provide an excellent example of a finite ground water supply which has the potential for becoming overtaxed as settlement and demands for fresh water within the area increase. Many decisions lie ahead in regard to allocation of ground water resources within the areas of the Outer Cape which are cohabitated by the towns of Provincetown, Truro, Wellfleet, Eastham, Orleans, and the Cape Cod National Seashore. Important decisions concerning the allocation of the ground water resources located beneath town lands and beneath park lands lay in the immediate future. In order for these decisions to be appropriately formulated by the managers of the Cape Cod National Seashore, many environmental factors must be explored.

One potential environmental effect of increased withdrawal of ground water from the inland portion of the Outer Cape is interaction of fresh ground water and salt ground water along the coast. This may be particularly important in areas of salt marshes in that the importance of salt marshes as primary nutrient producers for estuarine life is well known. However, the interaction of the two bodies of ground water in the vicinity of coastal salt marshes has never been studied in detail. Therefore, a detailed field study of the ground water transition zone beneath coastal salt marshes was begun during the summer of 1974. The peat underlying the salt marshes of the Outer Cape vary in thickness from more than 80 feet to less than 3 feet. These marshes also vary

enormously in their areal extent. The method of well drilling and emplacement (described in detail later in this report) necessitated the selection of thin and relatively small salt marshes so that the well points could be located substantially beneath the marsh peats and within the underlying fluvial glacial sands which constitute the coastal aquifer. Initial probing of the coastal salt marshes within the Town of Truro indicated peat thicknesses which were too great for the 20 foot capacity of the well drilling apparatus. Therefore, salt marshes in other areas were probed until two were found which were characterized by relatively thin deposits overlying the sandy aquifer and limited areal extent. These areas were selected as natural scale models of the flow patterns to be predicted for the larger but less manageable marshes located throughout the outer portions of Cape Cod. Finally, an additional area in Eastham was selected as a control. This area consisted of a sandy beach and offshore area without peat salt marsh deposits.

A total of 30 wells were installed within these study areas. They varied in depth from 2.5 feet to 17.5 feet and were distributed in the area along vertical transects so that variations in salinity and head levels at various tide stages would provide a measure of subsurface flow and how this flow varied.

FIELD PROCEDURES

The equipment and instruments which we used for the study shaped the planning of the individual field projects and strongly influences the scale of the results of the research. Therefore, a detailed description of the equipment, instruments and procedures used in the field is provided so that the strength and limitations of the results of this study can be fully appreciated.

The main tool for the study of ground water flow in the transition zone beneath salt marshes consists of specially designed shallow wells which would provide the ability to monitor both changes in head and changes in salinities at the location of the well point. These wells were constructed of either P.V.C. or A.B.S. 1 1/2" inside diameter plastic pipe to avoid chemical contamination of any of the water samples. The length of these wells varied according to the maximum length of holes which could be drilled or the desired elevation of the well point. The wells were especially designed to incorporate a lower sampling chamber which would isolate it from the water within the rest of the well stem. This device is shown in Figure 1. The isolated well point permitted the sampling of a small volume of water from the bottom of the well which would not be diluted or otherwise altered in chemical salinity by the water in the rest of the well stem. Thus, small changes in the salinity over a tidal cycle could be monitored if they existed.

The wells were installed through the use of a 5-horsepower Haynes power auger with a total capacity of 20 feet of 2 inch diameter auger

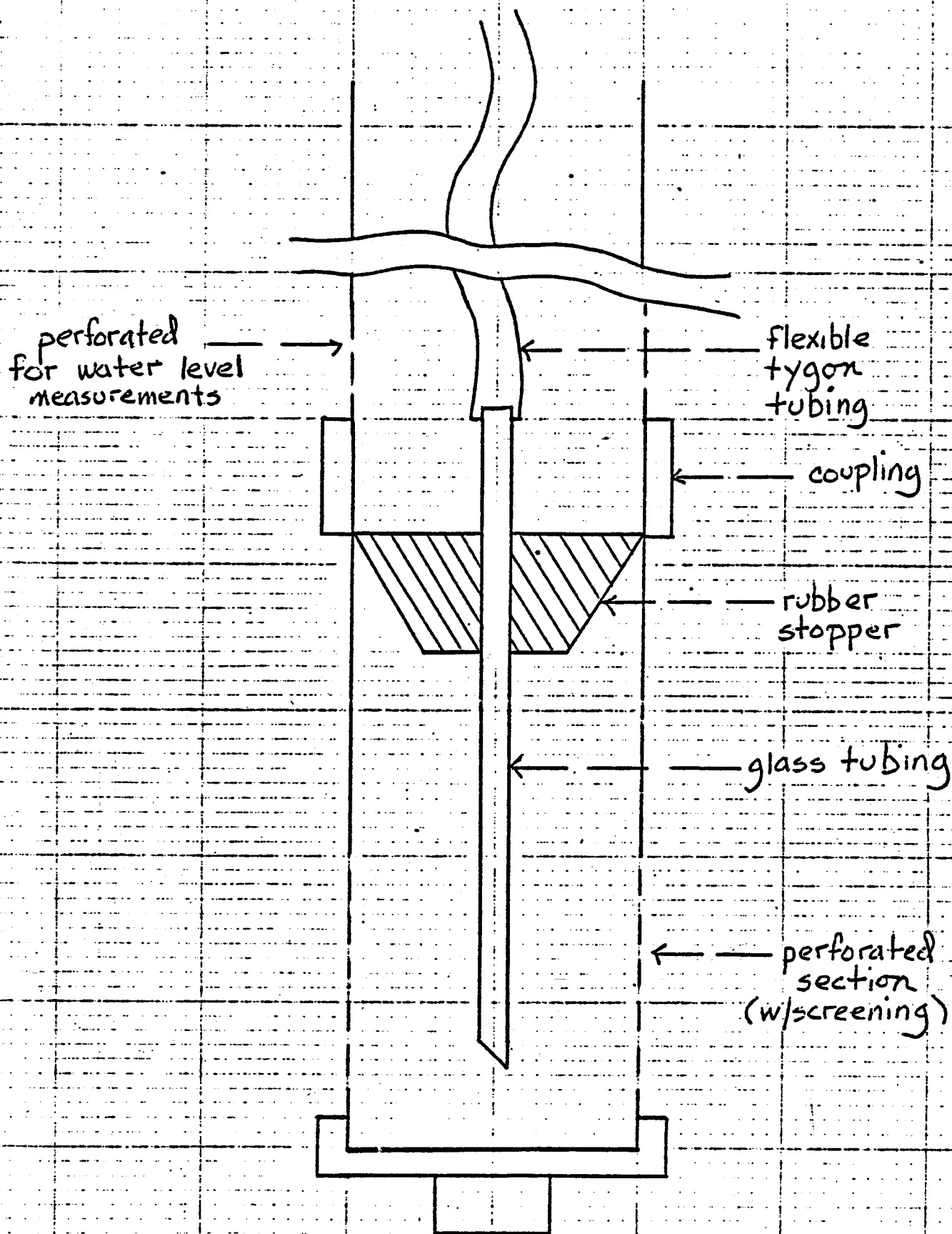


Figure 1. Schematic drawing of the plastic well stems used in this study. Note the small volume isolated sample chamber located at the base of the well stem. Water for salinity samples was withdrawn from this chamber via the then plastic hose leading up the well stem.

flight. This apparatus proved satisfactory to install wells to a depth of 17.5 feet. The procedure consisted of drilling a hole in the salt marsh or adjacent tidal flat with the powered auger to approximately 3 feet more than the depth of wells desired. The auger flight was then rapidly removed from the hole and instantly replaced with a plastic well pipe.

Upon completion of installation of all wells within a well field the absolute elevation of the wells was determined by optical surveying from a U.S. Geologic Survey elevation benchmark. The well head elevations were monitored during the summer of 1974 and during January of 1975 through the use of a steel tape against the previously determined elevation of the top of the plastic well stem. Salinities were monitored during these periods by withdrawing small samples of water from the isolated well points and measuring the salinity values through the use of a Yellow Springs Instruments model 33 STC meter. This instrument was available from the Cape Cod National Seashore and was calibrated on numerous occasions against AgNO_3 titrations. The estimated error in the precision of salinity values measured in this manner is plus or minus 0.5%..

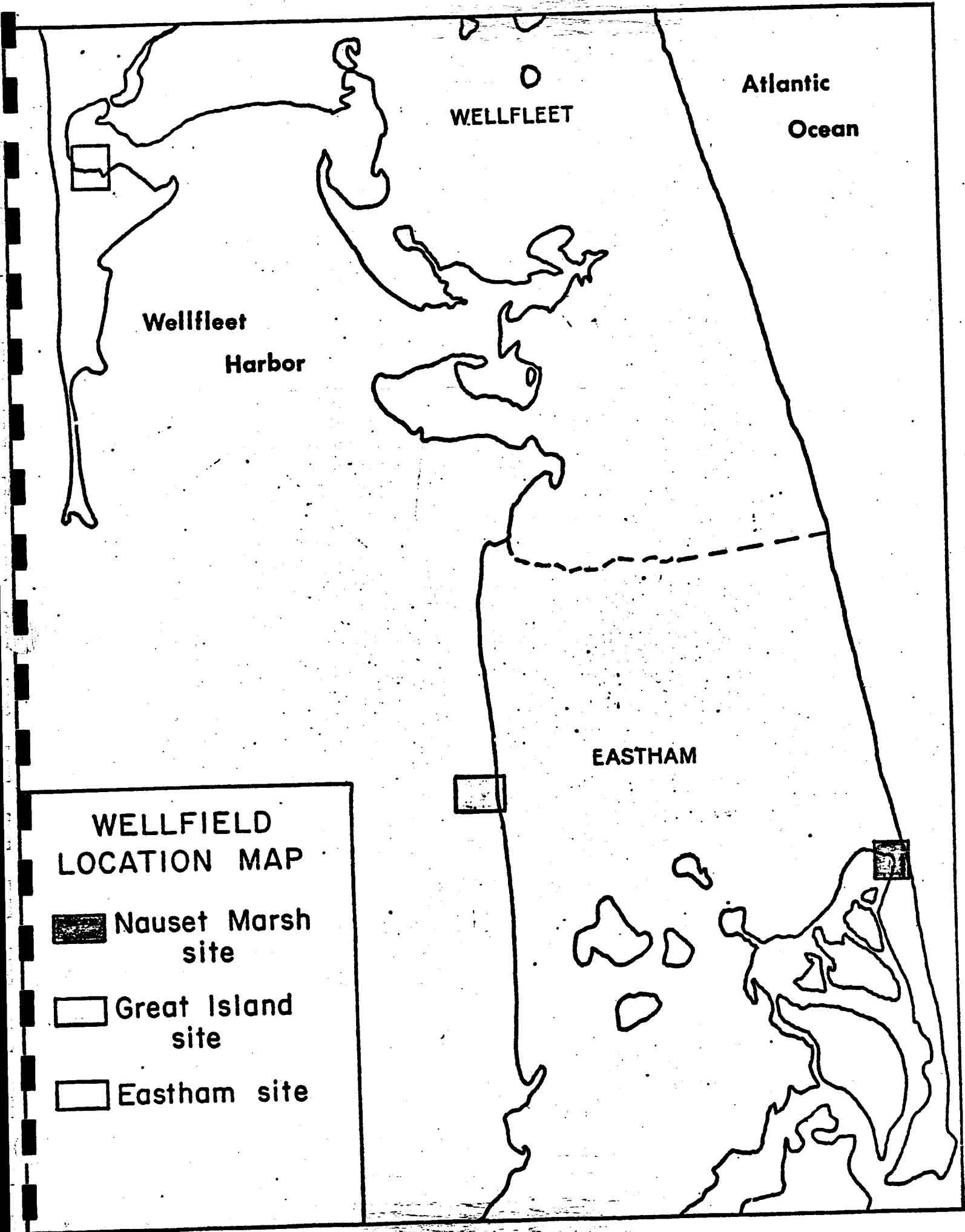
At some of the well sites there was concern that surface water may leak along the outside of the well stem to contaminate the in situ ground water at the well point. Experiments were conducted to determine whether this event actually occurred. Fluorescein dye was injected beneath the ground surface next to a well at the Nauset Well field. After high tide on several occasions the water was pumped from the well point and no trace of fluorescein dye was ever encountered. This

YSE-33
calibration

indicates that the seal between the outer portion of the well stem and the surrounding strata was sufficient to eliminate the possibility of downward leakage.

FIELD AREAS

The location of the three well fields is shown on Figure 2. These areas are referred to as the Nauset Marsh Site, The Great Island Marsh Site, and the Eastham Site. During the portion of this research which was funded by the National Park Service, the well field at Nauset Marsh was installed and preliminary work at the Great Island Marsh Site had begun. The Nauset Marsh Site consisted of an area of marsh peat and marsh grass approximately 100 feet wide located along the southern edge of a steep scarp on the hill which is occupied by the Nauset Life Saving Station. The hill and deposits underlying both the marsh and adjacent estuary consists of medium sized fluvial glacial and marine sands with some gravels and cobbles intermixed. Overlying these fluvial glacial and marine deposits in the area of the marsh there is an organic peat layer with a maximum thickness of approximately 6 feet. In the area beyond the seaward edge of the marsh an organic mud deposit, approximately 6 feet in thickness, overlies the fluvial glacial and marine sands and functions as an aquiclude over the entire area of intertidal and subtidal estuary bottom which was explored in this study. Eight exploration wells were drilled along the transect from the base of the sandy bluff, across the marsh, and out into the estuary. The total length of this well field transect was approximately 210 feet. The lithology and well locations in this area are shown in Figure 3. This well field was the only one which had been completed at termination of the National Park Service funding. Results and interpretation of these results are given later in this report. It should be pointed out that the marsh was originally selected for its



Nauset Marsh Wellfield

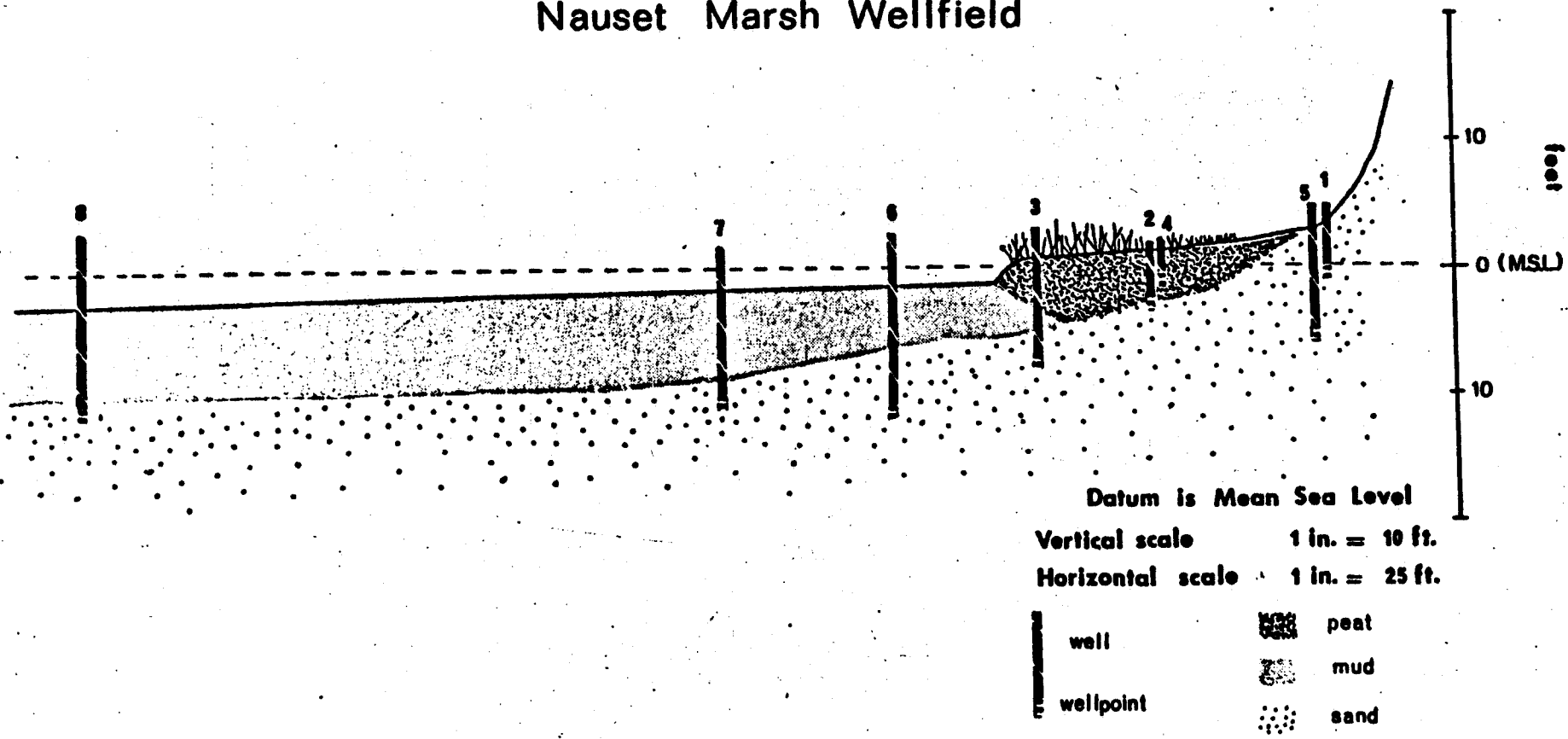


Figure 3. Nauset Marsh lithology and well field in cross section.

small size and relatively thin peat deposits. However, it became apparent that the organic mud deposits which floored the intertidal and subtidal regions of the adjacent estuary provided a hydrologic barrier to the flow of fresh water into the estuary. Therefore, the results from the study of this marsh were of uncertain value in a general extrapolation of the nature of the ground water transition zone beneath salt marshes in the Cape Cod area in that it was not entirely representative of most marsh areas. Therefore, further explorations were carried out to locate a second marsh area where the conditions of size and thickness of the organic peat were similar to that of the Nauset Marsh Site but the organic mud deposits were absent.

The second marsh site selected for the overall study was located at Great Island inside of Wellfleet Harbor. This marsh is located just south of the area known as The Gut and extended from a low sandy bluff, across a marsh and marsh peats, and well onto the intertidal sand flats of Wellfleet Harbor. The sandy aquifer which made up the bluff behind the study area and the underlying deposits beneath the marsh and adjacent intertidal areas consisted of glacial fluvial sands overlain by more recent marine deposits. Nevertheless, the sandy aquifer appeared to have uniform hydrologic characteristics throughout the transect. The marsh at this location is approximately 270 feet wide and occupies the upper portion of the well field transect. The marsh peats are generally less than 3 feet in thickness in this area. A total of 14 wells were located along this transect in the overall study. However, at the time of the completion of the National Park Service funding only approximately 7 of these wells had been located.

The overall length of the well field transect is 800 feet and extends from approximate locations of high high water to the approximate location of low low water across both the marsh and the adjacent sandy intertidal area. The lithology and location of individual wells in the completed well field are shown in Figure 4.

After the termination of the National Park Service funding, discussions of the project were carried out with Dr. M. Frimpter of the Water Resources Division of the U.S. Geologic Survey. These discussions proved valuable in determining that a third well field should be installed in an area without marshes to act as a control area. Therefore eight shallow exploration wells were located along the Eastham shoreline of Cape Cod Bay. Lithologies and locations of these wells are given in Figure 5.

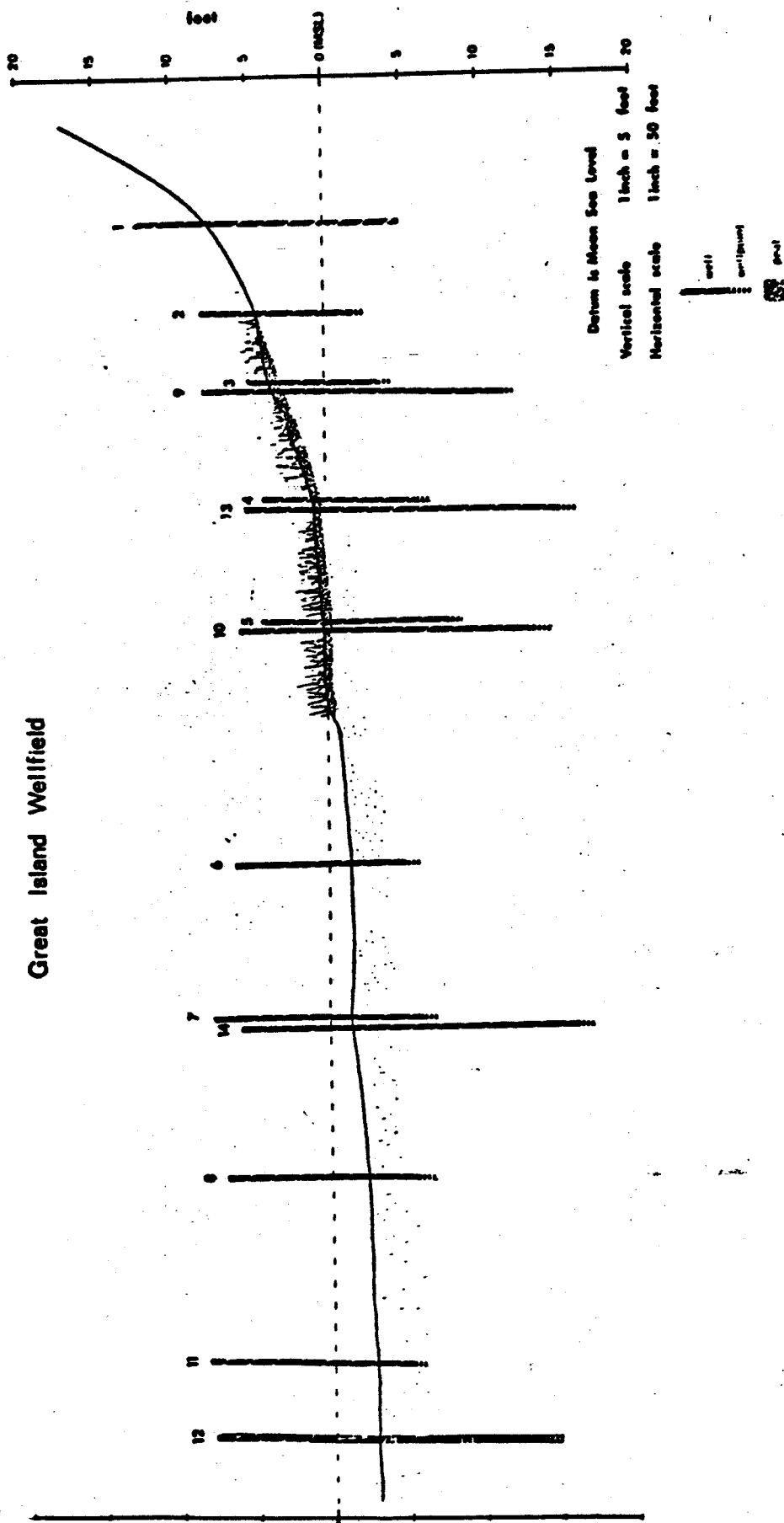


Figure 4. Great Island Well Field

Eastham Wellfield

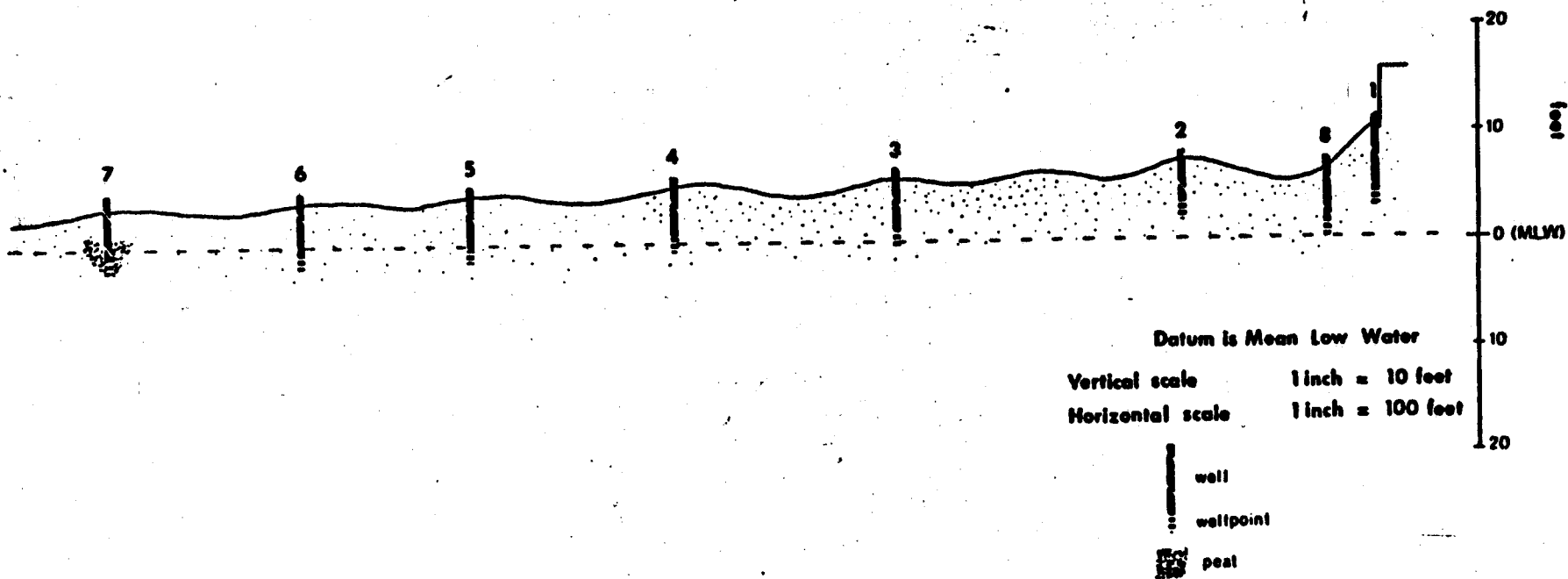


Figure 5. Eastham Well Field - Lithologies and well locations.

PROGRESS TO THE TERMINATION OF NPS FUNDING

As indicated in the introduction of this report the overall research project was sequentially funded by the National Park Service and the U.S. Geologic Survey. At the time of termination of the National Park Service funding of this project the Nauset Marsh Site was complete and the Great Island Well Field was partially installed. Therefore, results from the Nauset well site were the only ones which were essentially complete. This is not viewed as significant in that Geologic Survey funding had been arranged by this time and it was clear that the project would continue to its completion. However, for the benefit of this progress report the partial results available at the termination of National Park Service funding are given separately to indicate the significance of the latter work in developing an overall understanding of the processes which dominate the groundwater transition zone beneath coastal salt marshes.

Measurements of the salinity values at the eight wells of the Nauset Marsh Site well-field were conducted and these data are shown in Figure 6. The salinity of the open estuary water was 30 parts per thousand. A zone of high salinity is seen to infiltrate the marsh peats and extend a few feet downward into the underlying fluvial glacial and marine sand. However, the distribution of salinities at depths of more than 5 feet beneath the marsh surface indicates brackish to almost fresh values. Clearly a strong flow develops from beneath the land which carries a large discharge of fresh water beneath the marsh and the organic muds of the estuary floor. This strong fresh water flow partially entrains

Nauset Marsh Wellfield

Salinity Values

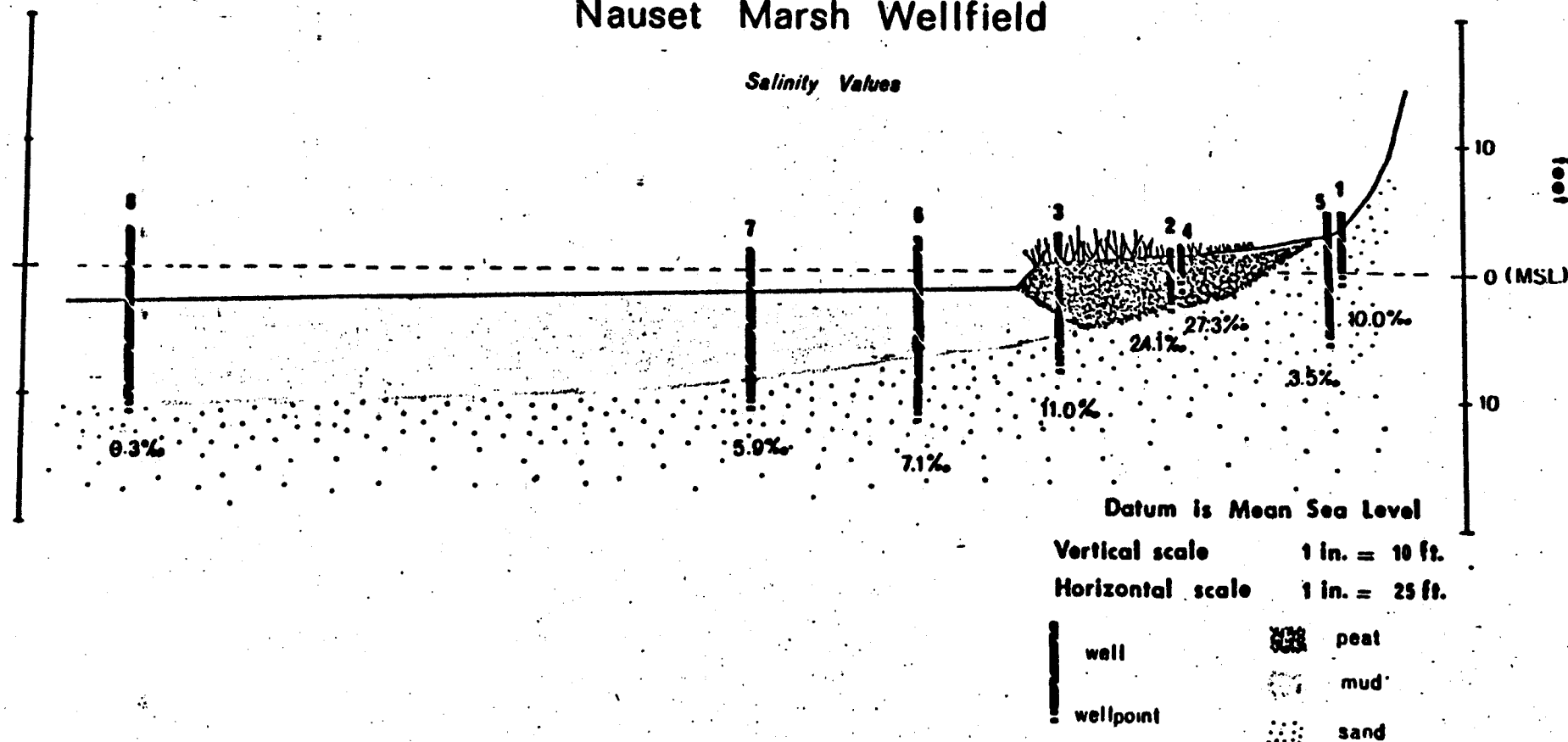


Figure 6. Salinity Values at Nauset - Cross section diagram.

the salt water which enters the aquifer via downward percolation through the marsh peats. The downward percolation of salt water through the marsh peats occurs only in times of high tide whereas the flow of fresh water from beneath the land is continuous. The volume of fresh water flowing through the aquifer appears to be much greater than the volume of salt water flowing downward through the marsh peats. Thus the salt water is quickly diluted by the fresh water flow and essentially fresh water is carried by the aquifer to a distance of at least 400 feet offshore beneath the organic mud aquiclude.

Were this study terminated at this point it is clear that the inference would be drawn that salt marshes and their associated peat deposits have little effect on the flow of fresh water beneath them. Indeed, the existence of the organic mud aquiclude has a dominant influence in this hydrologic situation. The organic mud prevents fresh water from entering the estuary and causes this fresh water to flow offshore to an unknown extent. Presumably where the organic mud layer is breached by tidal channels the fresh water escapes from the underlying aquifer. However, it must be stressed that it was fully realized that these results were inconclusive and incomplete at the time of termination of the National Park Service funding. Therefore, additional field work study and data analysis was carried out to complete the overall study. The results of this overall research project are given in the following two sections of this report.

RESULTS OF THE OVERALL STUDY

As a result of the predicted shift of funds from the National Park Service to the U.S. Geologic Survey this project was carried on in a continuous manner. During the month of August 1974 the well field at the Great Island Marsh Site and the well field at the Eastham control area were completed. The locations of these wells are shown in Figure 2. During January of 1975 a program of hourly sampling of each well in each well field over a tidal cycle was conducted. The results of this sampling program showed that no significant change occurred in the salinity of the water at any of the well points. Minor changes, up to 5%, were observed between salinity values measured during the summer of 1974 and during January of 1975. This indicates that long term changes in the overall flow pattern within the zone of transition may occur. Probable causes for these long term changes are differences in the rate of recharge of the fresh water aquifer and effects of the twice monthly cycle between spring and neap tides. However, these salinity data show that the long term changes are small.

The salinity data for the January 1975 sampling period at the Great Island and Eastham sites are shown in Figures 7 and 8. It is instructive to regard these figures carefully and to attempt to surmise the ground water flow patterns from the distributions of salinities. It will be demonstrated later in the report that such inference concerning the flow of ground water in the transition zone beneath salt marshes is inappropriate. Figure 9 shows the inferred mean flow direction of both salt and fresh water beneath the marsh at Great Island. Notice that the lense of saline water beneath the marsh implies a downward flushing of salt water from the marsh peats. This suggests that water

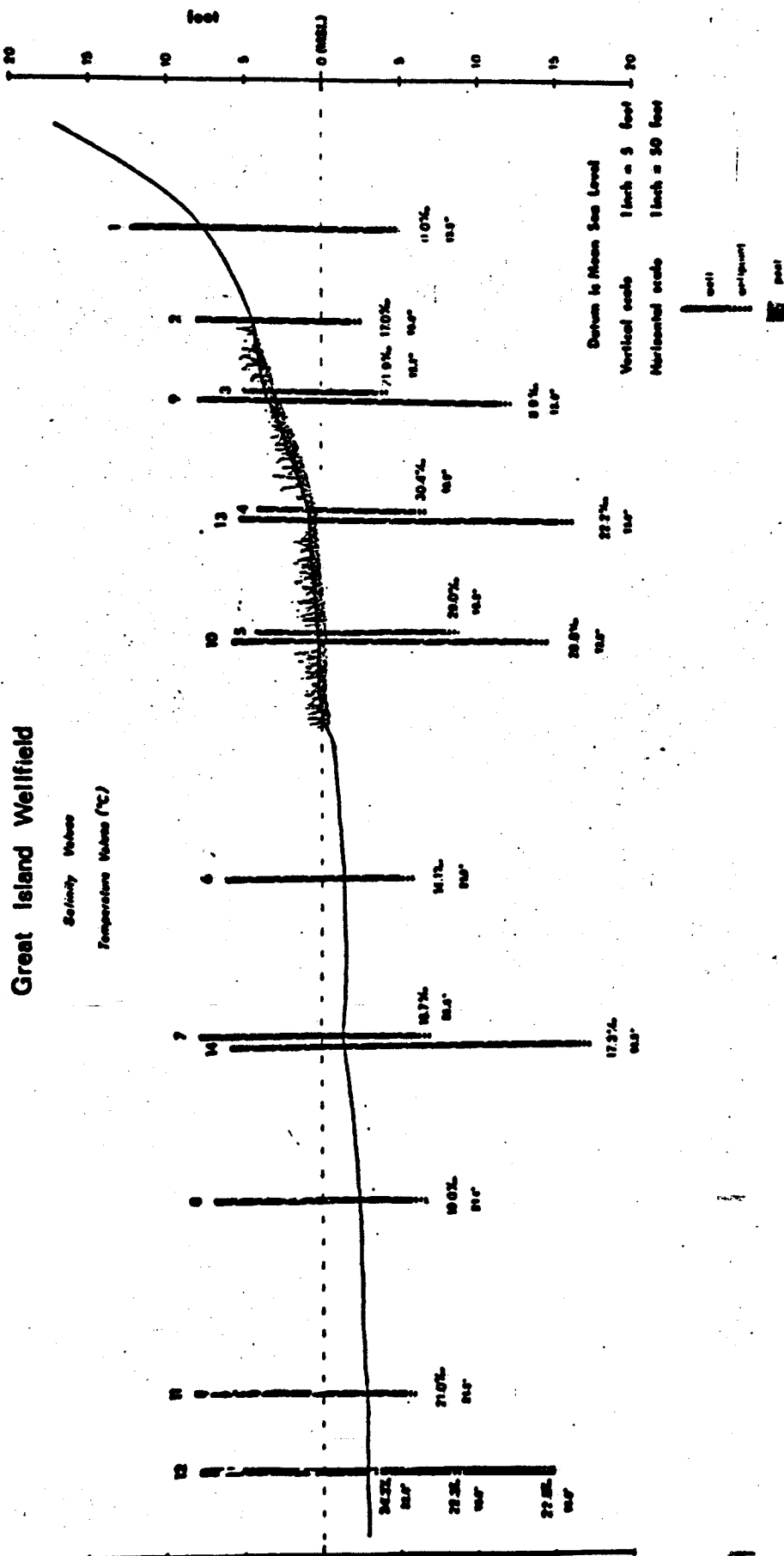


Figure 7. Salinity values at Great Island - cross section diagram.

Eastham Wellfield

Salinity Values

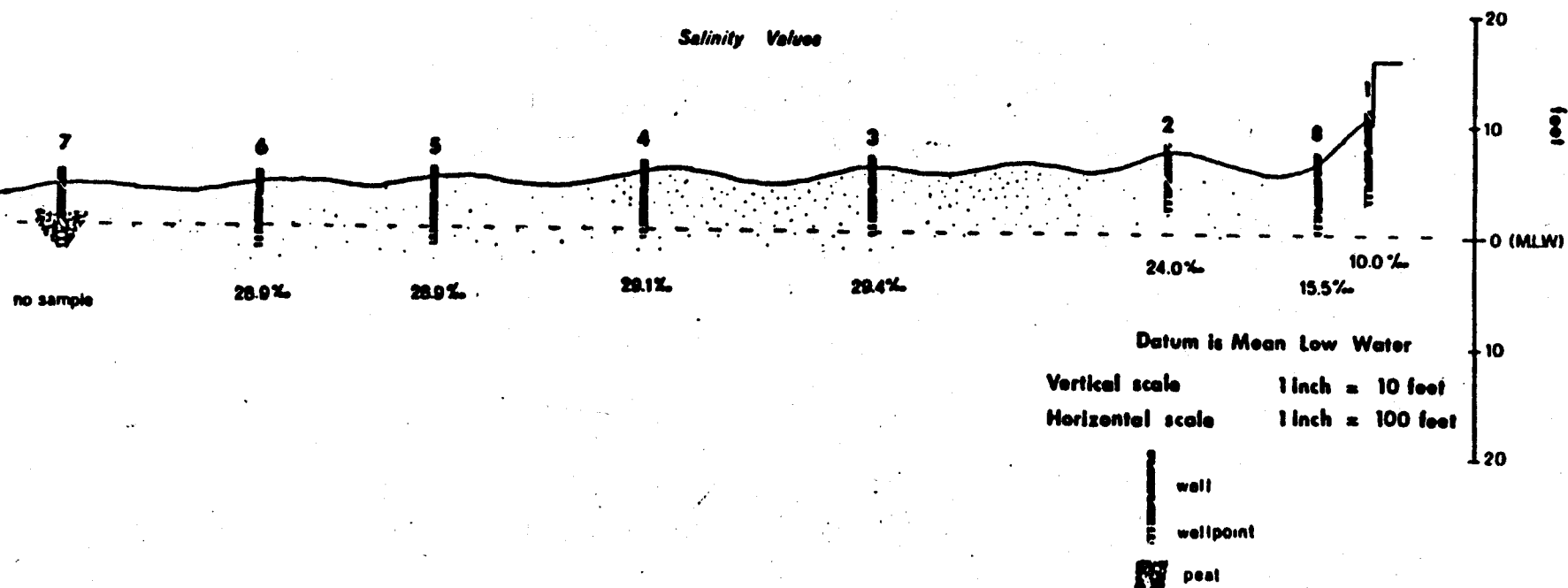


Figure 8. Salinity values at Eastham - cross section diagram.

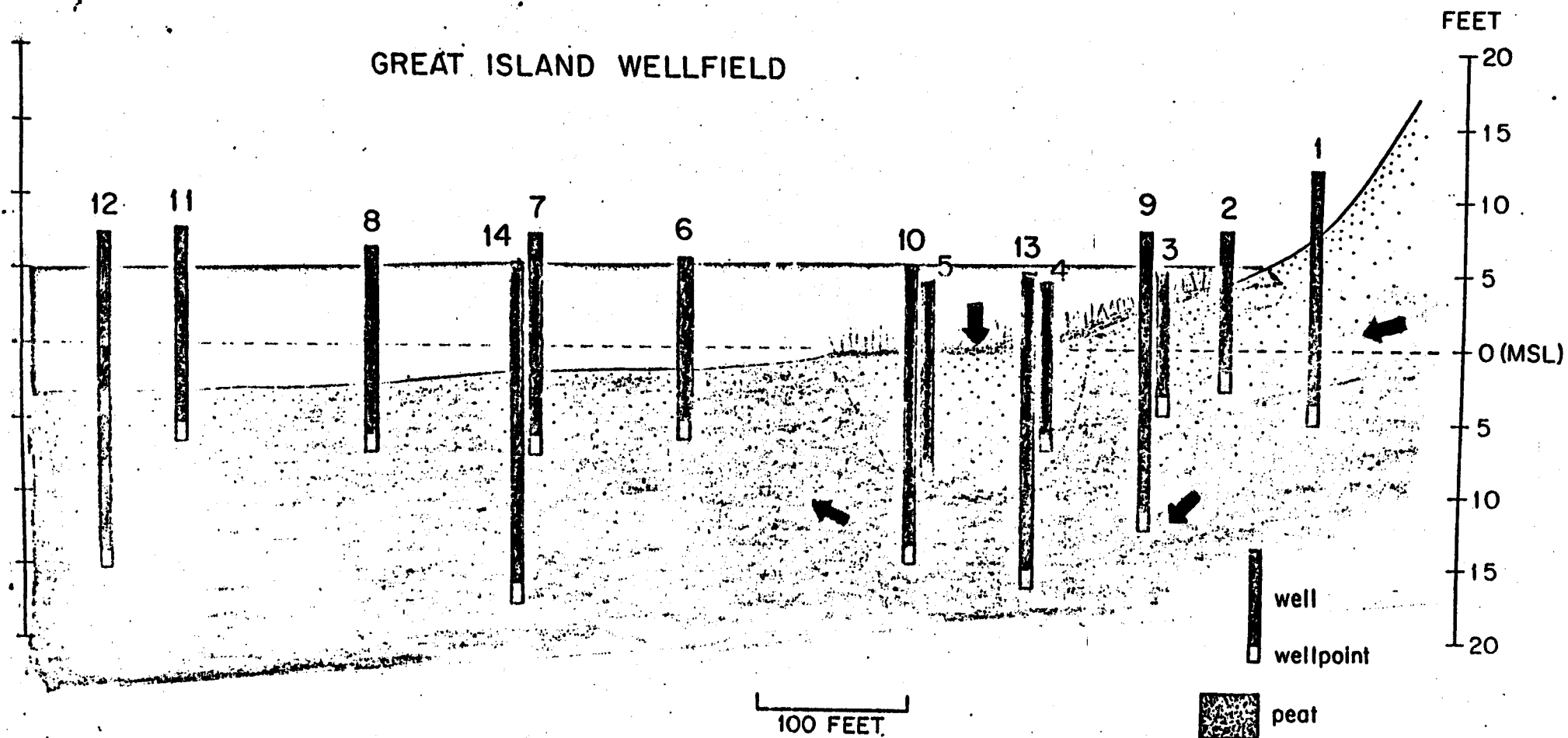


Figure 9. Great Island flow directions inferred from salinity values.

is trapped by the marsh peat and grasses during high tide and drains downward into the aquifer rather than across the surface of the marsh. The existence of water of these salinities beneath the marsh causes a density inversion with more dense saline water above less dense fresh ground water in the area beneath the marsh. It appears that the downward percolation of the dense salt water deflects the seaward flow of the fresh water. It may be inferred that the salt water entering the zone of transition beneath the marsh acts as a partial hydrologic barrier to the fresh water. Such a partial hydrologic barrier then would cause an additional storage capacity of fresh water beneath the land.

A similar pattern appears to develop at the Nauset site. However, the presence of the organic mudflats beneath the estuary waters causes the fresh water to be trapped within the aquifer and pass seaward without substantial mixing with estuarine waters. In the Nauset site area, shown in Figure 10, there appears to be a much more limited influx of salt water percolating downward through the marsh peats. It is significant to note at this time that small head variations in the order of 0.2 of a foot were noticed in the wells numbered 7 and 8 at the Nauset Site. These head variations appeared to be correlated with the rise and fall of the tide within the estuary. This indicates that although the organic mud layer acts as an aquiclude against the mass transfer of water between the fresh ground water and the salt estuarine waters, it still maintains pressure communication between these two zones. Finally, the inference of the shallow wells at the Eastham Site indicates that the zone of transition is much narrower in an area not supporting a coastal marsh system. These data are

NAUSET MARSH WELLFIELD

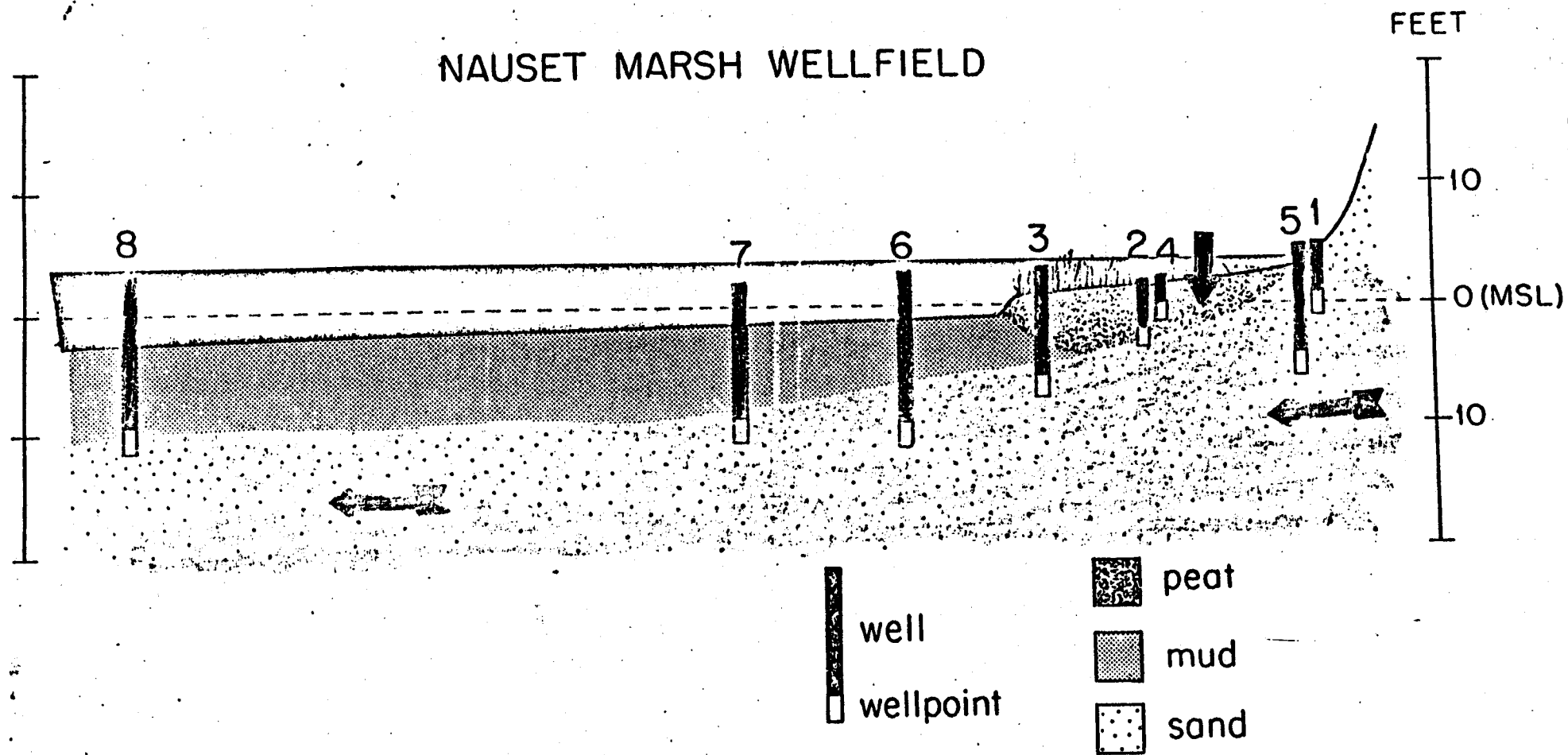


Figure 10. Ground water flow inferred from salinity values at the Nauset Well Field.

shown on Figure 11. In the Eastham Site the seaward portions of the sandy aquifer appear to be entirely saturated with salt water. The fresh ground water from beneath the land mixes with the salt ground water in a narrow transition range. This brackish water leaks out at the surface near the toe of the beachface and flows seaward at low tide as surface seeps. These comparative data appear to indicate that the salt marshes serve to greatly widen the zone of transition between fresh and salt ground water. In addition, the apparent blocking of the seepage of fresh ground water by the high salinity lens beneath the marsh would serve to increase the storage capacity of the aquifer at inland locations. However, it must be realized that inferring net flow directions from the distribution of salinity values is dangerous and subject to error. Therefore, strong conclusions cannot be drawn at this point.

In order to determine the flow velocities within a typical hydrological transect containing a marsh area, the January 1975 data from the Great Island Well Field was analyzed in detail. Rigorous mathematical theories for determining flow velocities from pressure distributions are not currently available in situations subject to significant spatial and/or temporal accelerations of the flow. Therefore, a first procedure necessary for the application of any classical method of determining ground water flow parameters from local head values rested on an approximation of the magnitude of local accelerations. Upon the advice, and with the cooperation of Dr. Peter Mangarella of the Ocean Engineering Program at the University of Massachusetts, the method of Lusczynski (1961) was used to calculate flow velocities and

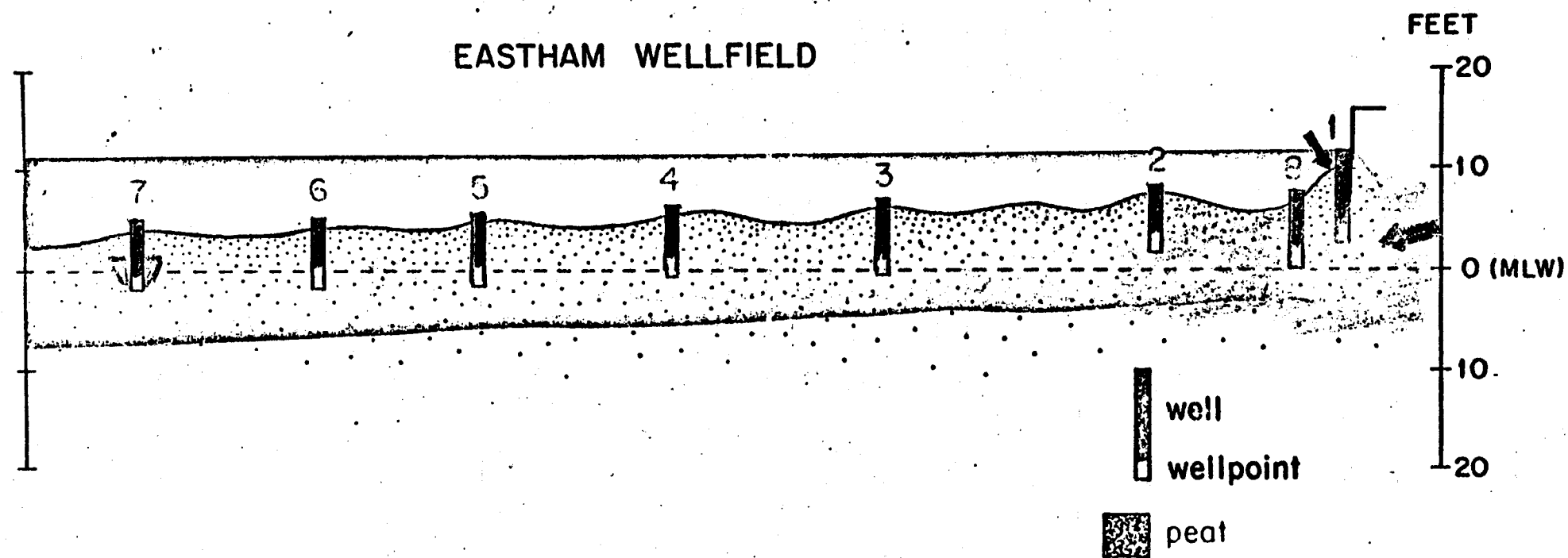


Figure 11. Flow at the Eastham Well Field as inferred by groundwater salinity distributions.

equal potential surfaces for the hourly records of head values and salinity distributions. It was assumed that this method (which is derived from Darcey's Law and therefore is intended for use in the steady state conditions) would not produce significant errors if the accelerations were small. Therefore, as a first approximation, this method was carried out on several sequential hours of data. The method also requires a value for hydrologic conductivity. Value chosen is 0.02 centimeters per second. This value was obtained from De Wiest (1965) for a medium coarse sand which corresponds to the description of the aquifer sands from the Great Island area. The maximum ratio of fluid acceleration to pressure gradient forces calculated in this manner was of the order of 0.00001. Therefore, even in this area where the flow is strongly influenced by rapidly changing tide levels the steady state assumptions of Darcy's law and Lusczynski's method are not significantly violated. It was also determined that owing to the shallow depth of the wells, Lusczynski's method could be simplified without producing more than a 5% error in the calculations of equal potential surfaces. Therefore, the lengthy conversion of observed head values to environmental head values was shortened by converting the observed head values to point water head values. The use of an assumed hydrologic conductivity value and the minor errors introduced by the shortening of Lusczynski's method subject the absolute values of the following computations to an error of at least 10%. However, for the purposes of this research the absolute values are of little significance, but the relative distribution of equal potential surfaces and flow vectors are important.

No substantial relative error is produced by these assumptions.

Figure 12 shows the elevation of the water surface in Wellfleet Harbor over a tidal cycle on the day that the ground water data were produced. Notice that the strong wind during this day caused an asymmetry to the tidal records. Also, the tide tended to remain at its high level for a longer period of time than a classical sine wave would predict. This apparently was also caused by the strong wind set up during that day. Figures 13 through 24 show the equal potential surfaces, flow lines, and flow vectors during 12 hours of the tidal cycle. Notice that the flow pattern inferred from our previous analysis of the salinity data is never realized in these computed flow diagrams. Indeed the suggested downward percolation of salt water from the marsh peats into the underlying sand aquifer is strongly contradicted by the flow data shown in figures 13-24. Figure 25 is a summary diagram showing that the flow within the coastal aquifer over the entire tidal cycle may be divided into two general patterns. These may be named the high tide pattern, and the low tide pattern. These patterns remain essentially constant during half of the tidal cycle with a rather sudden shift from one pattern to the other. During the low tide pattern the flow beneath the marsh is clearly directed upward rather than downward. During the high tide portion of the pattern the flow beneath the marsh is generally directed inland. Therefore we are left with an apparent dichotomy between measured head values and their corresponding computed flows, against the inferred flow from the salinity data. One attempt to rectify this apparent dichotomy involved the computation of the time average mean flow at each measurement point within the Great Island Well Field location. These data are presented in Figure 26. Notice that the

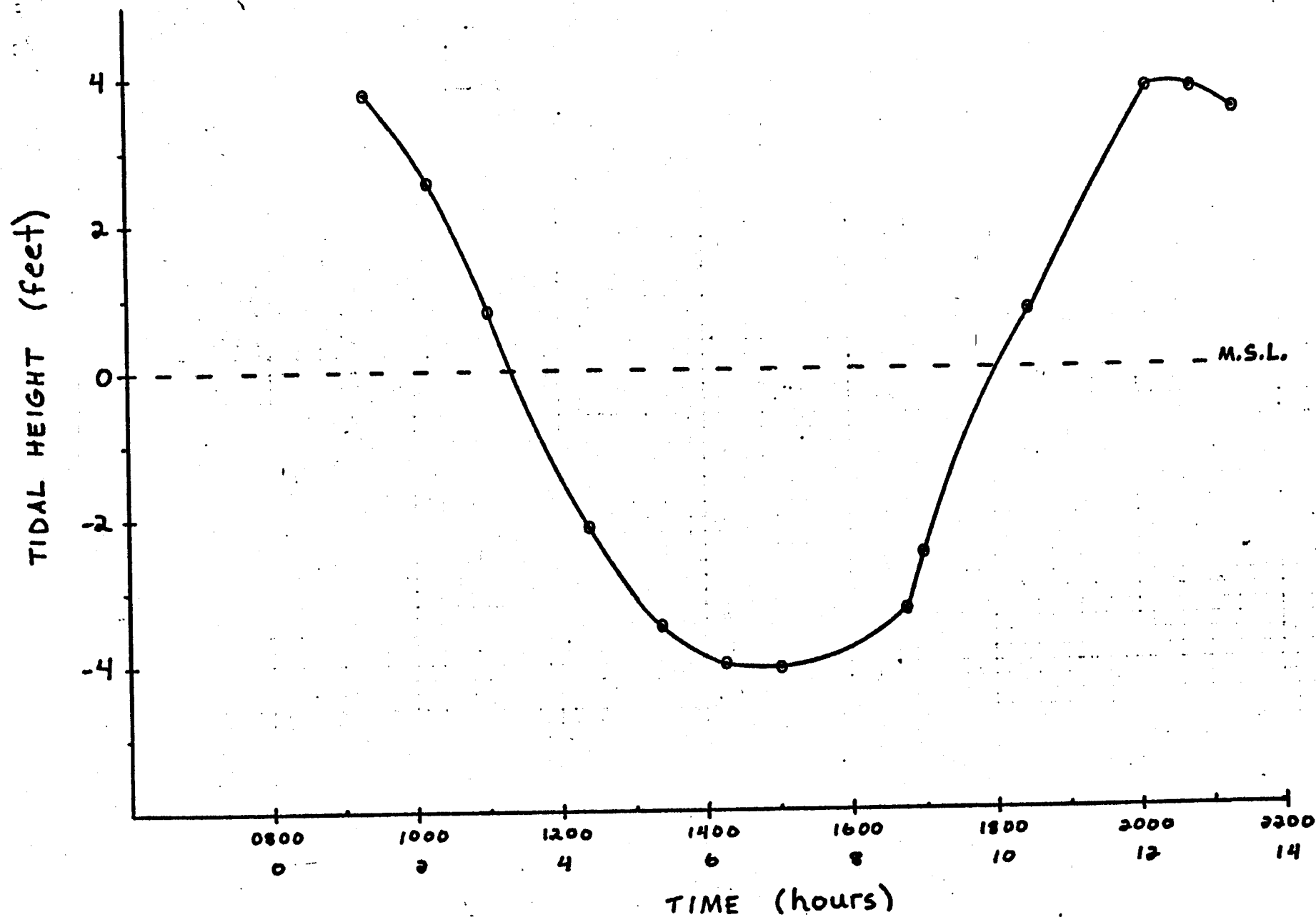


Figure 12. Tide cycle on day of well monitoring - Wellfleet Harbor.

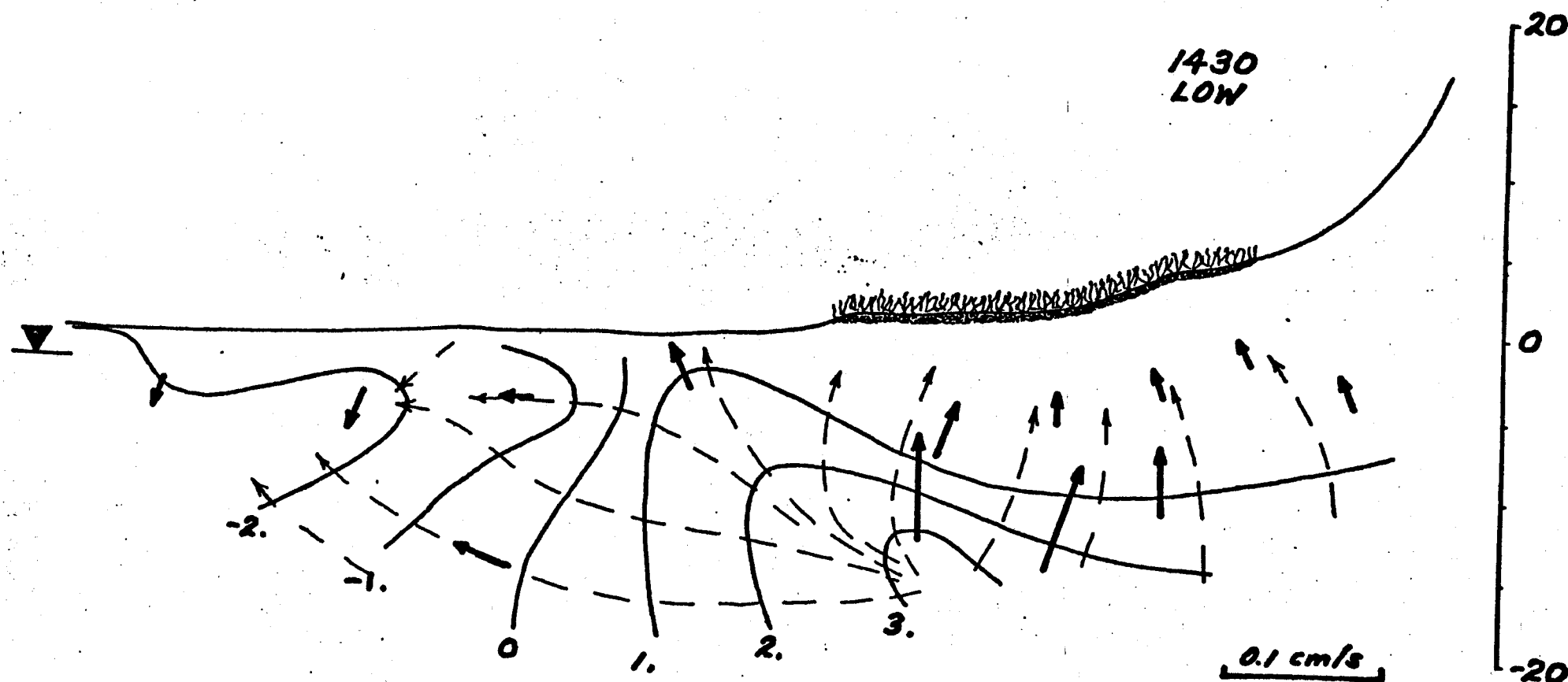


Figure 13. Groundwater flow beneath the Great Island Well Field. The tide level is shown by a triangular carrier. The solid contour lines are equipotential surfaces. The dashed arrows represent flow lines and the heavily lined arrows are computed flow vectors with the velocity scale given at the lower right. Note that the sequence of figures 13-24 is controlled by the tide cycle rather than time.

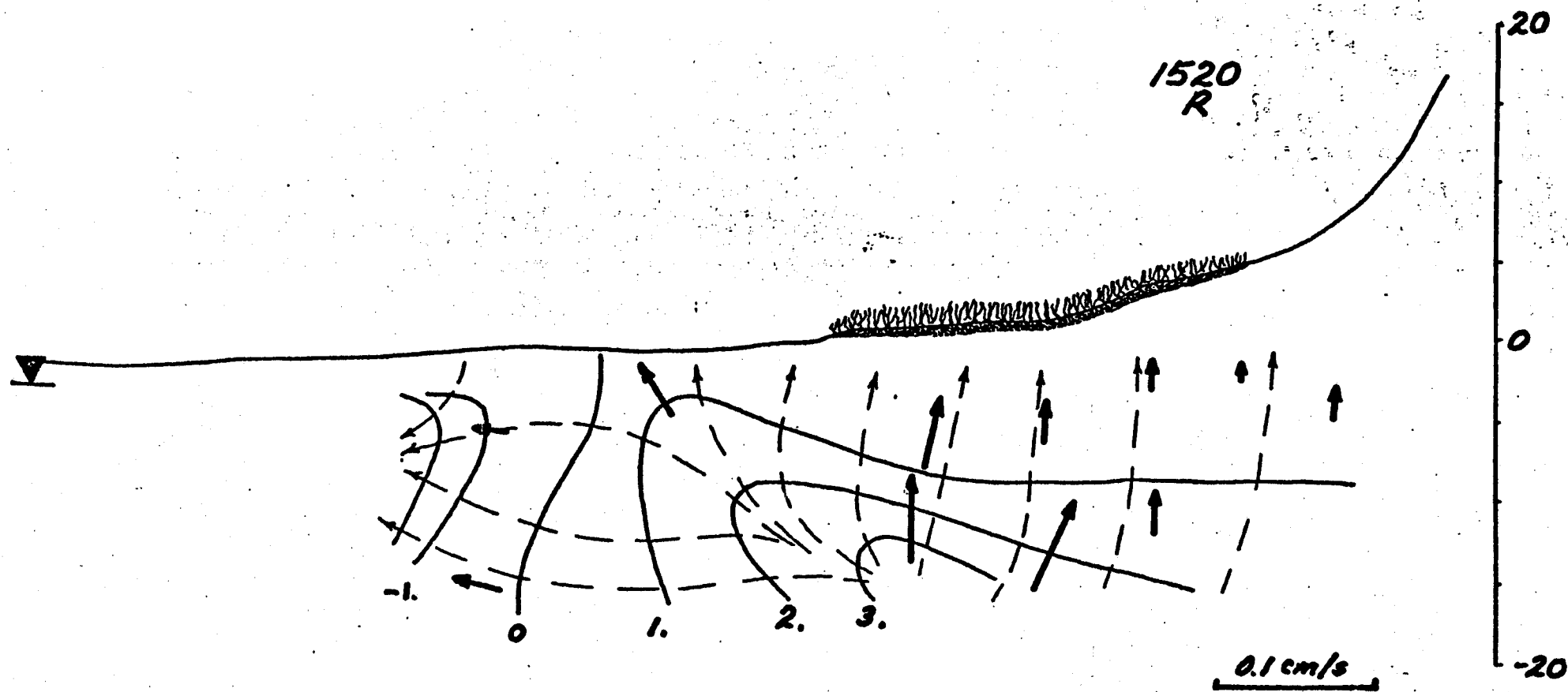


Figure 14. Groundwater flow at the Great Island Well Field. This flow is typical of the low tide flow pattern with upward flow beneath the marsh and upward and seaward flow in the intertidal area.

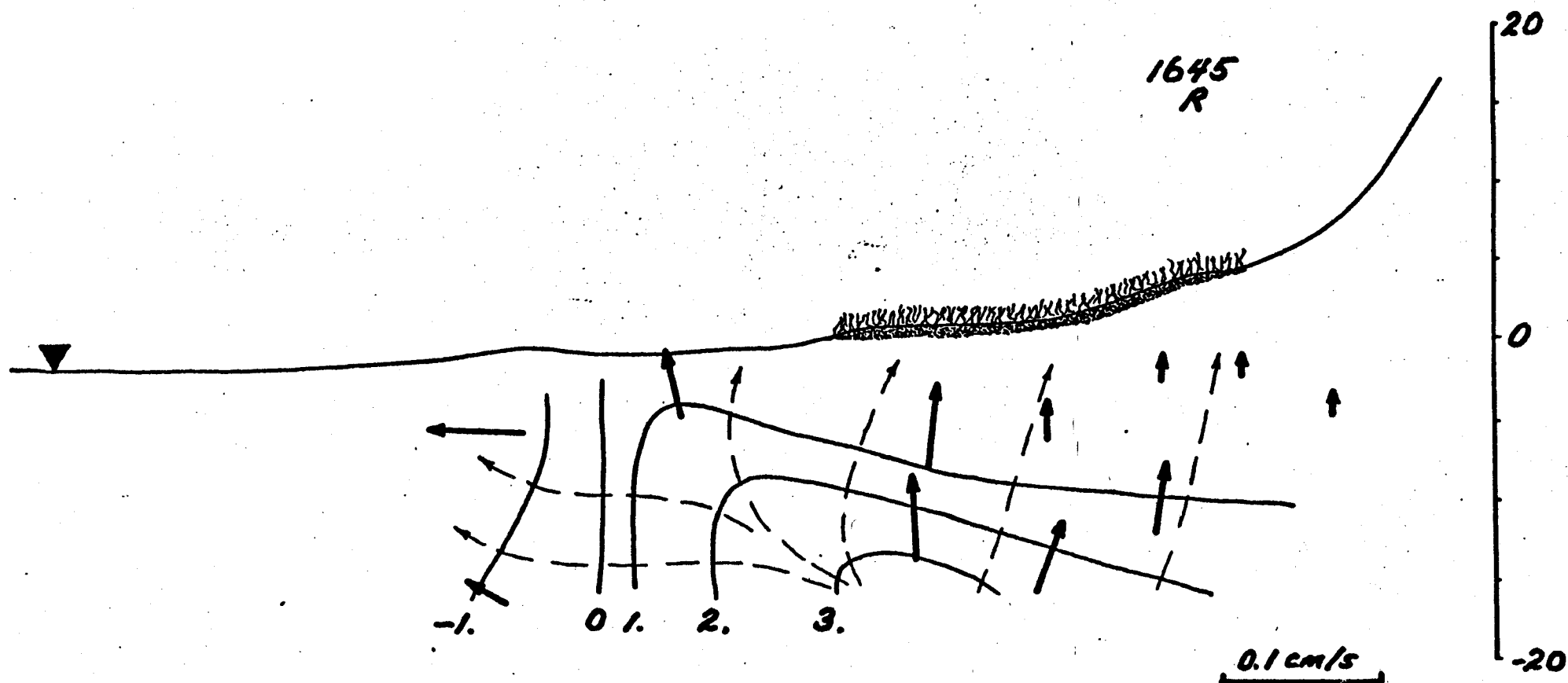


Figure 15. Groundwater flow at the Great Island Well Field. Little change has occurred since the previous hour.

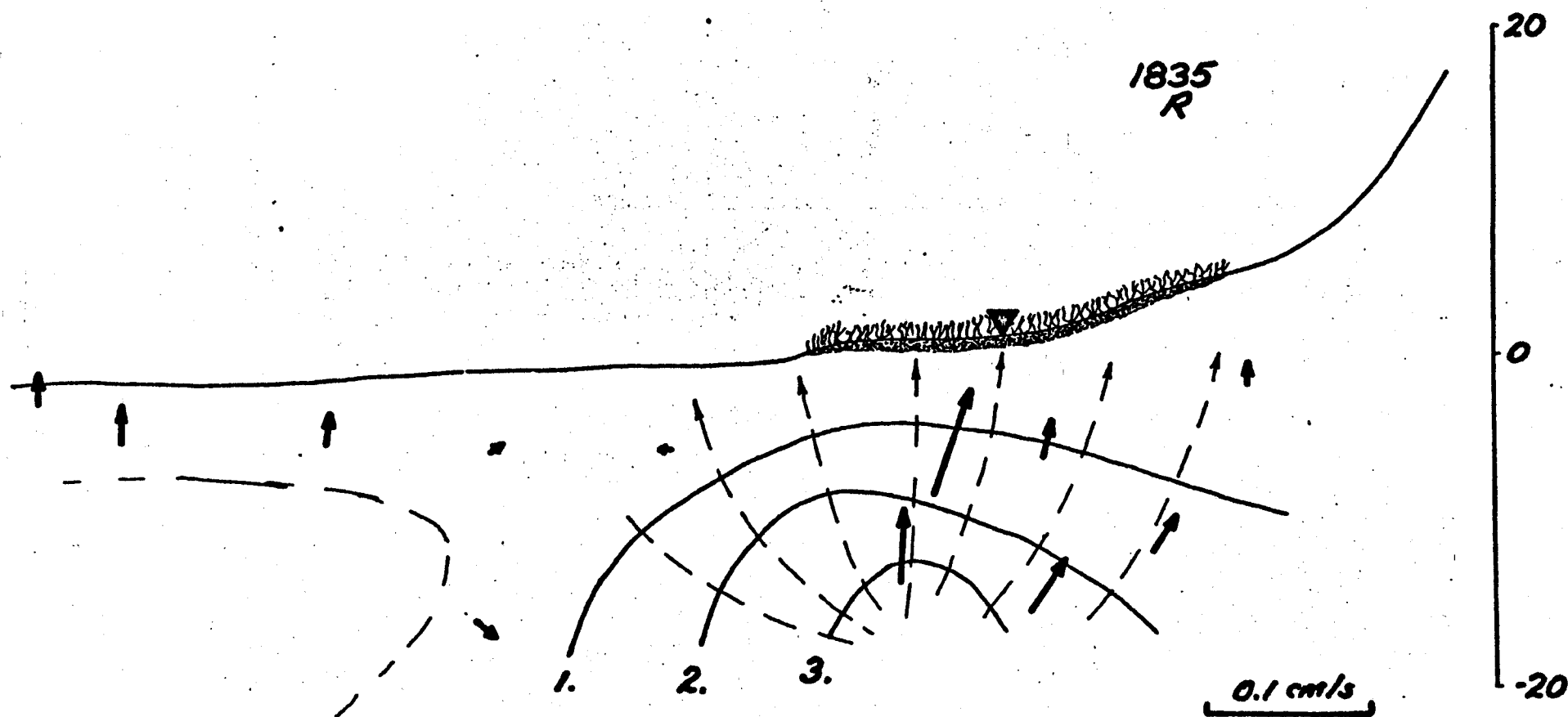


Figure 16. Groundwater flow at the Great Island Well Field. Notice the transition which has occurred since the previous hour. At this time the flow in the intertidal area decreases and changes direction. The first indication of landward flow in the groundwater zone occurs.

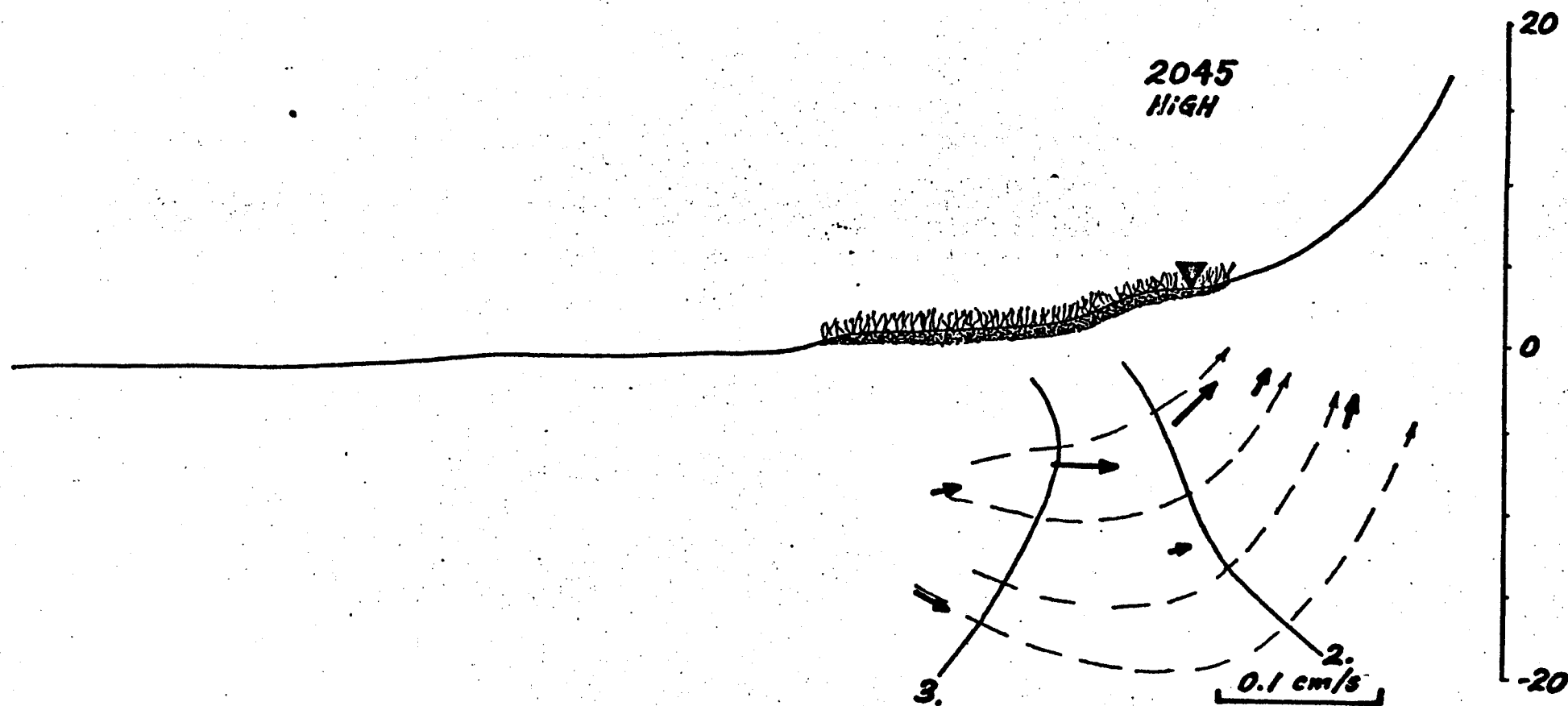


Figure 17. Groundwater flow at the Great Island Well Field. The flow has now changed to the typical high tide flow pattern with definite landward transport beneath the marsh. The large tidal range in this area eliminated the possibility of acquiring data in the intertidal area at this time.

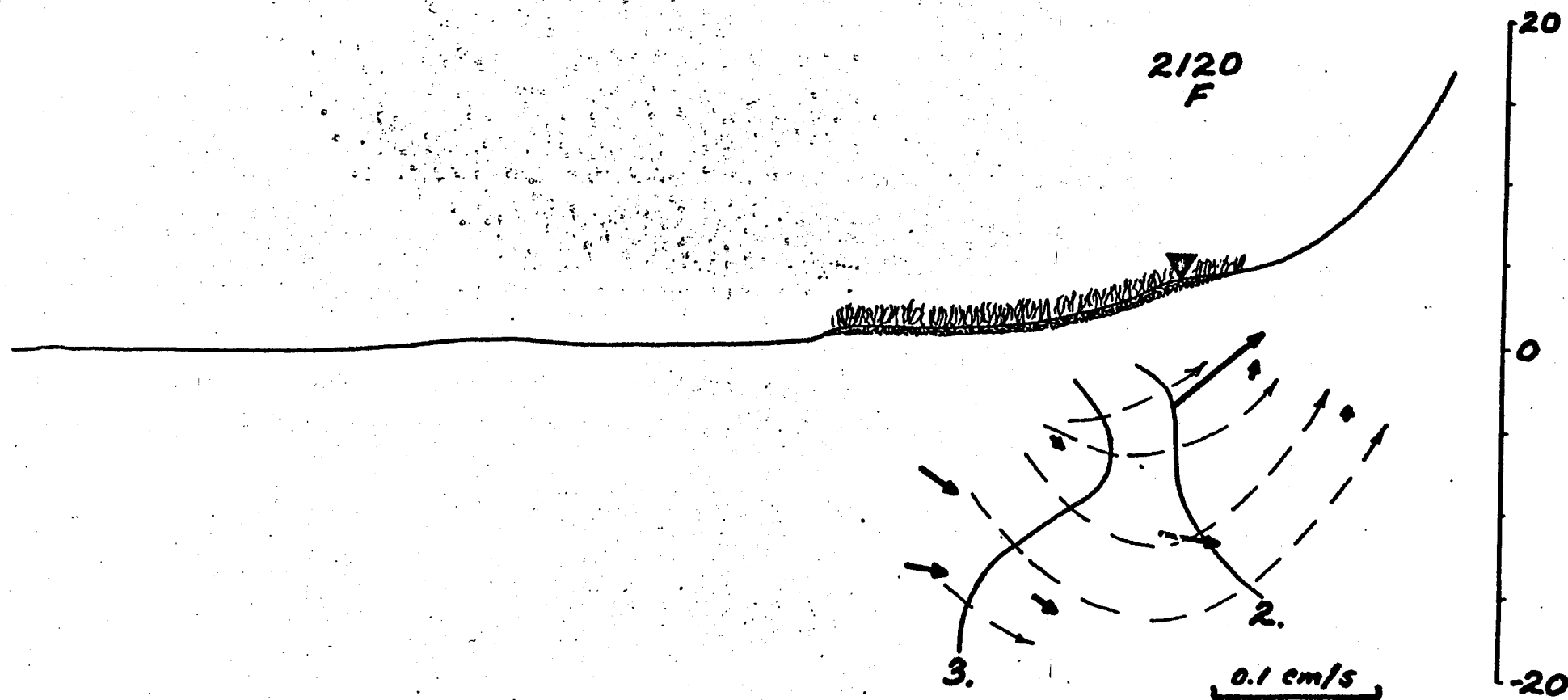


Figure 18. Groundwater flow at the Great Island Well Field. Notice that a downward component of salt water flow has now developed beneath the marsh.

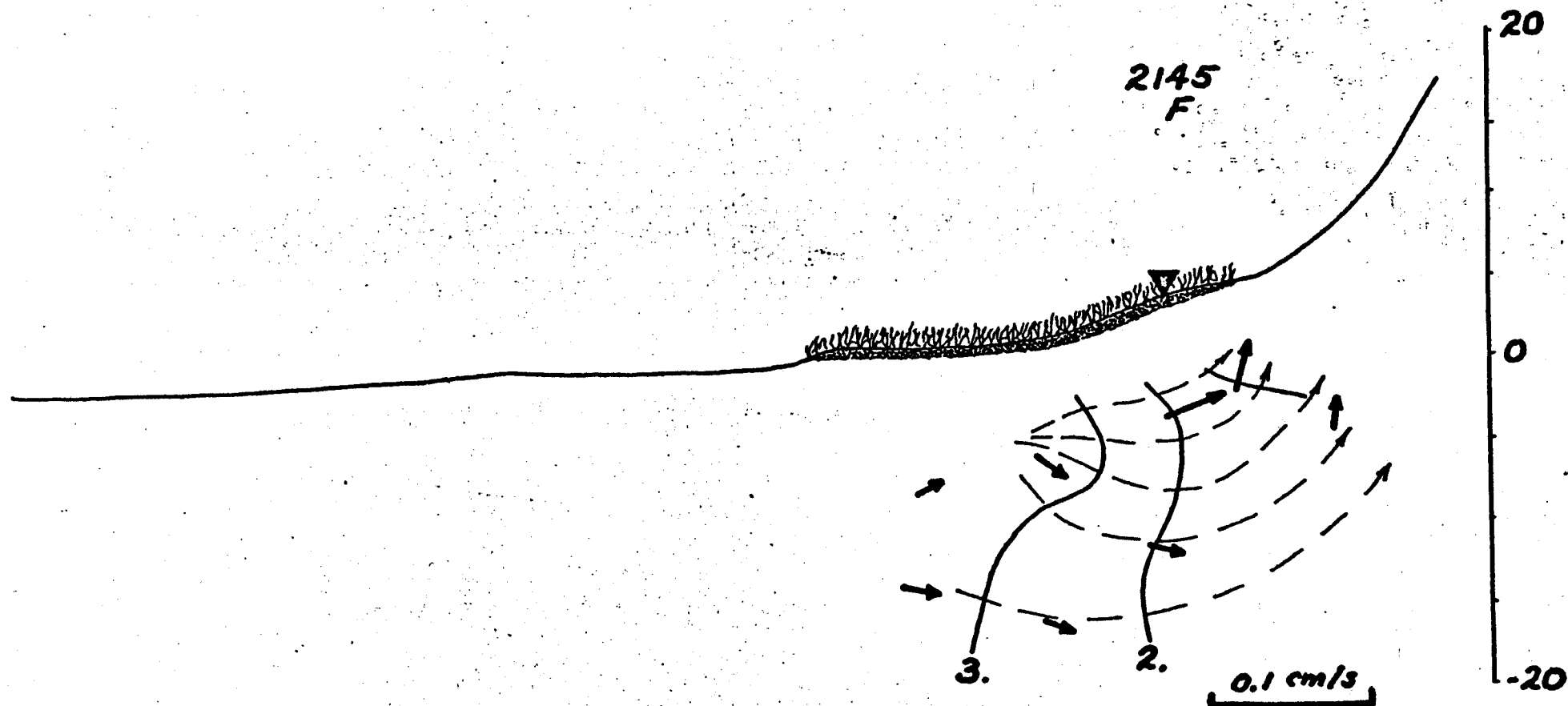


Figure 19. Groundwater flow beneath the Great Island Well Field. This pattern is very similar to the pattern of the previous hour.

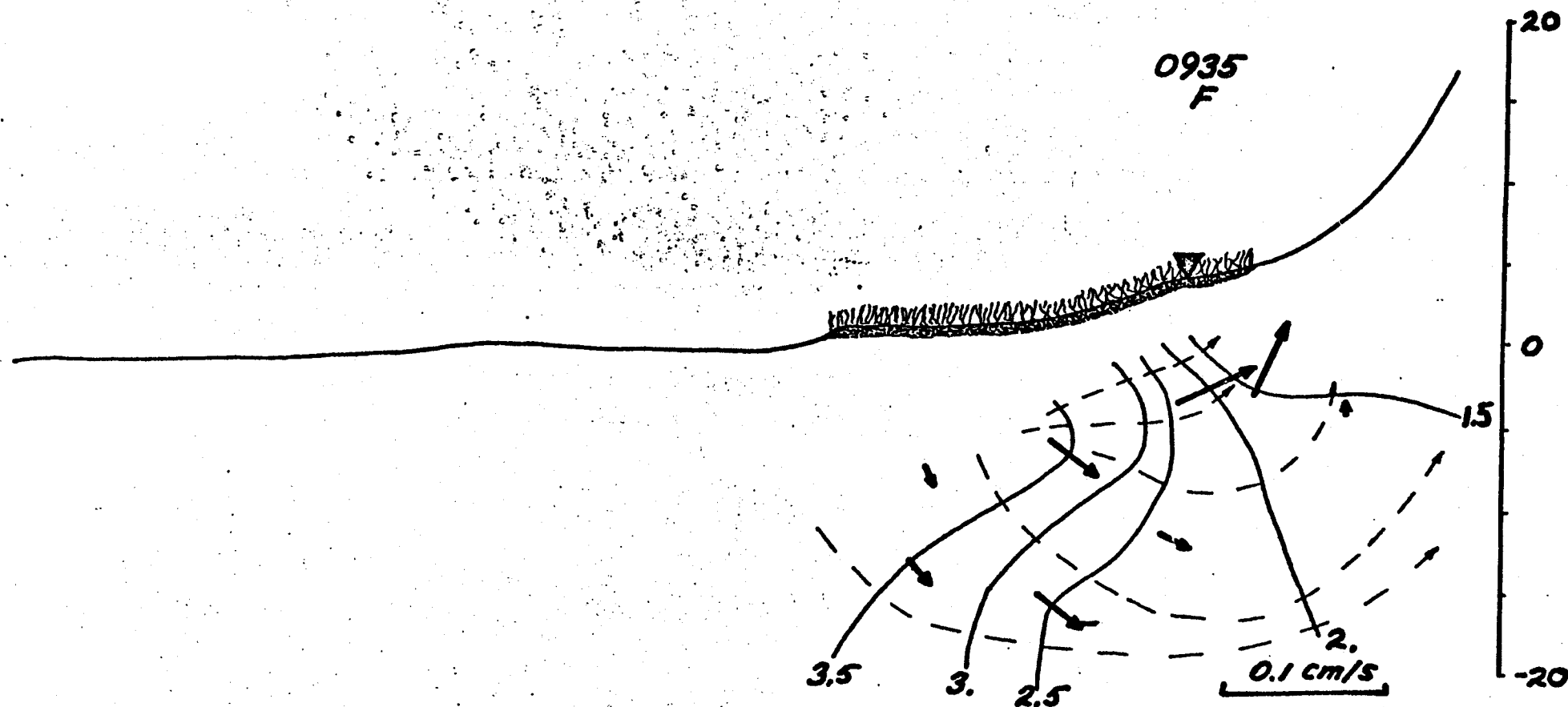


Figure 20. Groundwater flow beneath the Great Island Well Field. Notice the increase in the downward component of flow beneath the marsh. Also notice that there has been a jump in the time representing the fact that these figures are presented in a series related to the tide cycle.

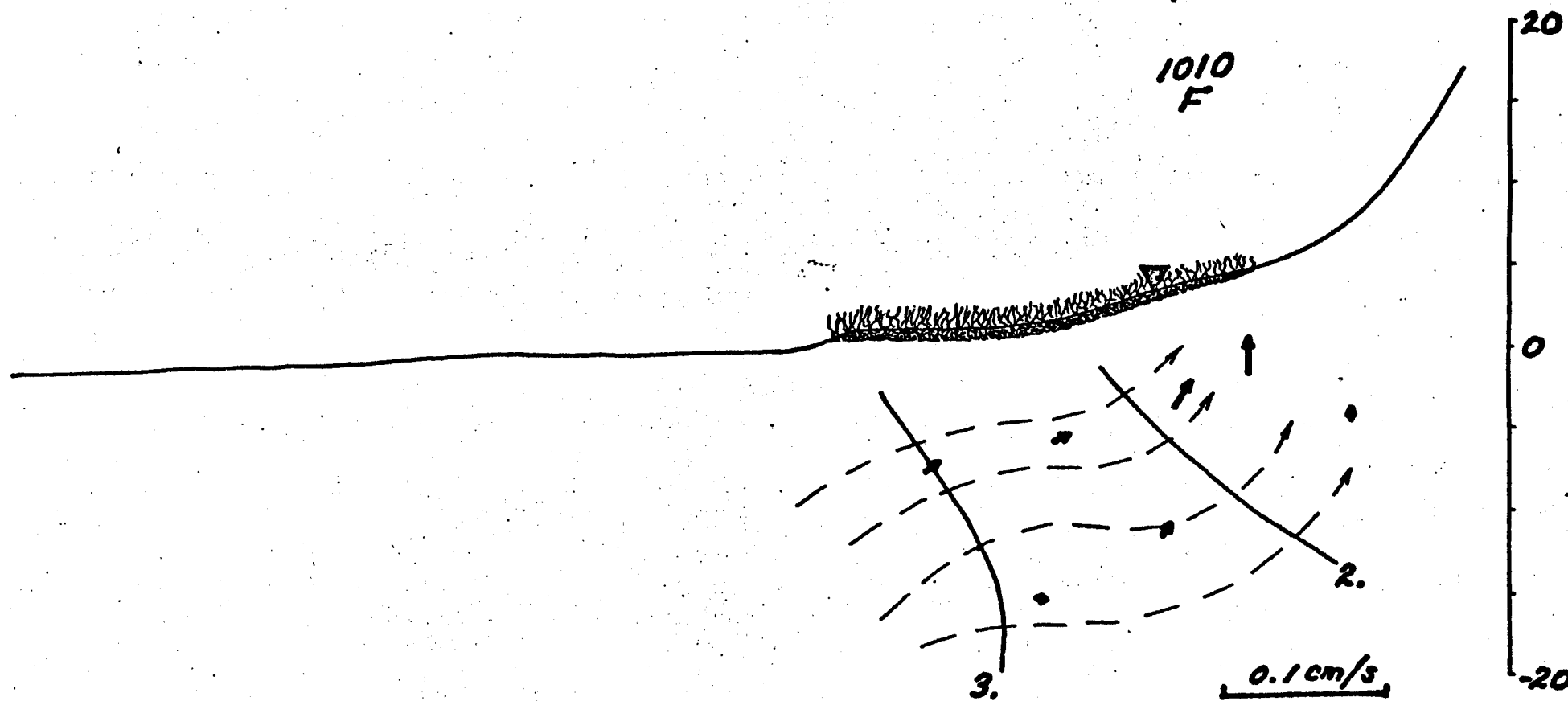


Figure 21. Groundwater flow beneath the Great Island Well Field. At this time the flow velocities are reduced due to a transition from the high tide flow pattern to the low tide flow pattern.

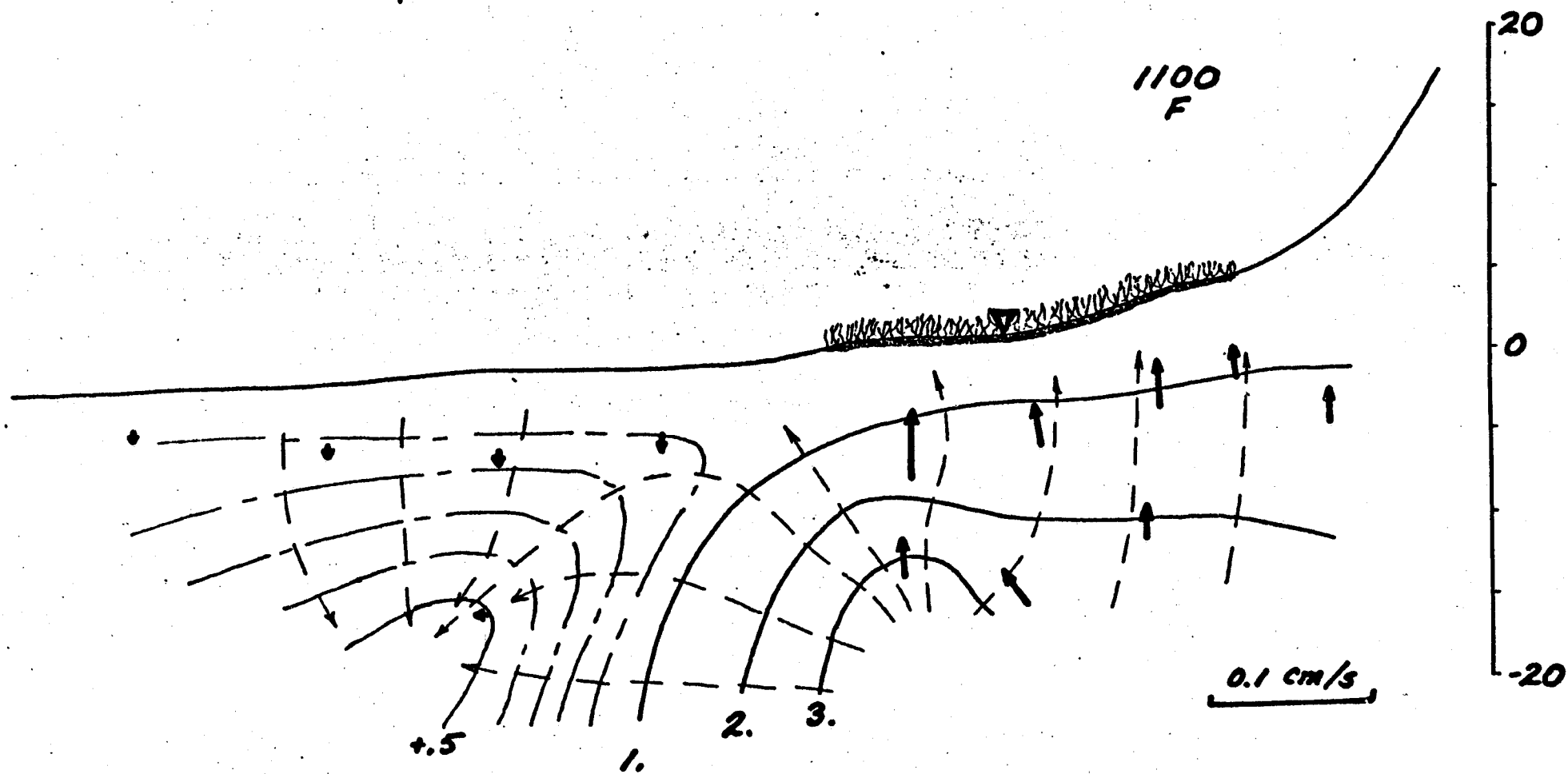


Figure 22. Groundwater flow beneath the Great Island Well Field. At this time the low tide flow pattern is well developed.

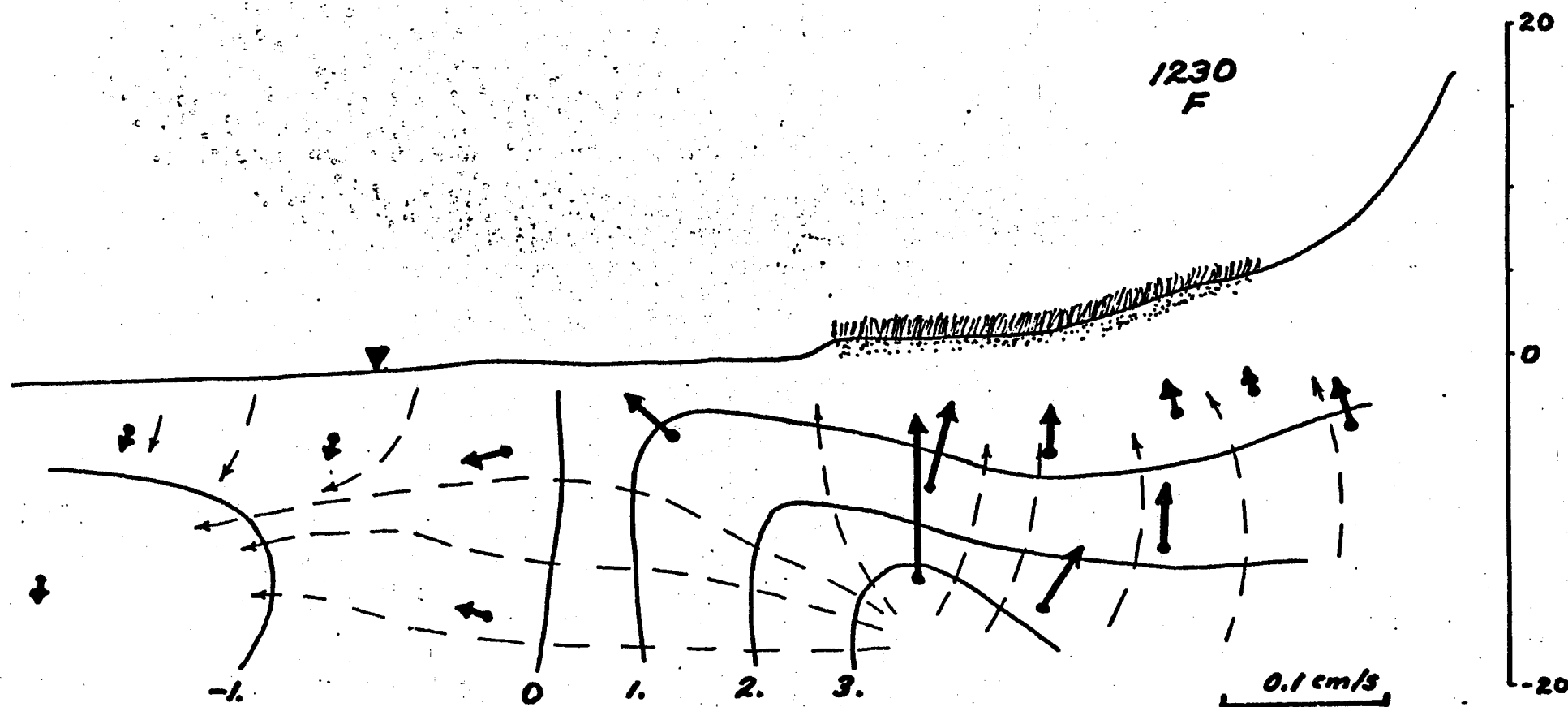


Figure 23. Groundwater flow beneath the Great Island Well Field. No significant change from the previous figure.

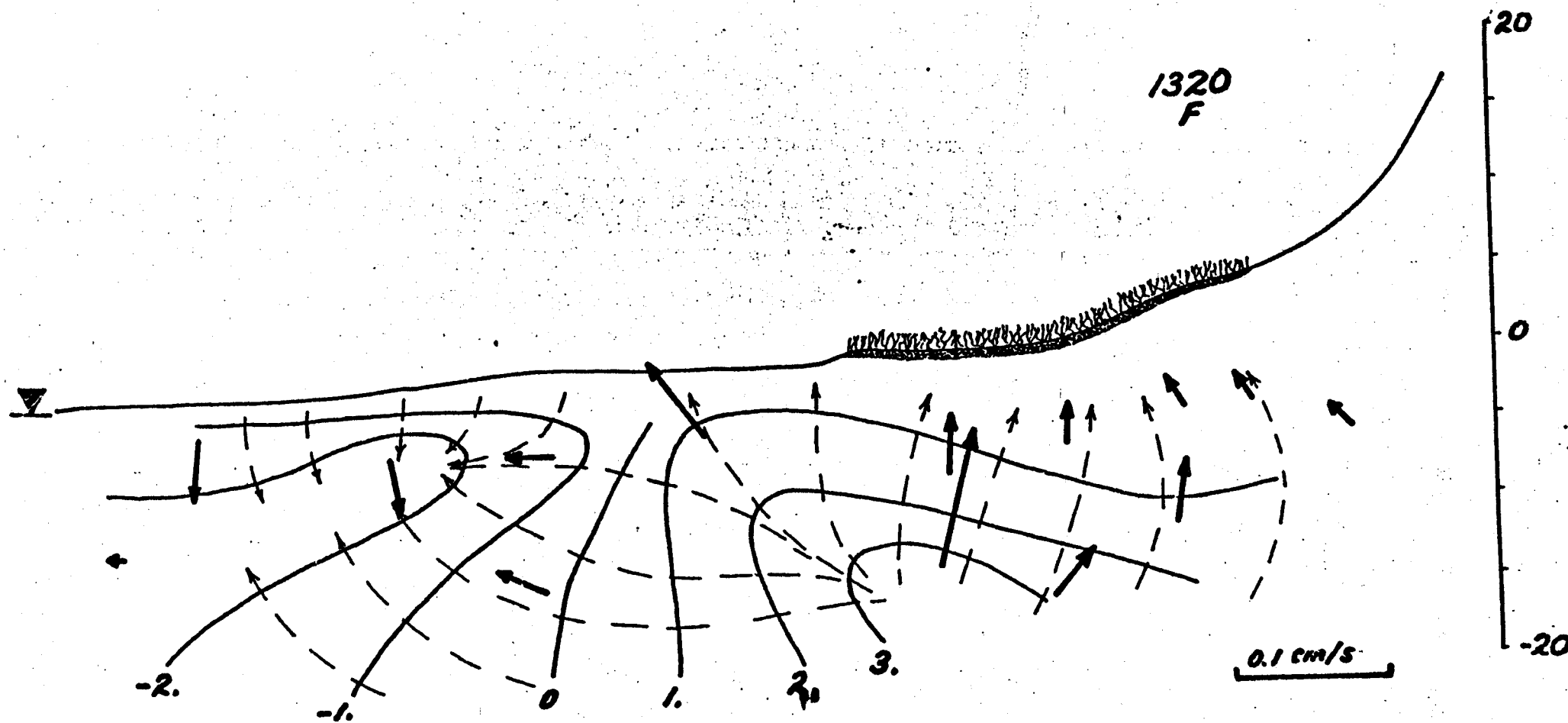


Figure 24. Groundwater flow beneath the Great Island Well Field. In this figure the low tide flow pattern is well developed and a strong upward flow is seen beneath the marsh.

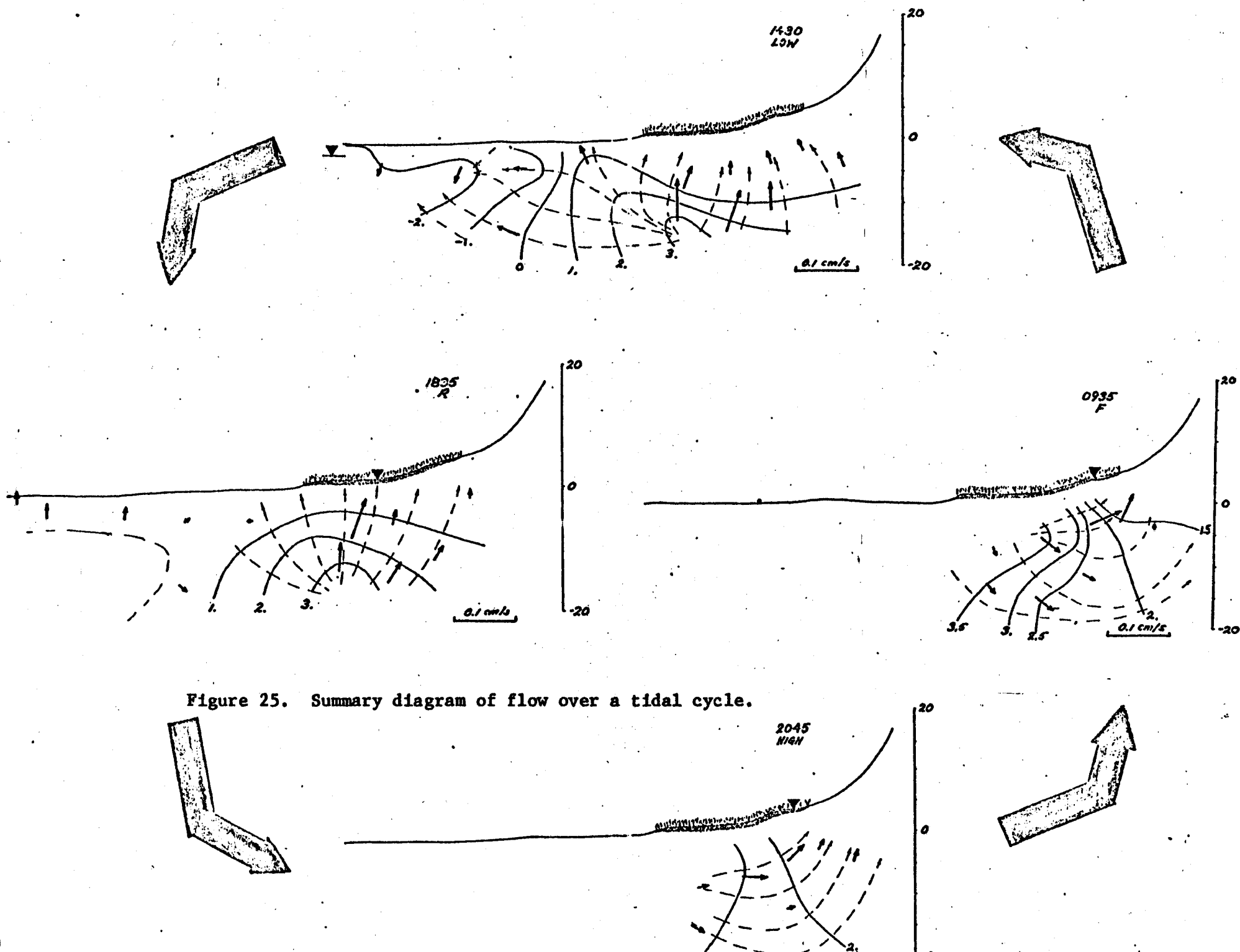


Figure 25. Summary diagram of flow over a tidal cycle.

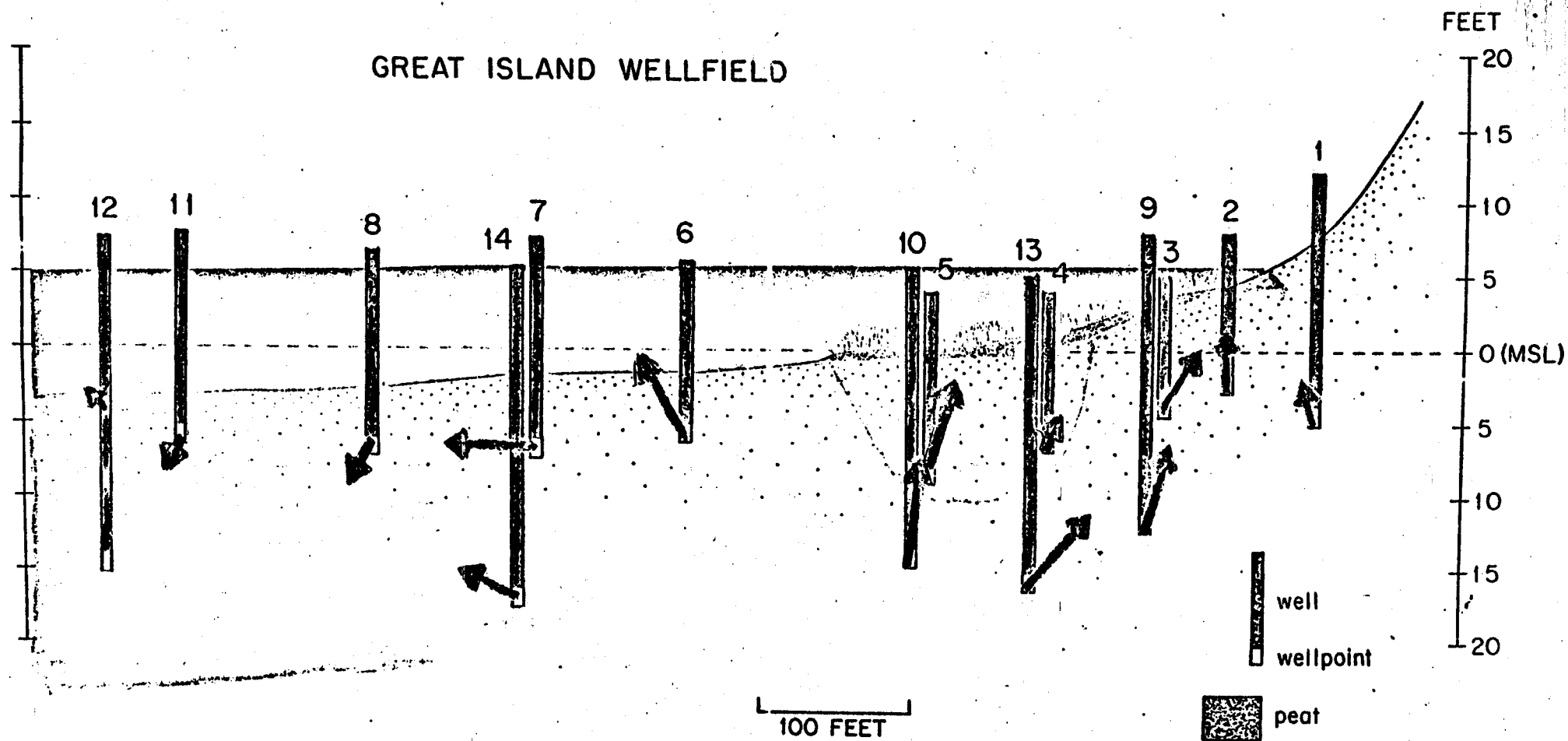


Figure 26. Time averaged flow under Great Island Well Field.

time average flow vectors still indicate flow which opposes that which would be inferred from the salinity data. The inference of the data presented in Figure 26 is that there is a net upward flushing of water beneath the marsh and a net seaward transport of fresh and brackish ground water beneath the tidal flats. The solution to the apparent dichotomy between flow data and salinity data is achieved by plotting the flow vectors for each two hours of record on a unified diagram. This diagram is presented as Figure 27. Attention must be drawn to the area beneath the marsh as this is a critical area. Notice that during the high tide portion of the cycle there is a downward and landward motion of the flow beneath the marsh. This flow is reversed during the low tide portion of the cycle. However, the salt water which enters the aquifer during the high tide portion of a cycle occupies a myriad of cavities and voids in the sandy aquifer. It becomes obvious that the upward flushing of fresh water during the low tide portion of the cycle is insufficient to completely replace the salt water residing in all cavities and voids within the aquifer. Thus the salt water diffuses downward beneath the marsh during each high tide portion of the cycle and is incompletely flushed during each low tide portion of the cycle. This produces an interesting type of dispersion of the salt water. The actual mechanism is dominated neither by molecular dispersion nor by flow advection. Instead, the complex mechanism of downward percolation and incomplete flushing dominates the distribution of salinities beneath the salt marsh. These processes are most apparent beneath the salt marsh but clearly dominate the net distribution of salinities throughout the entire well field transect.

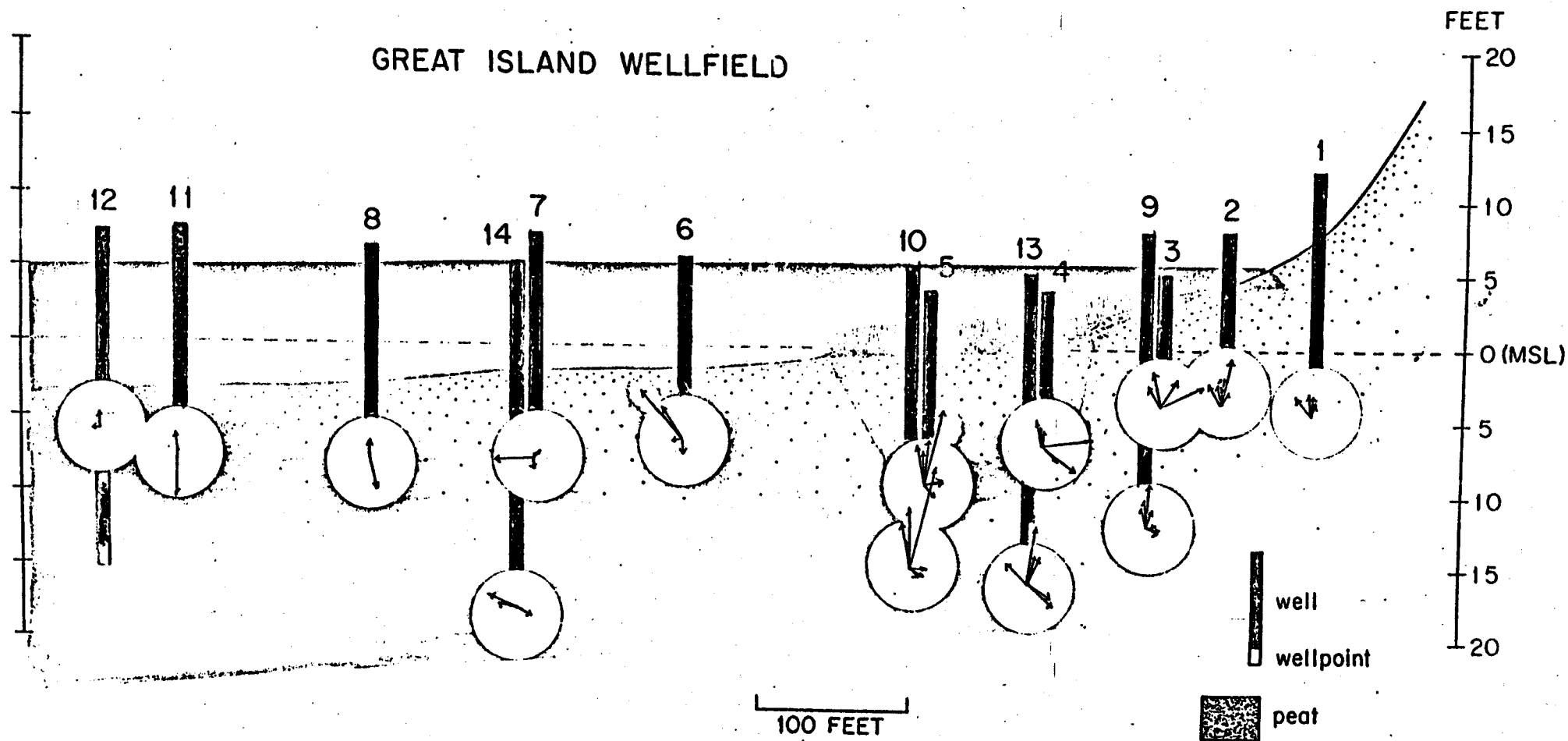
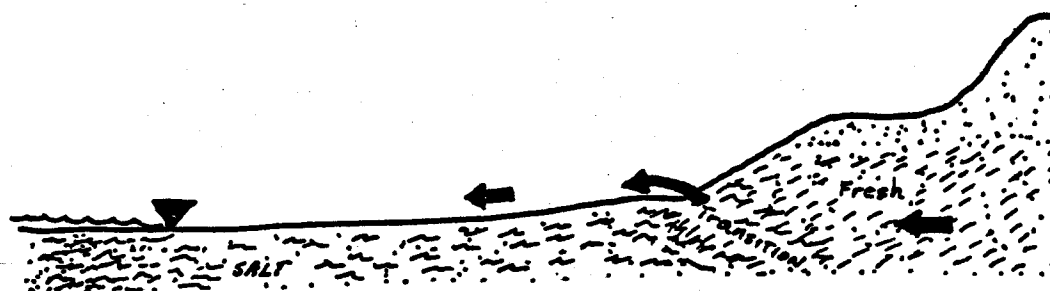


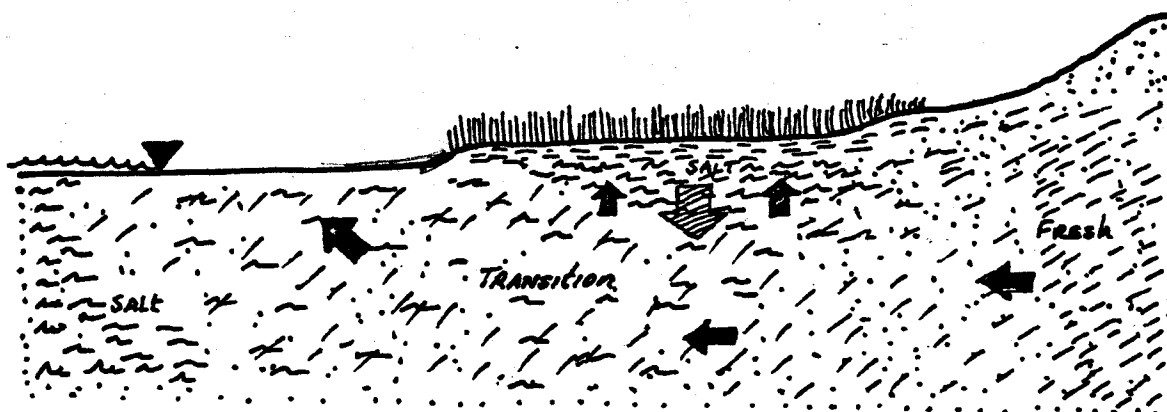
Figure 27. Combined plot of flow vectors for each two hours of record

From this, it becomes apparent that the major influence of the marsh and marsh peats on the underlying groundwater flow is that salt water is trapped and restrained from surface flow back into the estuary during the falling tide stages. As the result of the storage of this salt water in the marsh and marsh peat areas, the salt water eventually flushes downward into the transition zone within the aquifer. The overall result, therefore is a widening of the transition zone within the coastal aquifer.

The important finding in this study can be shown schematically in Figure 28 where the groundwater flow associated with areas sustaining salt marshes is compared to the groundwater flow in areas without salt marshes. This would correspond to a comparison of the Great Island Well Field with the Eastham Well Field. In this figure we can see that an area without salt marshes permits the surface drainage of the salt water during the falling portion of the tidal cycle. Thus a small amount of salt water is allowed to enter into the sea floor close to shore. Instead this portion of the aquifer is dominated by seaward flowing fresh water. The net result is a narrow zone of transition from salt water to fresh water and the outcropping of fresh water along a series of spring lines located close to the beach toe. In areas of sandy aquifers overlain by marshes, the situation is changed significantly. Surface drainage across the marsh is very limited. This results in a downward fluxing of salt water as a result of the cyclic nature of groundwater flow in the shallow portion of the aquifer. The net result of this downward flushing of salt water is a marked increase in the width of the groundwater transition zone. It is obvious that the increase of the width of the groundwater transition zone affects inland areas as well. The over-



LOW TIDE - NO MARSH



LOW TIDE - WITH MARSH

Figure 28 - Schematic diagram representing the differences in flow patterns and widths of transition zone on coasts with and without salt marshes. Incomplete cyclic flushing beneath salt marsh shown by opposing arrows.

- over similar
substrate w/o marsh

all effect of the salt marsh is therefore to increase the storage capacity of the entire aquifer system located inland but adjacent to salt marshes. Finally, it should be pointed out that where salt marshes exist in proximity to estuaries which are floored by impermeable organic mud layers, such as in the case of the Nausett Well Field, the transition zone is shifted seaward to the point where the impermeable mud layer is breached. Thus computations of aquifer storage capacities must take into account the fact that some estuaries are underlain by aquifers containing fresh water. Such situations naturally increase the overall storage capacities of the aquifer beneath the land well inland from such marsh and estuary systems.

CONCLUSIONS

The conclusions of this study which have environmental significance are:

1. Salt marshes which overlies sandy aquifers along coasts which do not exhibit an organic impermeable mud layer tend to significantly widen the transition zone between fresh and salt groundwater. This in turn results in an increase in the overall storage capacity for groundwater of the aquifer inland and adjacent to the salt marsh system. It appears appropriate to infer that when the areal extent of the salt marshes is much greater than the areal extent of the model marshes used in this study, that the overall widening of the zone of transition can be very significant.
2. It has been shown that estuary systems which are characterized by the existence of an organic mud layer which is impermeable to ground water flow, may be underlain by fresh water in the aquifer. Thus these systems also act to increase the overall storage capacity of coastal aquifer systems. Salt marshes adjacent to such estuaries appear to have minor effects on the overall distribution of fresh water beneath such estuaries.
3. The processes which dominate the transfer of chemical and biological pollutants from salt marsh surfaces to underlying aquifers are now seen to be controlled by an incomplete cyclic flushing related to the principal tidal period. This in turn suggests to other conclusions. The incomplete cyclic flushing process permits a downward transport of salt water or other chemical agents. Thus pollution of the marsh surface, or closely adjoining

areas, with effluent will result in a steady state condition closely resembling the distribution of salinity values at the Great Island Well Field. The downward motion of such contaminants will aid in the natural biological purification processes that are well known in all ground water systems. These contaminants will travel seaward within the aquifer and thus present no significant hazard to contamination of the general aquifer fresh water storage. In addition, it can be seen that substantial withdrawal of groundwater from areas immediate landward but adjacent to marsh systems can result in destroying the overall effect of the salt marsh on the groundwater system. That is, significant withdrawal of fresh water will reduce the influx of fresh water beneath the marsh, replace this entire zone with a salt water saturated aquifer, and thus significantly reduce the width of the transition zone. The consequence of this reduction in the width of the transition zone will be seen as a large scale reduction in the overall aquifer storage capacity in locations adjacent to such marshes. Hence, high discharge wells should not be located near marshes.

4. Salt marshes are not strongly effected by groundwater flow. The vigor and distribution of plant species is controlled mainly by tidal action of adjacent estuary or ocean water. Thus withdrawal of significant quantities of fresh water of coastal aquifer systems adjacent to salt marshes is unlikely to have significant detrimental effects to the salt marsh systems themselves.

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