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DEPARTMENT OF THE INTERIOR
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GEORGE OTIS SMITH, Director

WATER-SUPPLY PAPER 537

A STUDY OF COASTAL GROUND WATER

WITH SPECIAL REFERENCE TO CONNECTICUT

BY

JOHN S. BROWN

Prepared in cooperation with the
CONNECTICUT STATE GEOLOGICAL AND NATURAL HISTORY SURVEY
H. H. Robinson, Superintendent

WASHINGTON
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PREFACE

By O. E. Meinzer

The sea coasts of the United States, exclusive of Alaska and the island possessions, have a total length of 4,883 miles, measured in 30-mile steps, and 21,862 miles, measured in 1-mile steps.[1] These coasts are of special importance with respect to commerce, recreation, and national defense and are, on the whole, belts of intensive human activity. Because of this activity a considerable number of large water supplies and very many small water supplies are required, but the proximity of salt water makes it difficult, at many places along the coasts, to obtain supplies of good quality. Hence numerous inquiries are received by the Geological Survey as to the prospects of obtaining fresh water from wells sunk near the sea.

The need for a comprehensive paper on this subject has long been felt by those concerned with problems of water supply. The present paper largely meets this need. Though limited in time and facilities for his investigation, Mr. Brown has obtained very substantial results. His field work was done chiefly on the coast of Connecticut, but he has also had opportunity to study some of the keys along the Florida coast. He has added greatly to the value of his paper by presenting data from many sources on coastal ground water in the United States and by digesting the valuable but relatively inaccessible foreign literature on the subject. He has very successfully correlated the data obtained by other investigators with his own data and has applied the results effectively to the problems of water supplies on the coasts of this country.

The subject is complex. The great variety in climate, topography, stratigraphy, and rock structure along the seacoasts has resulted in a corresponding variety and complexity in the relations of the sea water to the ground water. Moreover, these relations vary with the depth below the surface, chiefly because of the difference in specific gravity of fresh and salt water, and they may be totally altered by heavy pumping. Mr. Brown has taken all these factors into consideration.

Coasts may be divided into three classes with respect to the most significant geologic conditions affecting contamination by salt water—(1) coasts underlain by porous, unconsolidated materials,

[1] U. S. Coast and Geodetic Survey.

such as sand and gravel, (2) coasts underlain by hard rocks with water-bearing joints and crevices, and (3) coasts underlain by alternate water-bearing and water-tight beds or by a single water-bearing formation protected from the sea by an overlying tight bed. In the areas investigated Mr. Brown has had opportunity to study all three of these classes, especially the first two. Hence his results, although of particular application to the coast of Connecticut, will be found valuable wherever the problem of contamination by sea water is encountered along the far-reaching coasts of this country.

A STUDY OF COASTAL GROUND WATER

WITH SPECIAL REFERENCE TO CONNECTICUT

By JOHN S. BROWN

INTRODUCTION

The United States Geological Survey began to study the water resources of Connecticut in 1903[1] and has continued the work, with some interruptions, to the present time. Since 1911 the investigations have been made through a cooperative agreement between the United States Geological Survey and the Connecticut State Geological and Natural History Survey, the expenses usually being shared equally by the two surveys. This cooperative work has been done under the direction of Prof. H. E. Gregory, former superintendent of the State Survey, H. H. Robinson, the present superintendent, and O. E. Meinzer, geologist in charge of the division of ground water in the Federal Survey. Special attention has been given to the ground water, and more than half the area of the State has been covered in detailed reports.[2]

In the summer of 1919 the writer made a systematic ground-water survey of the New Haven area,[3] which lies between Connecticut and Housatonic rivers and includes 18 towns centering around New Haven. This area borders Long Island Sound for about 30 miles and extends about 15 miles inland. On the coast are large cities and

[1] Gregory, H. E., Notes on the wells, springs, and ground-water resources of Connecticut: U. S. Geol. Survey Water-Supply Paper 102, pp. 127-168, 1904.

Pynchon, W. H. C., Drilled wells of the Triassic area of the Connecticut Valley: U. S. Geol. Survey Water-Supply Paper 110, pp. 65-94, 1905.

Fuller, M. L., Triassic rocks of the Connecticut Valley as a source of water supply: U. S. Geol. Survey Water-Supply Paper 110, pp. 95-112, 1905.

Gregory, H. E., Underground waters of the eastern United States: U. S. Geol. Survey Water-Supply Paper 114, pp. 76-81, 1905.

Gregory, H. E., and Ellis, E. E., Underground-water resources of Connecticut, with a study of the occurrence of water in crystalline rocks: U. S. Geol. Survey Water-Supply Paper 232, 1909.

Gregory, H. E., and Ellis, A. J., Ground water in the Hartford, Stamford, Salisbury, Willimantic, and Saybrook areas, Conn.: U. S. Geol. Survey Water-Supply Paper 374, 1916.

Ellis, A. J., Ground water in the Waterbury area, Conn.: U. S. Geol. Survey Water-Supply Paper 397, 1916.

Waring, G. A., Ground water in the Meriden area, Conn.: U. S. Geol. Survey Water-Supply Paper 449, 1920.

Palmer, H. S., Ground water in the Norwalk, Suffield, and Glastonbury areas, Conn.: U. S. Geol. Survey Water-Supply Paper 470, 1920.

Palmer, H. S., Ground water in the Southington-Granby area, Conn.: U. S. Geol. Survey Water-Supply Paper 466, 1921.

[3] Brown, J. S., Ground water in the New Haven area, Conn.: U. S. Geol. Survey Water-Supply Paper 540 (in preparation).

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many popular summer resorts. Because of the difficulty experienced in getting pure water suitable for domestic and industrial uses from wells near the sea a careful study of the coastal ground water and an investigation of the circumstances and causes of the contamination of wells by sea water and of possible remedies were made. The results of this special study were intended for publication as part of the paper on ground water in the New Haven area, but the mass of data collected on coastal ground water in Connecticut and elsewhere made it advisable to separate the two reports and give the present paper a somewhat broader scope.[3a]

ACKNOWLEDGMENTS

The writer is indebted to everyone who gave information or assistance in the field. Well drillers and factory officials were particularly accommodating in supplying data and assisting in the collection of samples. In preparing the report free use has been made of unpublished material and maps in the possession of the Connecticut State Geological and Natural History Survey, for which individual credit can not be given.

DEFINITIONS

The terms coast and shore are used very indefinitely by many people and are frequently confused. As far as possible the usage in this paper conforms to that proposed by Johnson,[4] who defines the shore as "the zone over which the water line, the line of contact between the land and sea, migrates." Practically, this is the zone between the limits of low tide and high tide, although it actually includes a narrow zone that is covered by water only during storms. Johnson defines a coast as "a much broader zone of indeterminate width, landward from the shore." The seaward limit of the permanently exposed coast is called the coast line. In technical descriptions the definitions given above will be followed. Popular usage, however, necessitates some discrimination in the application of these definitions. For instance, houses or settlements built on the coast near the shore are almost invariably known as "shore houses" or "shore resorts."

THE NEW HAVEN COAST

LIMITS

This paper deals principally with a portion of the Connecticut coast lying east and west of New Haven, which, for convenience, will be designated the New Haven coast. (See fig. 1.) The area shown in Figure 1 is about 30 miles long and 5 to 10 miles wide, but the actual coast line is much more than 30 miles long, and the part discussed lies chiefly within a few hundred feet of the shore.

[3a] A summary of the principal points in this paper has been published under the title "Relation of sea water to ground water along coasts" (Am. Jour. Sci., 5th ser., vol. 4, pp. 274–294, 1922).

[4] Johnson, D. W., Shore processes and shore-line development, New York, John Wiley & Sons, 1919.

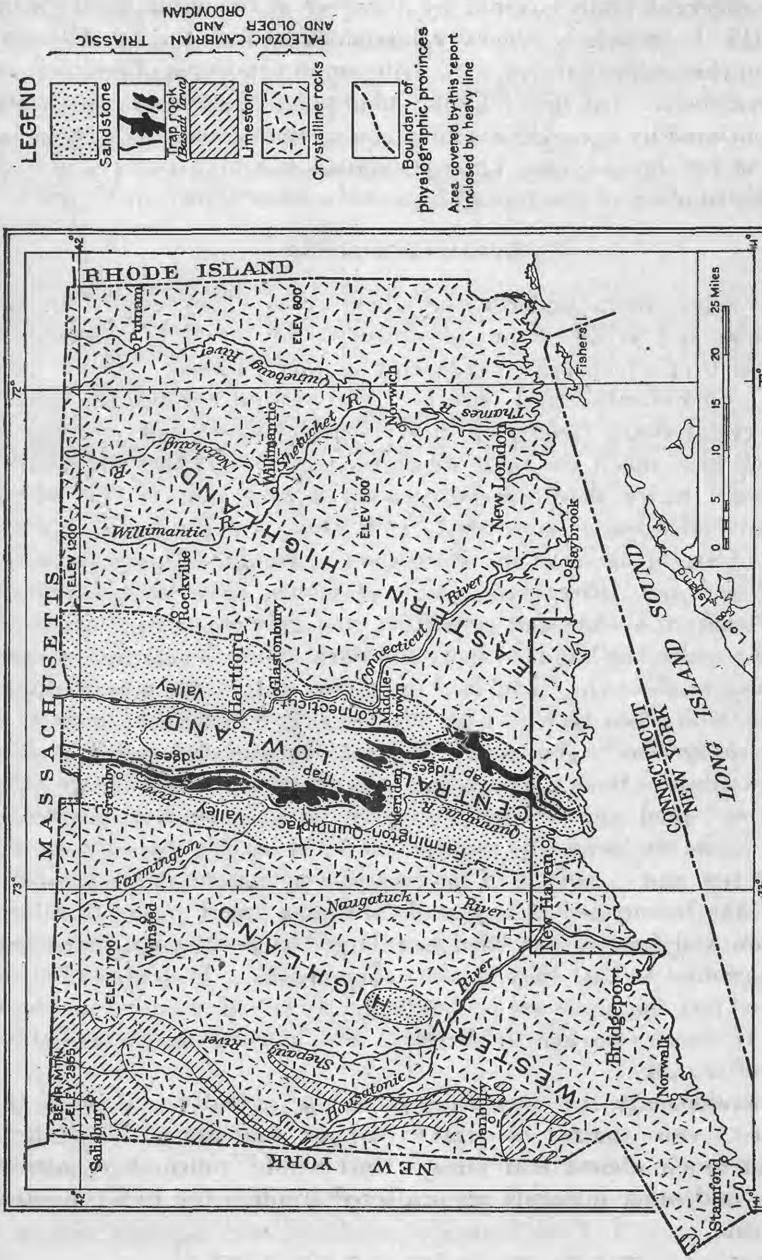

FIGURE 1.—Map of Connecticut showing physiographic provinces, bedrock geology, and area covered by this report

ROCK FORMATIONS

The New Haven coast contains a basement of indurated rock of many different kinds covered by a veneer of unconsolidated glacial drift (Pl. I), which is generally less than 50 feet thick. Although most of the area is covered with drift, small exposures of bedrock are very common. The bedrock may be divided into three main classes, differentiated by age, origin, and physical characteristics—crystalline rocks of pre-Triassic age, Triassic sandstone, and Triassic trap rock. The distribution of the rocks of these classes is shown in Figure 1.

CRYSTALLINE ROCKS

Crystalline rocks underlie the whole area. They consist mainly of gneiss and schist—some of igneous and some of sedimentary origin—all of which are considerably metamorphosed. These rocks have been described and classified into several formations by the Connecticut State Geological and Natural History Survey,[5] but as they all bear much the same relation to the occurrence and quality of ground water they will be considered as a unit in this paper. Schist usually has a tendency to split along a plane parallel to the plane of arrangement of its constituent minerals. This tendency is called cleavage. Frequently cleavage planes have been developed by weathering so that they constitute open crevices or parting planes. Gneiss usually has bands of light and dark minerals and only a slight tendency to cleavage. Much of the gneiss of the area was originally granite, which has been so little altered that its original character is easily recognized. The gneiss of Branford and Stony Creek is a good example. Both the gneiss and the schist are broken by irregular fractures called joints, which traverse them in several directions. These joints are formed by movements in the earth's crust and by the contraction and expansion of the rock due to changes in temperature. They may be inclined at any angle and may trend in any direction. Solution and frost action tend to enlarge the joints near the surface of the ground so that they become open cracks. At depths of a few hundred feet the joints are probably tightly closed or entirely absent. Plate II shows cleavage (schistosity) and jointing in the crystalline rocks of the area.

Mineralogically the crystalline rocks vary greatly. Most of the gneisses consist mainly of quartz, feldspar, and mica. The schists contain much quartz and mica. Hornblende, tourmaline, garnet, pyrite, and other minerals are scattered through the rocks in small quantities.

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[5] Rice, W. N., and Gregory, H. E., Manual of the geology of Connecticut: Connecticut Geol. and Nat. Hist. Survey Bull. 6, Hartford, 1906.

TRIASSIC SANDSTONE

The Triassic sandstone was formed from débris eroded from the crystalline rocks. It is not everywhere a true sandstone but ranges from coarse conglomerate to fine-grained arenaceous shale. Much of it, however, is a hard coarse-grained sandstone that consists chiefly of grains of quartz and feldspar cemented by a reddish iron oxide. Because of its prevailing color it is frequently called red sandstone, or "red rock." The Triassic sandstone occurs only in a small area around New Haven Bay (fig. 1). In this region it has been tilted so that the beds dip uniformly southeastward, generally at angles of 10° to 20°. The sandstone, like the crystalline rocks, is much jointed. In addition it contains bedding planes that separate the strata deposited at different times into thin layers. Near the surface these bedding planes have been weathered somewhat into open crevices like the joint planes. The total depth of the Triassic sandstone is unknown. In a deep well drilled at New Haven 4,000 feet was penetrated without reaching its base. The age of the Triassic sandstone is established by the evidence of fossils found chiefly outside the area here described.

TRIASSIC TRAP

Associated with the sandstones are large mases of igneous rock, either basalt or diabase, both of which are commonly called trap. This is a very hard fine-grained bluish rock. It is exposed at many places in steep cliffs, of which East Rock and West Rock, at New Haven, are good examples. The trap is generally minutely jointed, so that it breaks into small blocks. Vertical joints, which divide it into polygonal columns, are peculiarly characteristic of it. The joints are generally tightly closed and become visible only on weathered surfaces.

GLACIAL DRIFT

Drift is the general term for the débris, composed of soil, rock flour, clay, and boulders, that is stripped from the surface of the land and rearranged by the movement of glaciers or by the streams of water that flow from glaciers. Two kinds of drift are distinguished on the New Haven coast—till and stratified drift (Pl. I).

Till is the unassorted débris left by the glaciers. In it the fine and coarse material are mixed without regard to size or composition. Because the underlying rocks yielded many coarse fragments, boulders of crystalline rocks, sandstone, or trap, are very common in the till of Connecticut. Usually the boulders that predominate in any locality are derived from the underlying rock of that locality.

Stratified drift was deposited by the streams that flowed from the melting glaciers. These streams sorted out the glacial débris and deposited it in layers, more or less graded as to size. At some places it is coarse, containing boulders 1 to 2 feet in diameter. In most of the coastal belt, however, the stratified drift consists of sand, without many coarse pebbles and without much clay. Plate III shows the aspect of till and of stratified drift.

MUD OF NEW HAVEN HARBOR

A deposit of small extent but of unusual importance in this study is the blanket of fine black mud that covers the bottom of New Haven Harbor and extends up some of the tributary tidal marshes. This deposit is in part Recent, and it is receiving daily accretions of fine sand, clay, and sewage. The clay is derived chiefly from clay beds in the stratified drift farther inland, along Quinnipiac River.[6] This mud is practically impervious, and in open pools or excavations it holds water like a cup. It extends approximately to the high-tide shore line, where it thins to nothing, but offshore it thickens greatly, and excavations and well borings show 20 to 30 feet of it above the stratified drift along the present harbor front, which has been filled in beyond the original shore, and in the middle of the tidal marshes of Mill River and West River. This deposit probably underlies the harbor as far south as the narrow opening between Fort Hale Park and Sandy Point. No similar deposit has been found anywhere along the New Haven coast, probably because there are no other large land-locked bays, and because silt-supplying deposits such as the clays of the Quinnipiac Valley are lacking elsewhere.

SHORE FEATURES

LATE HISTORY OF THE CONNECTICUT COAST

The Connecticut coast, during and since the glaciation of the Pleistocene epoch, has undergone a marked subsidence, which has produced what is called a drowned coast. Valleys have been filled with sea water and have become bays and estuaries; hills have been surrounded by the ocean and have become islands; ridges have become peninsulas. The resulting coast line is very crooked. Wave action has to some extent straightened it by wearing away the headlands and building beaches between projecting points and across bays. Streams have aided by filling up bays and estuaries with sediment. These processes have greatly modified the original drowned coast and are still active. The land forms developed along the coast are of particular significance in this study and will be described briefly.

[6] See Loughlin, G. F., Clays and clay industries of Connecticut: Connecticut Geol. and Nat. Hist. Survey Bull. 4, 1905.

BEACHES, BARS, AND SPITS

Beaches are developed through the erosion and deposition of material by waves along the shore. In till and stratified drift beaches are generally developed rather rapidly, but on projecting rocky points the shore is generally swept nearly bare.

A beach is a fairly regular section of shore covered by sand or pebbles. It is usually terminated by rocky headlands, river outlets, or tidal inlets. Its composition, configuration, and extent vary with the topography and with the formation on which it is developed. In stratified drift very straight, sandy beaches are developed, such as those of Madison, Clinton, and part of Milford. If the land rises a few feet above sea level the beach is generally backed by a wave-cut terrace and sea cliff. (See Pl. IV.)

Bay-head beaches are built up across the heads of small bays, particularly where the coast line is rocky and crooked. The formation of such a beach gives the bay a rounded or U-shape appearance. The beach is a ridge of sand behind which generally lies a lagoon or marsh. Little Harbor and Joshua Cove, on the Guilford shore, exhibit this type of beach particularly well.

Bar beaches are wave-built ridges of sand connecting headlands or rocky points along the shore. Spits are incomplete ridges of similar origin. These ridges generally do not exceed 200 feet in width on the New Haven coast and are built approximately to the height of the maximum storm waves. Bar beaches usually face the sea on one side and a tidal marsh on the other; spits are washed by salt water on both sides. By growing forward in the direction of shore currents, a spit may connect with some opposing point of land, thereby becoming a bar, and may completely seal off the landward area, which becomes a marsh. (See Pl. V, *A*.) Small channels generally remain open, affording an outlet for fresh-water streams or an inlet for the tides, but some bars are unbroken. Hogshead Point, in Madison, and Milford Point, in Milford, are good examples of spits.

An unusual feature is the bar, sometimes called a tombolo, which connects an island to the mainland. An excellent example of a tombolo is the bar connecting Charles Island with the mainland in Milford (Pl. V, *B*). This bar is nearly a mile long and is completely covered at high tide. Double Beach, in Branford, is another well-known example.

TIDAL MARSHES

Tidal marshes are described by Shaler[7] as "wide savannas which are covered by the sea but for an hour or two a day, during the time of high tide, and which support a growth of low-grade flowering

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[7] Shaler, N. S., Beaches and tidal marshes of the Atlantic coast: Nat. Geog. Monographs, vol. 1, p. 158, 1896.

plants, mostly of grasslike form." Most of the tidal marshes represent drowned valleys that have been partly cut off from the sea by beaches, bars, or spits and then filled in with sediment and decaying vegetation. They are very extensive along the New Haven coast and are commonly called salt meadows. The salt water is sometimes sealed off from these areas in the summer by tide gates, and the grass is cut for coarse hay or bedding. Generally, however, the tidal marshes are waste land except where large areas have been filled in for building sites, as at New Haven, or where the sea has been shut out by tide gates for sanitary or other reasons.

ISLANDS

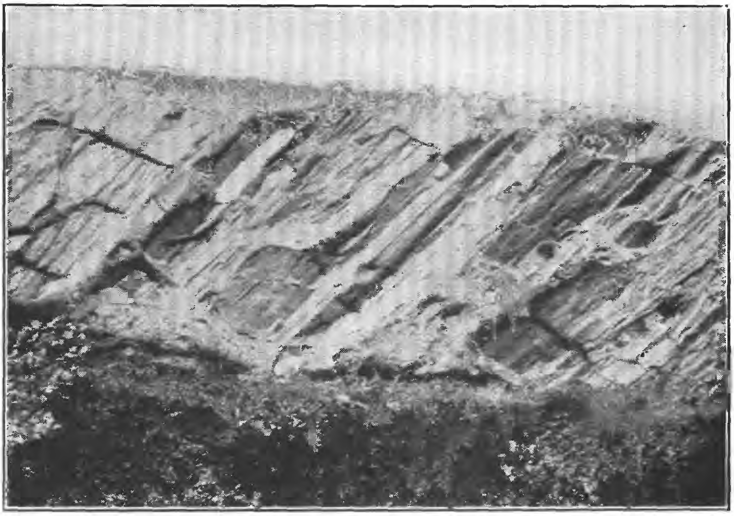
Most of the islands of the New Haven coast lie between New Haven and Guilford, particularly in the towns of Branford and Guilford. Nearly all of them are composed chiefly of bedrock, generally with a thin covering of till. When the land first sank to its present level there were probably numerous islands composed of till and stratified drift, but such islands have been destroyed by wave action, leaving only the more durable rock masses to show the former seaward extension of the land. Charles Island, near Milford, is an exception. It is apparently composed entirely of till and stratified drift and is being rapidly worn away.

GROUND WATER

SOURCE AND MOVEMENT OF GROUND WATER

Ground water is the water that exists in the saturated zone below the land surface—the water that supplies wells and springs. Practically all the ground water on the New Haven coast comes from the precipitation upon the drainage basins of its streams. Records at New Haven covering a long period of years show that the mean annual precipitation is about 45 inches.

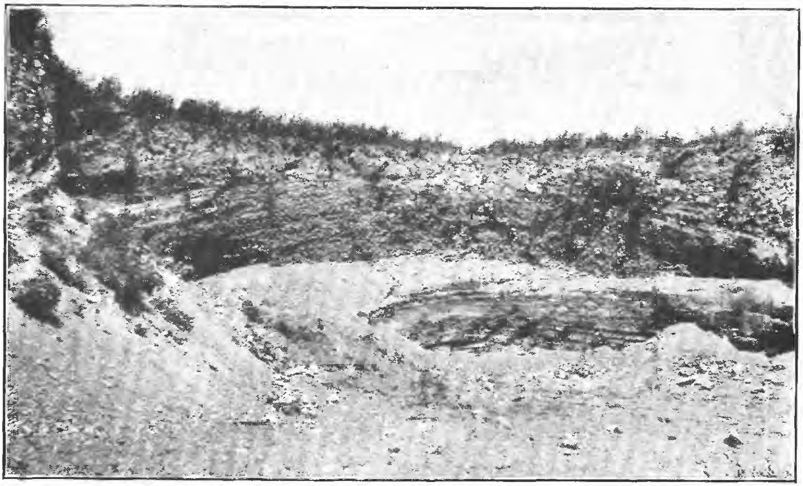
Rain water and melted snow sink into the rocks, filling the pore spaces between grains or particles as well as the larger voids in joints and in cleavage and bedding planes. The voids of all the rocks in a region of plentiful rainfall are usually saturated with water up to a certain level known as the water table, a gently undulating surface that conforms more or less closely to the topography. This ground water, under the influence of gravity, moves downward and outward from higher to lower levels and eventually discharges into streams, lakes, or the ocean. At some places it seeps out of the ground visibly as springs; at other places it seeps invisibly into brooks or, at the shore, mingles with the salt water of the ocean.



A. CLEAVAGE AND JOINTS IN SCHIST, GUILFORD, CONN.
Cleavage inclined at 45°; joints nearly horizontal

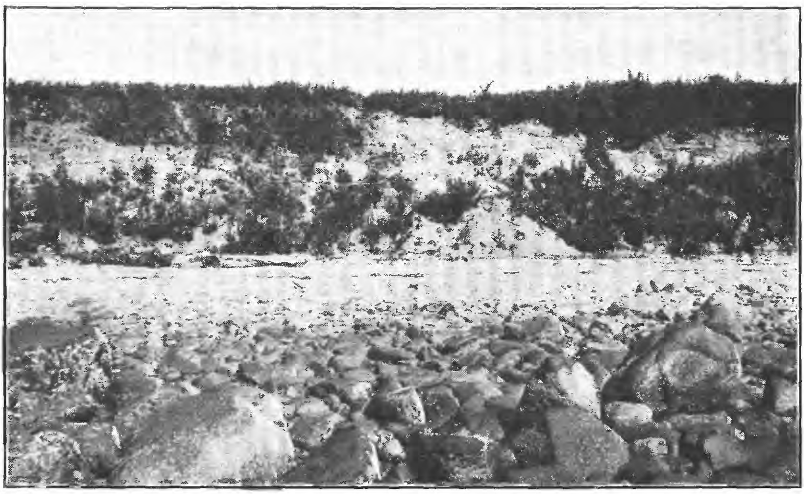
B. JOINTS (NEARLY HORIZONTAL) IN GNEISS, ESSEX, CONN.

A. SECTION OF TILL, ORANGE, CONN.



B. SECTION OF STRATIFIED DRIFT, MILFORD, CONN.

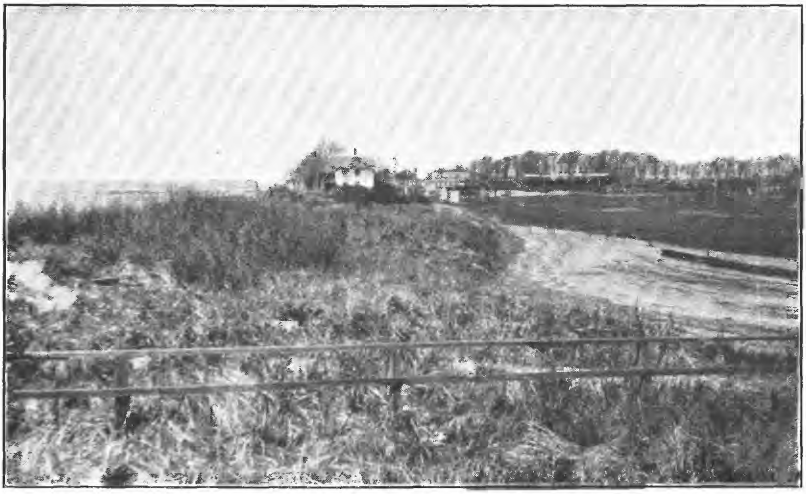
A



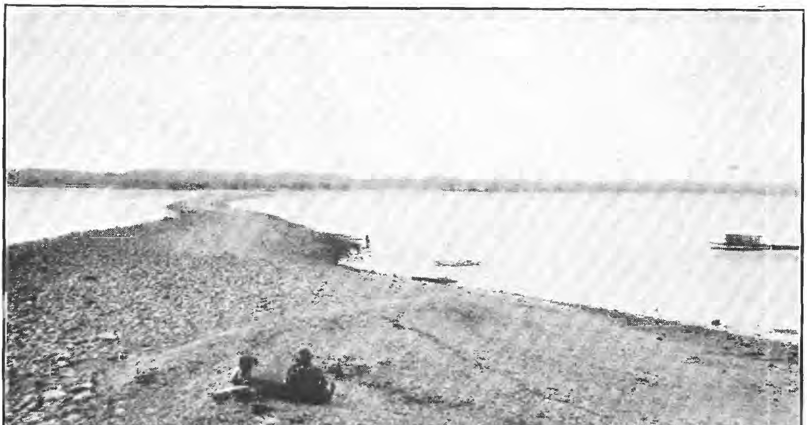
B

BEACHES AND SEA CLIFFS IN STRATIFIED DRIFT

A, Webster Point, Madison, Conn.; *B*, Pond Point, Milford, Conn.



A. BAR BEACH, MORGAN POINT, EAST HAVEN, CONN.



B. BAR OR TOMBOLO, TYING CHARLES ISLAND TO MAINLAND, MILFORD, CONN.

OCCURRENCE IN THE DIFFERENT ROCKS

The conditions of occurrence of ground water on the New Haven coast differ greatly with the different formations. In the bedrocks of the region—crystalline rock, sandstone, and trap—conditions are very much alike everywhere. Most of the ground water is stored in open joints, cleavage planes, and bedding planes. In nearly any quarry face or along cliffs, after a rain, water can be seen seeping out from these openings. Wells that penetrate the hard rocks derive their water from these fissures, which with their ramifying connections may extend for many hundreds of feet. Both the quantity of water yielded by such openings to a well and the depth to water are very uncertain, however, because the well may or may not penetrate large water-bearing fractures. Some wells several hundred feet deep are practically dry; others yield as much as 50 gallons a minute, but the average is much less.

In stratified drift, which consists of sand or gravel and is generally very porous, water circulates freely, filling the pore spaces between the particles. Where the stratified drift is fairly extensive the water table approaches a horizontal plane and stands nearly at the level of the adjacent body of water—stream, lake, or the sea—that constitutes the local controlling water level. Wells in stratified drift near the shore usually reach water at about the level of high tide.

In till the circulation of water is much more erratic and sluggish because the till is not assorted and contains some clay amd fine material. Wells in till usually yield less water than wells in stratified drift, and the depth to the water table is much more irregular and much less closely related to the level of adjacent bodies of surface water.

DEVELOPMENT AND USES OF GROUND WATER

Ground water along the New Haven coast is generally obtained from wells, which are of three types—dug, driven, and drilled. Dug wells are the predominant type used for domestic supply. They usually derive their water from the drift, though many of them are sunk to the contact with the underlying bedrock, and some penetrate the bedrock. They are usually about 3 feet in diameter, are lined with rough stones or tile, and are fitted with a rope, pulley, and bucket or with a hand pump for lifting water.

Driven wells are constructed by forcing into the ground a small pipe that is usually fitted at the bottom with a perforated metal screen or strainer and a drive point. They may be driven with a sledge hammer or a special driving apparatus, but they are practicable only in stratified drift. Where the water table is within 25 feet of the surface they are satisfactory and in many places are used for domestic supply. Driven wells are particularly useful for large pumping plants. A gang of driven wells is attached to one suction main and pumped from a central station. In the city of New Haven from 3,000,000 to 5,000,000 gallons of water are pumped daily from driven wells.[8]

Drilled wells are generally used to obtain water from bedrock. They are excavated by churn drilling. Along the New Haven coast these wells are nearly all 6 inches in diameter and usually less than 200 feet in depth. Their water is derived from fractures in the rock, and the supply is somewhat uncertain. Drilled wells generally supply water for household use in places where the drift is too thin to yield sufficient water.

Aside from domestic use, the ground water obtained on the New Haven coast is used chiefly by industrial plants, most of which are in New Haven. In these plants ground water is used for a great many special purposes, most of which can be classified under three heads—(1) making steam; (2) cooling and refrigerating, as in ammonia pipes, water jackets, and condensers; (3) rough uses, such as washing floors, coal, and acid pickle. The quantity used for the second and third purposes is much greater than for the first. Most of the ground water of the area is rather hard compared with surface water from streams, which is generally preferred for making steam.

A great part of the coast is reached by public waterworks, which furnish most of the water for domestic use and much of that for industrial use.

COASTAL GROUND WATER

THE PROBLEMS

The practical aspects of the problems of coastal ground water in Connecticut are very simple, but their solution is difficult. Wells near the sea may be affected in two principal ways—they may become salty by the admixture of sea water, and their water level may rise and fall with the tides.

The first effect will be spoken of in this report as contamination, in distinction to pollution, the latter term being reserved to designate the unsanitary condition of water due to sewage and industrial wastes. Contamination by sea water is by far the most troublesome of the problems here discussed. Sea water, even in small quantity, renders ground water unfit for many uses. Its saltiness makes the water undesirable for domestic use. In contact with plumbing and mechanical apparatus it is very corrosive. In boilers it causes foaming. In chemical and metallurgical operations it may be ruinous. For instance, wire companies in New Haven have found that salty water

[8] Brown, J. S., Ground water in the New Haven area, Conn.: U. S. Geol. Survey Water-Supply Paper 540 (in preparation).

used in washing acid pickle renders the wire brittle. A coke company in New Haven once inadvertently quenched a pile of coke with salt water and as a result upset the smelting process in which the coke was later used.

Several phases of the problem of contamination by sea water must be considered. One is the width of the zone in which sea water may penetrate inland from the coast line; another is the depth at which sea water may occur within this zone at a given distance from the shore; a third and very important one is the tendency of pumping to induce saltiness in wells near the sea. An especially serious problem in Connecticut is that of obtaining good water for summer residences at places not provided with a public supply. Many of these residences are on beaches, bars, and small islands. The extent of the contaminated zone and the effects of pumping vary with the topography and geology of the locality, but with the proper information at hand it is possible to predict fairly accurately the probable quality of the water available at a given locality and the safe draft that may be made upon it.

The data on contamination by sea water obtained from the New Haven coast were somewhat incomplete because the most populous areas are provided with public water supplies and wells are not common; also because most of the pumping plants are in New Haven, where special geologic conditions modify the general rules. For this reason the data gathered on the New Haven coast have been supplemented by observations made elsewhere and by a comparison with conditions on many coasts, as revealed in the literature of coastal ground water. The conclusions are applicable in large measure to all the coast of the United States.

In addition to the local problems of coastal ground water, there are some larger regional problems of scientific and perhaps of practical interest, on which only speculation is possible from the meager data here presented. For instance: Are the hydrologic conditions on arid coasts the same as on humid coasts? In what respects are these conditions different in limestone and other hard sedimentary rocks from conditions in crystalline rocks and in unconsolidated sediments? Are they different on sinking and on rising coasts? What are the effects of cold climates and of tropical climates? Correct answers to these and other questions by a study of present conditions might shed valuable light on the problems of the origin and effect of connate sea water, most of which was confined in sediments laid down at or near shore lines.

METHODS OF INVESTIGATION

The field work for this study consisted of mapping the geology of the area, particularly the glacial geology, and collecting records of wells, springs, and pumping plants that might yield information on the problems suggested above, particularly contamination by sea water. The geologic and topographic conditions near wells were carefully observed, and also the depth to water, depth of the wells, and details of their use.

The only practicable and reliable method of determining the degree of contamination in wells is by analyzing the water to find the amount of oceanic salts that it contains. In order to interpret the analyses properly a knowledge of the general characteristics of ground water and of sea water is necessary.

The following table is based on analyses of 49 samples of ground water from the New Haven area:

Dissolved constituents in ground waters of the New Haven area

[Parts per million]

	Maximum	Minimum		Maximum	Minimum
Silica (SiO_2)	99	6.2	Sulphate radicle (SO_4)	232	6.3
Iron (Fe)	1.7	.04	Chloride radicle (Cl)	885	1.6
Calcium (Ca)	127	4	Nitrate radicle (NO_3)	185	Trace.
Magnesium (Mg)	79	1.7			
Sodium and potassium (Na+K).	496	3.4	Total dissolved solids	1,803	46
			Total hardness	641	19
Bicarbonate radicle (HCO_3).	466	13			

These ranges are about the same for water from stratified drift, till, Triassic sandstone, and crystalline rocks in this and surrounding areas.

Average composition of sea water

[Parts per million. From U. S. Geol. Survey Water-Supply Paper 258, p. 82, 1911. (After Dittmar.)

Calcium (Ca)	419
Magnesium (Mg)	1,304
Sodium (Na)	10,707
Potassium (K)	387
Carbonate radicle (CO_3)	72
Sulphate radicle (SO_4)	2,693
Chloride radicle (Cl)	19,352
Total dissolved solids	35,000

The salinity of sea water varies considerably in different oceans or seas, but the ratio of the different constituents to each other is nearly constant.[9] Moreover, the Atlantic Ocean has an average concentration very near that of the average composition given, or 35,000 parts per million of total solids.

Aside from its much greater concentration sea water differs in composition from Connecticut ground water in its very high proportion of chloride, especially as compared with sulphate and carbonate radicles, and in the fact that magnesium is present in much greater quantity than calcium, while silica is nearly negligible.

[9] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 123, 1920.

The high proportion of chlorides, especially sodium chloride, or common salt, is the paramount feature of sea water.

The complete analysis of the salts in any water is a laborious and time-consuming process, and for that reason a short cut is generally used to determine the approximate amount of contamination by sea water. As chloride is so characteristic a constituent of sea water and can be determined very easily and accurately by simple chemical tests, it is generally used as the criterion by which to judge the amount of contamination by sea water. This is true not only in the present report but in practically all the previous investigations which are cited herein. The actual test usually consists of a determination of chloride (Cl),[10] which is the acid radicle in sodium chloride (NaCl), or common salt. But in accepting the presence of chloride as an indication of sea water discrimination must be used, for the chloride may come from sources other than the sea. In some regions it may have been leached from the rocks and so be a normal constituent of the ground water. Very little chloride is to be expected from the rocks of Connecticut, however. The Triassic rocks would be most likely to yield chloride, but the quantity that can be attributed to them does not exceed about 10 parts per million. A small amount of chloride in the ground water of Connecticut and in other coastal regions is due to wind-blown salt spray carried over the land, especially on atmospheric dust, and brought down by rains. Chloride from this source has come to be known as "normal chlorine," and on the New Haven coast runs from 3 to 6 parts per million, decreasing rapidly inland.[11] Such small amounts of chloride are insignificant in comparison with the amounts of contamination considered here. A third and important source of chloride in ground water is sewage and other animal waste. This factor must be carefully considered in interpreting the results of any given analysis. However, even water polluted by cesspool or barnyard drainage seldom contains chloride in excess of 25 to 100 parts per million except where the site is very poorly chosen. In this investigation samples from such wells were rejected.

As a guide to field observations it was necessary to have a convenient method for determining on the spot the approximate degree of contamination in many wells. Accordingly a small assay kit was carried in the field and chloride tests were made wherever desired. The test consisted in titrating a measured quantity of water with a standard solution of silver nitrate ($AgNO_3$), potassium chromate (K_2CrO_4) being used as an indicator. This is a standard laboratory test and can be made in less than 5 minutes. The apparatus con-

[10] The term chloride in this paper will be understood to mean chloride radicle (Cl) unless otherwise specified.

[11] Jackson, D. D., The normal distribution of chlorine in the natural waters of New York and New England: U. S. Geol. Survey Water-Supply Paper 144, 1905.

sisted of a 50 cubic centimeter measuring cylinder, a small pipette graduated to twentieths of a cubic centimeter, a white porcelain dish, a stirring rod, and small bottles of silver nitrate solution and potassium chromate solution. In nearly all places where tests were made in the field, check samples were collected and submitted to the water laboratory of the United States Geological Survey in Washington. The comparison of results obtained in the field and in Washington indicates that for its intended use this field method was entirely satisfactory. The field results seldom vary more than a few per cent from those of the laboratory and are frequently almost identical. Such errors as arose in field work were due to difficulties in keeping the apparatus clean, as some dust collected on the glassware and no distilled water was carried for rinsing. After experience had indicated the results to be expected, it was often unnecessary to perform field tests, and laboratory samples only were collected. In addition to the samples for chloride determination, a few samples were collected for more complete analysis, particularly for the purpose of checking up the value of the chloride content as an indication of the presence of sea water.

Samples were collected from all wells or springs that appeared likely to yield instructive evidence of either the presence or the absence of salt water. In many places samples were taken at several different times to note any seasonal or other fluctuations in the quality of affected water. Samples were collected from certain wells at high tide and at low tide and at hourly periods to determine any possible relations between stage of tide and quality. Samples at hourly or shorter intervals were taken during the pumping of water from wells to see if any definite variations could be ascribed to this cause.

The statements of users of affected water as to its characteristics and variations were recorded and if possible verified.

SOME RESULTS OF PREVIOUS INVESTIGATIONS

GENERAL REVIEW

Before considering in detail the data gathered in Connecticut and elsewhere the salient results of previous investigations will be reviewed. In the United States and its territories the subject of contamination of coastal ground water has not been studied thoroughly, although it has been considered incidentally in several reports. The literature of coastal ground water in the United States and several foreign countries is reviewed on pages 84–97.

On most coasts fresh water is usually obtainable, even very near the shore, in shallow wells, but many deep wells, even at some distance from the shore, are brackish. Lindgren [12] shows that on

[12] Lindgren, Waldemar, The water resources of Molokai: U. S. Geol. Survey Water-Supply Paper 77, pp. 26–47, 1903.

Molokai, Hawaii, fresh water occurs in a thin body above the salt water that pervades the mass of the porous rock of the island. The fresh water and salt water mingle in an intermediate brackish zone. The fresh water is discharged by numerous springs along the beach. In Florida Sanford [13] found conditions somewhat like those in Molokai. In the porous limestone of the keys fresh water floats in a thin sheet above salt water. In sand and in beach ridges the depth of fresh water is greater, and on the mainland fresh water is obtainable in shallow wells very near shore. Many drilled wells in crystalline rocks on the Maine coast, particularly on small islands, yield salt water,[14] or they may yield fresh water at first and brackish water after pumping for a time.

The presence of fresh artesian water beneath salt water along certain coasts and coastal islands is a well-known phenomenon. This occurs where porous beds that have a fresh-water intake at their outcrop dip seaward but are protected from the entrance of sea water by an overlying impervious bed. Such conditions exist at places on the Atlantic Coastal Plain, in the south end of San Francisco Bay, and elsewhere. Submarine springs of fresh water have also been recognized at many places, particularly off the coasts of Florida [15] and Hawaii. [16]

Geologists and engineers have long recognized that pumping may seriously affect the quality of water in wells near seacoasts. When wells near the shore are heavily pumped the water table may be sufficiently lowered to establish a reversed movement. Mason [17] calls attention to city supplies in Liverpool and in Galveston, Tex., that were ruined by sea water induced by overpumping. Lindgren [18] describes pumping tests on Molokai in which the salt content of wells increased markedly. Dubois [19] has recorded similar facts in Holland, and Herzberg [20] in Norderney, off the German coast. Perhaps the best illustrations of the effects of overpumping are those from the coast of England, where information from many wells has been recorded. (See references, pp. 91–93.)

The influence of tides upon the water table has been mentioned by many writers, and it is popularly supposed that nearly all wells near the sea rise and fall with the tides. A careful investigation of flow-

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[13] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, p. 261, 1913.

[14] Clapp, F. G., Underground waters of southern Maine: U. S. Geol. Survey Water-Supply Paper 223, p. 67, 1909.

[15] Matson, G. C., and Sanford, Samuel, op. cit., pp. 289, 397.

[16] Lindgren, Waldemar, op. cit., p. 26.

[17] Mason, W. P., Water supply, p. 336, New York, John Wiley & Sons, 1905.

[18] Lindgren, Waldemar, op. cit., p. 44.

[19] Dubois, Eugène, Études sur les eaux souterraines des Pays-Bas: Musée Teyler Archives, 2d ser., vol. 9, pp. 1–96, Haarlem, 1905.

[20] Herzberg, Baurat, Die Wasserversorgung einiger Nordseebäder: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901.

ing artesian wells on the Long Island coast has been made by the United States Geological Survey.[21] Fluctuations as great as 5 feet between tides are recorded. Similar fluctuations in the water level of flowing wells near the shore are authoritatively recorded from South Carolina [22] and San Francisco Bay (see references, p. 88), and have been noted in France. The fluctuations of nonflowing wells near the sea have not been so widely studied. Dubois [23] and others give figures for such fluctuations and many such fluctuations are reported from England.

THE THEORY OF BADON GHYBEN AND HERZBERG

Wherever a coast is formed of pervious rocks containing ground water that receives continual additions from rainfall, this ground water must move downward and laterally toward the shore and mingle ultimately with the salt water of the sea. Such movements have long been a matter of common knowledge. Even on small porous, sandy islands fresh water can generally be found at an altitude slightly above mean sea level. It might be supposed that in such places the salt water surrounding the island would penetrate the sand to mean sea level and immediately absorb all the fresh water that might percolate downward to its surface. For several physical reasons this does not happen. Such islands are found, in reality, to contain a dome-shaped lens of fresh water floating upon a concave surface of salt water. The fresh water is enabled to float upon the salt water because it has a considerably smaller density. This principle was apparently first applied to the hydrology of seacoasts by Badon Ghyben,[24] a Dutch captain of engineers, as the result of investigations made in Holland in 1887 (see p. 93), but gained little notice from hydrologists at that time. It was also published about 1900 by Herzberg,[25] of Berlin, who apparently had no knowledge of the work of Badon Ghyben. Herzberg found in drilling wells on the island of Norderney, one of the East Friesian islands off the coast of Germany, that the depth to salt water was roughly a function of the height of the water table above mean sea level and of the density of the water of the North Sea. Figure 2 shows the application of his theory.

Let H = total thickness of fresh water.
h = depth of fresh water below sea level.
t = height of fresh water above mean sea level.

[21] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, New York: U. S. Geol. Survey Water-Supply Paper 155, 1906.

[22] Artesian wells (municipal report of the city of Charleston, S. C.), p. 18, 1881.

[23] Dubois, Eugène, op. cit.

[24] Badon Ghyben, W., Nota in verband met de voorgenomen put boring nabij Amsterdam: K. Inst Ing. Tijdschr., 1888–89, p. 21, The Hague, 1889.

[25] Herzberg, Baurat, Die Wasserversorgung einiger Nordseebäder: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901.

Then $$H = h + t.$$

But the column of fresh water H must be balanced by a column of salt water h in order to maintain equilibrium. Wherefore, if g is the specific gravity of sea water and the specific gravity of fresh ground water is assumed to be 1,

$$H = h + t = hg$$

whence $$h = \frac{t}{g-1}.$$

In any case $g-1$ will be the difference in specific gravity between the fresh water and the salt water. Herzberg gives the specific gravity of the North Sea as 1.027, whence $h \doteq 37t$.

Drillings on Norderney and islands near by are said to have given results varying but a few meters from those derived from the formula, but it is not clear whether the salt water encountered at the expected depths was of approximately the composition of sea water or was merely too salty for use.

As Herzberg's paper appeared at a time when there was great interest in coastal water supplies in the Netherlands, particularly at

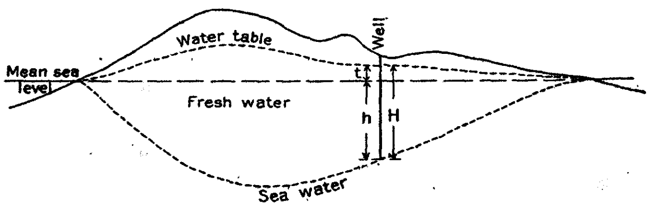

FIGURE 2.—Section of the island of Norderney, Germany, showing the application of Herzberg's theory. (From Herzberg)

Amsterdam, and in Belgium, it was widely quoted and much discussed by Dutch, Belgian, and French writers, whose principal works are reviewed in this paper (pp. 93–97). The law of equilibrium between salt and fresh water is frequently alluded to as the "theory of Herzberg." This theory appears to apply particularly to small islands and narrow land masses that are made up of freely pervious material, especially sand. It can not be applied to large land bodies or to continents, for it implies that sea water should be found in every locality where the water table is below sea level. There are well-known interior land areas which lie many feet below sea level but in which the ground is entirely free from sea water. The application of the theory is also greatly modified by the kind of rocks and their structure. The importance of Herzberg's theory, however, is not to be ignored and has been most convincingly demonstrated by Pennink [26] on the coast of Holland. The most significant results of this investigation are summarized below.

[26] Pennink, J. M. K., De "prise d'eau" der Amsterdamsche duin waterleiding: K. Inst. Ing. Tijdschr., 1903–4, pp. 183–238, The Hague, 1904.

RELATIONS OF SALT AND FRESH WATER ON THE COAST OF HOLLAND

The Amsterdam water supply about the year 1900 was derived from open drainage channels sunk below the water table in a belt of dunes on the Holland coast. This belt of dunes is about 5 miles (8 or 9 kilometers) wide, and its crest is 10 to 20 meters above sea level. It is bordered on the west by the North Sea and on the east by a belt of polders [27] 4 to 6 meters below sea level, which were created by dewatering the Sea of Haarlem about 1850. In seeking to supplement the Amsterdam water supply, a line of test wells was driven across the belt of dunes. Chloride determinations were made on the ground water at many different depths in these wells, and a cross section showing the actual contact between fresh water and underlying salt water was constructed, as shown in Figure 3. It is clear that salt water actually underlies the land at a depth of 100 to 200 meters below sea level over a belt several miles in width adjacent to the Holland coast; that the depth to salt water is greatest where the land and its underlying body of fresh water are highest; and that the level of salt water rises under areas of low ground which have a depressed water table, such as the polders of the old Sea of Haarlem.

Certain irregularities in the distribution of salt and fresh water are easily accounted for by the local geology. Near the surface the dunes consist of sand. Beneath this sand, to a depth of 20 or 30 meters below sea level, are alternating beds of sand, sandy clay, and peat. Below that is an indefinite thickness of coarse sand and gravel with lenticular clay beds. The varying permeability of these strata accounts for some irregular lenses of salt water surrounded by fresher water. The general line of contact between salt and fresh water is very regular, however, and the zone of gradation, or diffusion, is surprisingly thin. (See pp. 34–37.)

LABORATORY EXPERIMENTS APPLIED TO COASTAL GROUND WATER

D'Andrimont,[28] a Belgian geologist who has written extensively on coastal ground water, has investigated the relation between saline and fresh waters by means of experiments in which conditions were made as nearly as possible analogous to those on coasts. Below is given a translation of his description of his most important experiment.

> De Heen, professor of physics at the University of Liege, having courteously placed his laboratory at my disposal, I began a series of experiments upon the permeability of earth and the circulation of ground water. I desired, in parti-

[27] In the Netherlands and Belgium the term "polder" is applied to a tract of marshy land lower than the sea, which has been diked and reclaimed to cultivation.—Standard Dictionary.

[28] D'Andrimont, René, Note préliminaire sur une nouvelle méthode pour étudier expérimentalement l'allure des nappes aquifères dans les terrains perméables en petit: Soc. géol. Belgique Annales, vol. 32, pp. M 115–M 120, 1905.

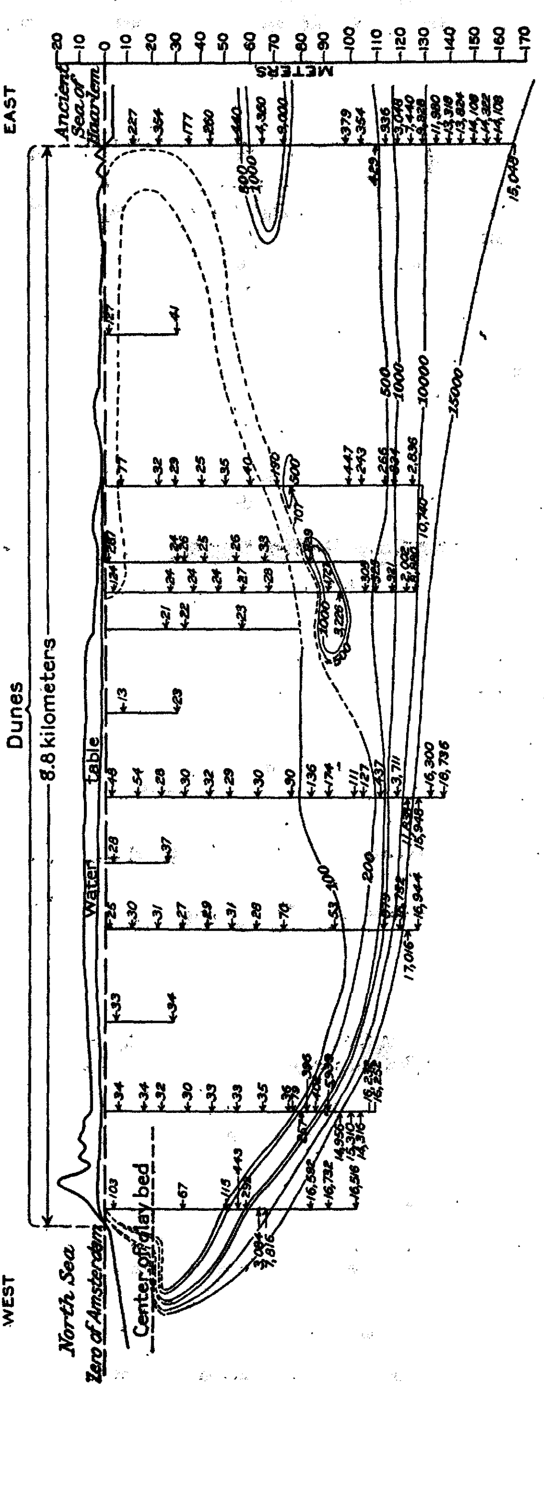

FIGURE 3.—Relations between salt and fresh water on the Holland coast. (Redrawn from Pennink.) Figures give milligrams of chloride per liter

cular, to attain in a glass vessel, 60 centimeters square and 30 centimeters high, the condition of ground water near the sea as I have always conceived it.

* * * * * * *

The vessel was filled with dune sand. I gave the sand a profile resembling as nearly as possible that of the Belgian coast. I inclined the vessel in such a way that the surface of the sand and the impervious bottom of the vessel sloped slightly toward the lowest point of the profile, which represented the North Sea. First, into the depression representing the sea I poured a solution of potassium bichromate, of a density equal to that of sea water, so that all the sand was saturated by capillarity and given an orange-yellow color up to the level corresponding to sea level. Next, I poured uncolored fresh water upon the surface representing the continent. I had previously placed at certain places along the walls of the glass some grains of potassium permanganate, in order that the colored streams flowing from them would indicate definitely the path taken by a drop of water after the moment it reached the ground water level.

These are the phenomena I observed:

The saline, yellow-colored water was repelled toward the bottom of the vessel. The depth to the zone of contact was everywhere proportional to the height of the fresh-water surface. The form of the contact surface was exactly that (fig. 1)[29] which I suggested in the first article [30] that I published on this subject May 25, 1902, although my only information at the time was the observations made upon the island of Norderney, which showed that a lens of fresh water could float upon salt water of greater density.

A very inconsiderable zone of diffusion was formed. After standing eight hours, the distinction between the saline and the fresh water was quite sharp. At the same time I performed the opposite experiment; that is, I poured saline water upon fresh water; after a very short time the saline water had mingled with the fresh. During all the time I was adding fresh water it flowed out along the artificial beach. The water had an upward movement all along the beach.

When an artificial drain was made upon the upper part of the body of fresh water, a protuberance was formed in the contact surface between the fresh and salt water.

If an oscillation comparable to a tide was created, the contact surface between the fresh and salt water oscillated also.

D'Andrimont in another paper [31] describes extensive experiments made by Pennink,[32] some of which verified his own opinions regarding coastal ground water.

Whittaker [33] has conducted many experiments on the filtration of saline coastal water through different materials and has found that great variations can be produced in the chemical composition of mixed sea water and ground water by this means. As a result he has concluded that "By varying the source of the Chalk water and the proportion of sea water, I think every water from the Chalk and Thanet sand could be imitated."

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[29] D'Andrimont's Figure 1 is practically the same as Figure 2 of the present paper, p. 17.

[30] D'Andrimont, René, Notes sur l'hydrologie du littoral belge: Soc. géol. Belgique Annales, vol. 29, fig. 5, p. M 136, Liège, 1902.

[31] D'Andrimont, René, Sur la circulation de l'eau des nappes aquifères contenues dans des terrains perméables en petit: Soc. géol. Belgique Annales, vol. 33, Mém., pp. 21–33, Liège.

[32] Pennink, J. M. K., Over de beweging van grondwater: De Ingenieur, No. 30, July 29, 1905.

[33] Whittaker, William, The water supply of Essex from underground sources: Great Britain Geol. Survey, 1916, pp. 24–34.

CONTAMINATION IN SHALLOW WELLS

Shallow wells on the New Haven coast are either dug or driven and usually end in drift. Most of them are in stratified drift. As a rule the dug and driven wells are less than 30 feet deep. The table below gives a summary of the data on contamination in such wells near the shore. Distances from the shore were generally obtained by pacing, and altitudes above sea level were estimated from the topographic maps. Altitudes above normal high tide were obtained by hand level. All altitudes given represent the land surface at the wells.

Different degrees of contamination, based on the following arbitrary scale, are distinguished. The presence of 25 to 100 parts per million of chloride, where no cause for pollution is evident, is considered to indicate a trace of sea water. The presence of 100 to 300 parts per million of chloride is considered definite evidence of contamination. The presence of chloride of 300 to 1,000 parts per million, which is generally readily apparent to the taste, indicates a high degree of contamination. Water that contains more than 1,000 parts per million of chloride is very unpalatable and is considered highly contaminated, although the actual percentage of sea water may be small. If determinations were made of two samples taken from the same well on different dates both are given. If determinations were made of samples taken on more than two dates the minimum and maximum figures for chloride are given. Detailed descriptions of the wells listed are given under the corresponding numbers on pages 58–83.

Contamination by sea water in shallow wells on the coast of Connecticut

No. on Plate I	Distance from shore line at high tide	Elevation above mean sea level	Elevation above average high tide	Chloride radicle (Cl)[a]	Apparent degree of contamination by sea water
	Feet	*Feet*	*Feet*	*Parts per million*	
1	150		3		Reported very salty.
2	500	25		8.4	None.
3	250	40		7.6	Do.
7	150	20			Do.
8	200	20			Do.
9	100		18	10	Do.
10	500	20			Reported none.
12	100		5	21	Slight, if any.
13	20		4	98	Trace.
14	60		3		Reported brackish.
16	75	5			Ruined by storm tides.
17	200	10		174	Probably a trace.
18	200	12	14		None.
19	50		5		Reported none.
46	50	10			Do.
47	50		8		Do.
50	500		5	[b] 21	None.
52	25		2	7.8	Do.
53	75		10	164	Definite.
55	100		8	94	Trace.

[a] Determinations by Margaret D. Foster and others.
[b] Field test by J. S. Brown.

Contamination by sea water in shallow wells on the coast of Connecticut—Continued

No. on Plate I	Distance from shore line at high tide	Elevation above mean sea level	Elevation above average high tide	Chloride radicle (Cl) [a]	Apparent degree of contamination by sea water
	Feet	*Feet*	*Feet*	*Parts per million*	
56	400	10			None.
57	150	10			Reported none.
58	50		2.5		Do.
59	125		4	86	Trace.
60	250		8	21	None.
61	10		3		Reported very brackish.
62	6		4		None.
63	25		7	9.4	Do.
64	In salt marsh.		1	[b] 209	High.
66	10		1	37	Probably a trace.
67	50		5	[b] 12	None.
68	100		7	43	Trace.
69	600	20		[b] 10	None.
70	5		1	15	None except when covered by tides.
71	50	15		315	Definite. Apparent to taste.
72	100	10			None.
73	375	20		21	Do.
74	250		4	49	Slight, if any.
75	50		5	39	Do.
77	100	15		49	Probably a trace.
78	50	10		46	Do.
79	100	10		15	None.
80	75		4	[b] 31	Very slight, if any.
81	250		18		None.
82	250		18		Do.
83	100		4		Reported very salty.
84	75		5		Reported none.
85	100		16		Do.
86	100	10		21	Do.
87	50		7		Reported brackish
88	100		5	25	Probably none.
89	0		2	1930	Very high. Not usable.
90	100		18		None.
92	250		14	31	Do.
93	75		11	12	None. Reported brackish when very low.
94	75		8	11	Do.
95	150		8	156	Evident.
96	150		7		Reported none.
97	150		25	28	None.
99	100		14		Do.
100	100		4	83–607	High. Apparent to taste
101	250	10			None.
102	25		14	20, 28	Reported occasionally brackish.
103	50		3	22, 96	Trace.
104	200		5	11, 13	None.
105	50	8			Do.
107	150	15			Do.
113	25		7	29, 64	Probably a trace.
114	150		5		None.
115	200	10			Do.
116	100	5–10			Do.
117	50	5			Do.
122	25		4		Reported brackish.
123	50		5.5		Do.
124	75		5	60	Trace.
126	250	20		25 & 26	None.
130	200–300	20		25	Probably none.
131	75	10		40	Do.
132	100		4	77	Trace.
133	25		2	157	Definite.
135	700	10		13	None.
136	125	10		48	Trace.
137	100		14	158	Definite.
138–142, 144–146	150–500	5–20			None.
147	90		2.5		Probably none.
148	100		3	51 & 75	Trace.
149	100		7		Reported none.
150	500	20		7.2	None.
151	100	10		13	Do.
152	25		2	1230	Very high.
153	250	15		90	Probably a trace.
155	200–300	15		12	None.
156	10		4	12	Do.

[a] Determinations by Margaret D. Foster and others. [b] Field test by J. S Brown

Contamination by sea water in shallow wells on the coast of Connecticut—Continued

No. on Plate I	Distance from shore line at high tide	Elevation above mean sea level	Elevation above average high tide	Chloride radicle (Cl)[a]	Apparent degree of contamination by sea water
	Feet	*Feet*	*Feet*	*Parts per million*	
157	100	10			None.
158	100	10			Do.
159	100	10		17	Do.
160	350		2	9.7	Do.
161	135		3.5	122	Definite.
162	150	10			None.
163	150	10			Do.
164	50		7.5	39	Trace.
165	100		18		None.
166	50		2		Do.
167	125		5.5		Do.
168	115		5.5		Do.
169	300	10			Do.
170	250	10			Do.
171	95		3.5	18	Do.
172	80		4	16	Do.
173	400	5			Do.
174	150	15			Do.
185	400-500	10			Do.

[a] Determinations by Margaret D. Foster and others.

Relation of contamination by sea water in shallow wells to distance from shore line at high tide on the coast of Connecticut

	Number of wells	Wells contaminated	
		Number	Per cent
More than 100 feet from shore line at high tide	54	8	14.8
50 to 100 feet from shore line at high tide	35	14	40
Less than 50 feet from shore line at high tide	30	17	56.6

The most striking conclusion from the data presented above is that on the New Haven coast the zone in which the shallow ground water is contaminated by percolation or diffusion of salt water is extremely narrow. The greatest distance from the shore at which contamination, even a trace, is suspected is 250 feet (No. 153), and contamination more than 100 feet from the high tide shore line is unusual. Wherever there is a body of land whose area is measurable in acres—even though it is a small island or a narrow peninsula—there is a body of fresh ground water supplied by the rainfall upon the area. Along the shores of extensive bodies of land beneath which there is a permanent water table, ground water is fresh to the very verge of the high-tide shore line, and the only zone of contamination is that between the limits of low and high tide. Within the zone of contamination the ground water becomes very salty at high tide and freshens as the tide recedes. On sandy beaches fresh water often seeps from the beach sand at low tide. Lanphier Spring (No. 70), in Branford, is a good example. This spring issues from beach sand at the foot of a low sea cliff cut in stratified drift. Normal high tides do not overtop it, but perigee tides and storm tides completely cover the outlet. The water remains salty, however, only for an hour or two after the recession of the tide. The sample collected June 28, 1919, tested 15 parts per million of chloride, a normal amount for uncontaminated water.

The same conditions have been observed by the writer at Cedar Keys, Fla., where the ground water is fresh to the shore line. Open pits are often constructed on the beaches of small islands to furnish water for stock. The pit shown in Plate VI, *A*, is about 40 feet from the reach of average high tides but is flooded by storm tides. Several shallow dug and driven wells, the location of which is shown in

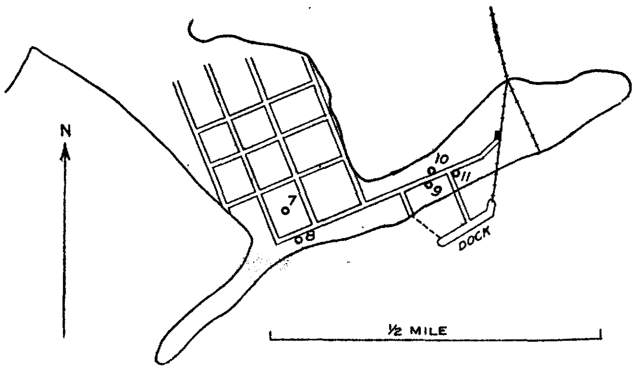


FIGURE 4.—Map of Cedar Keys, Fla., showing location of wells sampled

Figure 4, were also examined. Results of chloride tests of water from Cedar Keys and vicinity are given in the following table:

Contamination by sea water in shallow wells near Cedar Keys, Fla.

Number	Type of well	Distance from shore line at high tide	Chloride (Cl)[a]	Apparent degree of contamination by sea water
		Feet	*Parts per million*	
1	Driven (abandoned)	60	----------	Good domestic water.
2	Open pit	40	195	Definite.
3	Driven	100	571	High. Noticeable to taste.
4	Open pit	40	516	Do.
5	do	40	1,400	Very high.
6	do	120	92	Probably a trace.
7	Dug	350	55	Do.
8	Driven	125	15	None.
9	do	150	72	Probably a trace.
10	do	150	27	Unknown.
11	do	200	30	Do.
12	Dug	150	205	Definite.

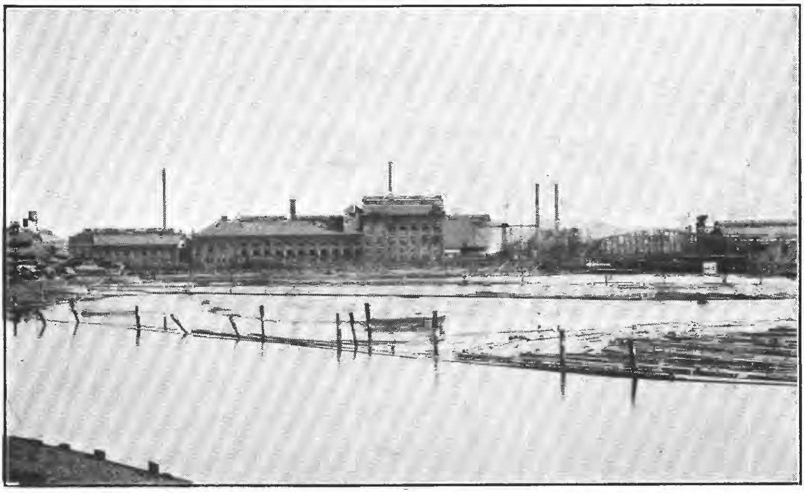
[a] Determinations by Margaret D. Foster.

The annual rainfall at Cedar Keys is very nearly the same as at New Haven, and the sandy ground is comparable to the stratified drift of Connecticut. It is plain from the above table that at Cedar Keys, as on the New Haven coast, contamination of ground water by sea water affects shallow wells only in a very narrow zone, not

A. WATER HOLE YIELDING FRESH WATER ON THE BEACH OF A SMALL ISLAND NEAR CEDAR KEYS, FLA.

B. HOUSE OF ROBERT MITCHELL, SOUTHWEST OF GUILFORD, CONN.

Well 110 just in the rear



A. PLANT OF NEW HAVEN GAS LIGHT CO., NEW HAVEN, CONN.

View from freight yards near bridge, showing proximity of wells to tidewater

B. VIEW OF NEW HAVEN, CONN., FROM EAST ROCK

Showing salt marshes of Mill River

more than 200 feet from the shore. Wells 7 and 12 are pumped heavily, and their salt content is more probably due to the effects of pumping than to original salinity.

The conclusion that sea water mingles with the shallow ground water over only an insignificant area near the shore line appears to apply to nearly all coasts under natural conditions. Wherever the natural conditions are disturbed, however, as by a heavy drain due to pumping, conditions are immediately altered, and contamination may extend for great distances inland. It would be logical to suppose that on arid coasts, where rainfall is insufficient to maintain a body of fresh ground water, sea water would penetrate to a much greater distance inland, but data on the matter are lacking. Undoubtedly, too, the character and structure of the rocks along shores influence the ease of penetration of salt water inland. We have just seen that on sandy parts of the Florida coast fresh water saturates the ground to the shore. Yet Sanford[34] says that the main Florida Keys, which are composed chiefly of limestone very full of seams and crevices, "may be underlain by salt water at about tide level; this is the condition in islands as wide as 3 or 4 miles in the Bermudas and also on many Florida Keys." A most remarkable and obvious example of the penetration of sea water inland into fissured limestone is afforded by the so-called sea mills of the island of Cephalonia[35] in the Mediterranean Sea. On the shore of this nearly tideless sea a stream of salt water flows down a channel a few hundred feet in length and disappears into caverns in the limestone. At one time the stream was utilized to turn a mill. Where the water goes is not known, but it probably returns to the surface in some unknown locality, possibly through a submarine outlet. Crosby and Crosby suggest heating at depth as the cause of circulation, and Fuller suggests a mixture of fresh and salt water so proportioned as to sustain a permanent flow in the form of an inverted siphon.

CONTAMINATION IN DEEPER WELLS

The deeper wells on the New Haven coast are usually drilled with the percussion type of drill rig and are practically all 6 inches in diameter. Wells 100 to 300 feet deep are fairly common as sources of domestic water supply. A few wells of greater depth have been drilled by manufacturing concerns in the hope of obtaining supplies of water for industrial use, but most of these have been failures, either because the quantity of water was insufficient or because its quality was unsatisfactory. Although the number of deep wells

[34] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, p. 261, 1913.

[35] See Crosby, F. W., and Crosby, W. O., Massachusetts Inst. Tech. Quart., vol. 9, pp. 6–23, 1896. Also Fuller, M. L., Geol. Soc. America Bull., vol. 18, pp. 221–232, 1907.

near the shore on which reliable data were obtainable is small, the data are of considerable value. These data are summarized in the following table. If determinations were made of two samples taken from the same well on different dates both are given. If determinations were made of samples taken on more than two dates the minimum and maximum figures for chloride are given. Detailed descriptions of the wells listed are given under the corresponding numbers on pages 58–83.

Contamination by sea water in deeper wells on the coast of Connecticut

No. on Plate I	Distance from shore line at high tide	Elevation above mean sea level	Elevation above average high tide	Depth	Chloride radicle (Cl) [a]	Apparent degree of contamination by sea water
	Feet	*Feet*	*Feet*	*Feet*	*Parts per million*	
11	200	25		85	12	None.
15	250	20		35	29	Probably none.
48	50	15		150		Salty. Abandoned.
54	35		10	23	26	None at present. Originally bad.
65	300	10		65	11	None.
76	[b] 100	5		503		Reported very salty. Abandoned.
91	50		7	60		Reported brackish.
98	60		12	150		Reported variable.
108	100		5	90		High. Abandoned.
109	50		5	65	23	None (?).
110	50		6	27?	31–125	Definite.
111	100		7	90	182; 409	High. Worse when used.
112	75		3	38		Reported none.
118	250	15		100		Do.
119	250	15		100		Do.
120	250	15		50		Do.
121	250	15				Do.
125	100	15		50	37–516	High. Unusable at times.
127	250	20		63	24; 26	None.
128	100		15	40	18; 19	Do.
129	200	20		50	17	Do.
135	700	10		300	35	Uncertain.
143	300		5	150	11	None.
154	200	15		52.5	4.7	Do.
175	500	30		300–400	169	Uncertain.
176	100	20		70		Reported none.
183	[b] 100	5		610		Very salty. Abandoned.
184	250?	5		212		Do.
186	[b] 400	5		257		Do.

[a] Determinations by Margaret D. Foster.
[b] On filled land.

This table shows that of 29 recorded wells ten were definitely contaminated and two others (Nos. 135 and 175) were suspected of being slightly contaminated. Another well (No. 54) was once bad but was remedied by partial filling at the bottom. It is probable also that some of the wells for which no analyses are available would on analysis show a slight degree of contamination. It appears therefore that about half the drilled wells in a zone a few hundred feet wide along the shore show some evidence of contamination. Moreover, as wells that yield bad water are generally abandoned and forgotten, and as the records of such failures are almost impossible of discovery and verification, the ratio is actually higher. Nearly all the drilled wells on the New Haven coast penetrate bedrock and draw their water from open joints and crevices. The possibility of obtaining water of any kind from the crystalline rocks is difficult of prediction, and the result of attempts to determine in advance whether the water in deep wells will be salt or fresh is doubly uncertain. One well may penetrate crevices connected only with the fresh ground water and may yield water of good quality very near the shore; another may penetrate crevices connected with the sea and yield only salt water.

It is certain, however, that the danger of obtaining salt water increases greatly with the depth of drilling, and that if salt water is once reached there is very little chance of finding fresh water at greater depth. The following examples, more fully considered under the individual descriptions, represent the general experience of well drillers in this respect:

Well 54, originally 35 feet deep and ending in crystalline rock, at first yielded good water, but after a severe storm the water became brackish. The bottom of the well was then filled with earth and shells to a depth of about 10 feet, after which the water became fresh again and has remained so. Well 76 was drilled on a filled-in tidal marsh near Branford River. It penetrated 40 feet of stratified drift and 463 feet of bedrock. The water was bad all the way down and was very salty at the bottom. Well 246 yielded good water at a depth of 60 feet in bedrock but encountered salt water below that depth and was abandoned at about 90 feet. Well 183, on filled land in Bridgeport Harbor, penetrated 90 feet of stratified drift (sand) and ended in bedrock at 610 feet. It yielded salt water both in the sand and in the bedrock. At 500 feet it was sealed with a watertight casing, but only salt water was obtained below. Well 184 was very much like well 183. Well 186 was on filled land in an old tidal marsh and penetrated stratified drift to 196 feet, then bedrock to 257 feet. The water was salty practically from the surface. A reliable report from Rowayton describes a drill hole 1,600 feet deep which yielded salt water all the way. As a rule in Connecticut fresh water does not occur below salt water—in fact, its occurrence in that position could hardly be expected on such a shore, where the rocks are uniformly porous from the surface down. As salt water is heavier than fresh water it is practically certain that once a body of salt water is reached, all the underlying water will be saline. Of course exceptions are doubtless to be found in the crystalline rocks, where fractures containing only fresh water may exist below fractures filled with salt water.

It should, however, be clearly understood that there are many coasts where beds containing salt water are sealed off by impervious beds from underlying beds containing fresh water. This is particularly true of such coastal plains as our Atlantic Coastal Plain, where alternating pervious and impervious sedimentary beds dip seaward at low angles. Even in New Haven Harbor there is a small but good example of this structure, which affords an exception to the rule that fresh water does not occur beneath salt water on the New Haven coast.

The distance inland at which salt water may be expected in deep wells on the New Haven coast probably does not exceed 500 feet at most places, because of the fact that water-bearing fractures in the bedrock are practically absent a few hundred feet below the surface, and there is very little circulation of ground water. Contamination in wells 135 and 175, which are 700 feet and 500 feet, respectively, from the shore line at high tide, is reported as uncertain, but they probably have a slight trace of sea water. Well 135, which is a deep well drilled in the bottom of a shallow dug well, shows only 13 parts per million of chloride in the water of the dug well and 35 parts in the water of the deeper well. According to Herzberg's theory and the results of the drilling in Holland, the chloride should increase with depth if sea water is present in the rocks at all. There is no apparent cause of pollution from the surface in the deeper water—in fact, surface pollution would be much more likely in the shallow well. Well 175 is in a thickly settled area in Bridgeport, on the grounds of a large factory, and the chloride content of its water may possibly originate from sewage; therefore, it is uncertain whether the contamination can be correctly attributed to sea water.

The safe ratio of depth of well below sea level to distance from the shore is hard to estimate but is placed at about 1 to 1—that is, a well 100 feet from the shore line at high tide should not be drilled more than 100 feet below sea level if any fresh water has been obtained above. If an approximately adequate supply can be obtained nearer the surface it is, indeed, much better to use a lower ratio and drill no deeper than is absolutely necessary. The lowest ratio of depth to horizontal distance from tidewater in a badly contaminated well is that of No. 125, which is 100 feet from shore and extends to only about 35 feet below sea level, a ratio of about 1 to 3. This well is exceptional, however, and the ratio of 1 to 1 is believed to be generally safe.

CONTAMINATION UNDER SPECIAL TOPOGRAPHIC AND GEOLOGIC CONDITIONS

TIDAL MARSHES

Very few wells are sunk within the limits of tidal marshes, probably in part because the land is not used and in part because the water is generally bad. The only well in a tidal marsh is No. 64, which is a shallow pit about 4 feet deep, around which a bank of earth has been thrown up to exclude tidewater. A field test April 15, 1919, showed

209 parts per million of chloride in the water, which is evidence of contamination, but in a degree much less than might have been expected. Well 13, driven 30 feet deep on the edge of a tidal marsh, shows 98 parts per million of chloride, which is also remarkably low. Well No. 152 is a shallow driven well on the edge of a tidal marsh not more than 25 feet from the daily reach of high tides. Figure 5 shows the relation of this well to the tidal marsh and to the beach. The land between the marsh and the beach is only 3 or 4 feet above high tide. The water is highly saline, containing 1,230 parts per million of chloride. The water of well 89, on the very edge of a tidal marsh, is even more saline, containing 1,930 parts of chloride.

The conclusion seems warranted that most of the tidal marshes contain brackish ground water. As a rule the salinity of the ground water is much less than that of sea water, because the tidal water which overflows the marshes is diluted by fresh water from streams as well as directly by rainfall. The underlying ground water is often further diluted by fresh ground water seeping from adjacent areas. In the more or less stagnant marshes, such as those of Milford, Madison, and Clinton, which receive but little inflow from streams and are separated only by low, narrow strips of land from the sea, the ground water is probably very saline. These marshes may be compared to the dunes and polders of the Sea of Haarlem, in Holland, where salt water rises nearly to the surface. (See p. 18 and fig. 3.)

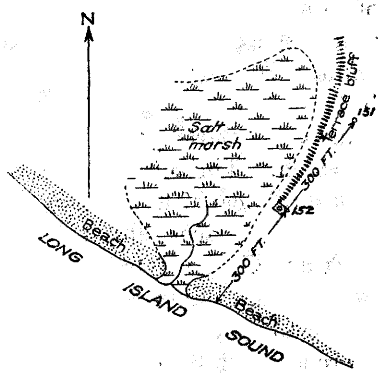


FIGURE 5.—Sketch map of vicinity of well 152, west of Clinton, Conn., showing relation of well to tidal marsh

In narrow tidal marshes along river estuaries the ground water is much fresher. The tidal marshes of Quinnipiac River, Mill River, and West River are so blanketed by a thick cover of impervious mud that the salt water is excluded from the underlying stratified drift, as explained on pages 33–34.

BAR BEACHES AND SPITS

Bar beaches and spits (see p. 7) have seldom been chosen as locations for wells. Numerous indefinite reports were obtained of wells in such places, most of which had been abandoned, but only a few were worthy of record. Well 1 is on the sandy spit known as Milford Point, at the old Smith place, now owned by Mrs. Warner and Mrs. Ford. The spit at that point is about 300 feet wide and is barely above storm tides. The sand, which is slightly wind-worked, supports a scanty growth of coarse grass, shrubs, and a few cottonwood and cedar trees. The owners state that many attempts to get usable water at their house have failed. One well 8 or 9 feet deep is said to have yielded fresh water for a few hours but became "salty as the ocean" at high tide. They now use cisterns entirely. Practically the same thing occurred on a bar beach in Branford at the abandoned Lounsbury well (No. 83). Mrs. Farnsworth reports that on the narrow bar beach west of Savin Rock, Orange, at the mouth of Cove River, poor but usable water was once obtained from a shallow dug well. At Barry's Boat House, about 200 feet south of Well 19, in Orange, a driven well 35 feet deep on a bar beach yielded only salt water. Well 55 is on a bar beach (Pl. V, *A*) but draws its water from bedrock, which is thinly covered by sand. The sample indicates only a trace of sea water (94 parts per million of chloride). Residents on other parts of the beach, where it is composed entirely of sand, say that good water is unobtainable, and there are no wells in existence. Well 161, a shallow dug well, on Cedar Island in Clinton Harbor, is practically on a spit, as the island is a sand bar built entirely by wave action. This well yields water which contained 122 parts per million of chloride and is generally considered brackish. The only deep boring recorded on a spit or bar is that on Pleasure Beach, Bridgeport (No. 184), where, after penetrating to a depth of 212 feet, only salt water was obtained.

From all the evidence it appears that the ground water of bar beaches and spits is brackish or salty. The extreme porosity of the sand causes the water table to sink so far at low tide that there is a distinct influx of salt water landward at high tide. Furthermore, high storm waves sometimes completely overtop these ridges, thus undoubtedly saturating them with salt water. On unusually high and wide areas a small amount of usable water might be obtained from carefully made shallow wells. However, on most bar beaches and spits the ground water doubtless becomes exceedingly saline at no great depth below the water table.

ISLANDS

Conditions on islands do not appear to differ materially from those on the mainland except where the available intake for ground water is exceedingly small. The nature of the land surface and of the rock composing the island influences the character and quantity of the ground water. A covering of till or of stratified drift promotes absorption of rainfall and equalizes the supply of ground water reaching the water table, but bare rock surfaces promote run-off. The well on Charles Island (No. 10), now abandoned, yielded fresh water. The island is several hundred feet in diameter and undoubtedly supports a body of fresh ground water of considerable extent. On Darrow Island there are three wells (Nos. 59, 60, and 61) each on a separate land mass connected to the rest of the island by a bar beach or narrow ridge. Well 59 penetrates till and bedrock nearly to sea level in the center of a land mass only about 250 feet in diameter. It supplies a summer cottage, but the water is reported to be brackish when much used. A sample, taken June 22, 1919, when the well had been unused all winter, showed 86 parts per million of chloride, which probably indicates a trace of sea water. Well 60 penetrates till on the center of a land mass at least 500 feet in diameter and yields good water containing only 21 parts per million of chloride, which is probably not an abnormal quantity for a well on an island that is constantly dashed by salt spray. Well 61 is on the edge of a small rock mass about 150 feet in diameter, almost in a tidal reentrant. The water is said to have been brackish and unfit for use. Wells 92, 93, 94, 95, 96, and 97, all on small islands, are shallow dug wells that penetrate till and bedrock approximately to sea level. (See table, p. 22.) All yield usable domestic water, though the analysis of No. 95 shows a definite trace of sea water, and Nos. 93 and 94 are reported to yield brackish water occasionally during the summer in dry weather and in periods of maximum use. Well 100 is in the center of a small body of stratified drift about 200 feet in diameter on an island. The water was not originally brackish but has become so with use.

The wells referred to above are all shallow dug wells that penetrate approximately to sea level. The only deep well drilled on any of the islands off the New Haven coast is No. 98, on Elton Island, which is said to be 150 feet deep and which starts in bedrock. Although the well is only 60 feet from the shore line at high tide and about 12 feet above mean sea level, reports state that it yielded a small supply of good water and that even when it was pumped dry by a suction pump set at a depth of 140 feet, salt water did not enter. Other reports, however, state that the well was abandoned because the water was not good.

It seems from all the available evidence that on the New Haven coast good water, in small quantities, may be obtained even on very small islands where there is a cover of till or stratified drift. An island having an area of an acre—or about 250 feet in diameter—will usually supply sufficient water for the ordinary requirements of a household. The supply available increases with the size of the island, and probably in considerably greater ratio, for the relative losses about the perimeter become smaller. Islands composed of very porous sand are generally underlain by salt water at slight depth and may contain only brackish water up to the level of the water table. Deep wells are not advisable on islands only a few hundred feet across because, theoretically at least, all such islands are underlain by salt water if water-bearing rocks extend to any considerable depth. It is probably true that deep wells on small islands might occasionally yield fresh water, but the probability of obtaining salt water increases rapidly with depth.

EFFECT OF FRACTURES IN BEDROCK

Sea water enters through fractures into wells that are dug or drilled in bedrock near the shore. It might be expected that where there are many joints leading from the shore toward a well, or where cleavage planes dip inland toward one, the probability of contamination would be greatly increased. Clapp [36] suggests that in certain contaminated wells on a peninsula in Maine the sea water enters at the side of the peninsula farthest from the wells, because the cleavage of the rocks dips from that side toward the wells.

Well 54, which is about 35 feet from high tide, was drilled 35 feet deep in granite gneiss, which at the shore is much fractured in many directions. This well was ruined by a high storm tide, but after its bottom was partly filled it yielded good water again. Well 98, on Elton Island, penetrates 150 feet of granite gneiss, going about 140 feet below sea level. High tide washes the bare rock 60 feet away. The rock is massive but has a poorly developed joint system trending toward the well and a suggestion of cleavage dipping steeply seaward, away from the well. It is probable that the absence of prominent fractures accounts for the fact that the well yielded good water at this depth so near the shore. Well 110 is on a bare rock peninsula only 50 feet from tidewater on two sides. On the shore at one side is a narrow zone of nearly vertical joints trending directly toward the well, but they do not show at the well or on the opposite shore. The surrounding rock is massive granite gneiss. The well is badly contaminated (see p. 55), and it is possible that the fractures noted afford the passage for sea water.

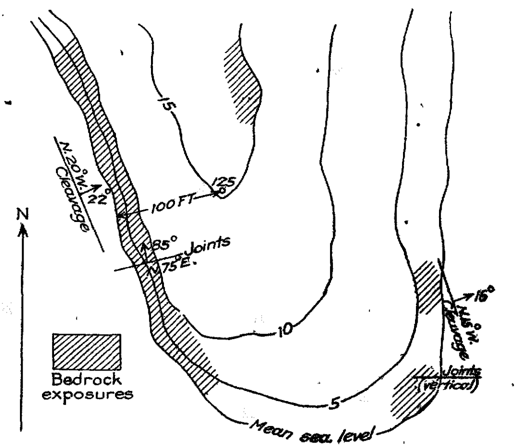


FIGURE 6.—Sketch map of Mulberry Point, Guilford, Conn., showing bedrock structure near well 125

Wells 125 and 128, on Mulberry Point, Guilford, afford an interesting comparison. In Figure 6 are shown the strike and dip of joint and cleavage planes in the bedrock near well 125. This well is 50 feet deep, penetrating about 35 feet below sea level, and is 100 feet from the shore. The bedrock of the region is chiefly granite gneiss, but this contains large inclusions of schist. On the shore just west of the well the bedrock exposed is all schist, which con-

[36] Clapp, F. G., Underground waters of southern Maine: U. S. Geol. Survey, Water-Supply Paper 223, p. 67, 1909.

tains wide, open cleavage planes that dip 22° E., directly toward the well, as well as large joints trending in the same direction. The well is badly contaminated, expecially when in use, the several chloride determinations ranging from 37 to 516 parts per million. This fact seems to indicate that the fractures supplying the well contain but little water and lead directly from the sea, so that drawing off a little water invites the entrance of sea water. However, well 128 is practically of the same depth and at the same distance from the shore, on which is exposed the same schist with many open cleavage planes dipping toward the well, yet the water from this well is never brackish and at two different times tested only 18 and 19 parts per million of chloride, probably only a normal amount for the location.

The observations on the New Haven coast indicate that a high degree of fracturing in the bedrock on the shore increases the chances of contamination in wells near by and that the trend or inclination of fractures toward a well may also be of importance, but only as indicating greater likelihood of the existence of a fracture connecting

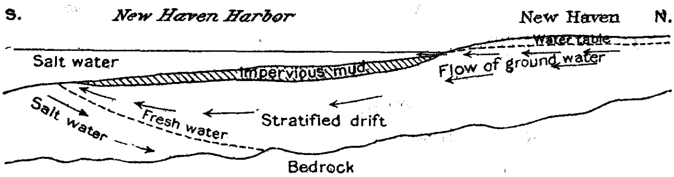


FIGURE 7.—Section illustrating artesian conditions in New Haven Harbor, Conn.

the well with the sea. There is no apparent reason why cleavage planes dipping toward a well should admit water much more readily than a series of connected fractures. An important factor and one difficult of evaluation is the quantity of fresh water fed to a well by fractures on land. If this quantity is large and the water is under sufficient pressure sea water will be excluded, even under conditions where contamination would otherwise readily occur.

ARTESIAN CONDITIONS IN NEW HAVEN HARBOR

The blanket of mud that forms the most recent deposit on the floor of New Haven Harbor and its tributary tidal marshes acts as a practically impervious stratum and excludes the salt water of the harbor and the marshes from the stratified drift sands beneath. The main features of the New Haven artesian system are illustrated by Figure 7. The sands in this vicinity average 100 to 200 feet in thickness and are, for the most part at least, filled with fresh water. The wells of Sperry & Barnes (No. 23), which are on filled land nearly 1,000 feet south of the original shore line at high tide, draw comparatively fresh water from the sand beneath the fill and the mud.

In a test well of Sargent & Co., 660 feet south of the original water front, fresh water was obtained beneath the mud down to a depth of 110 feet. Some of the wells of the present Sargent pumping plant (No. 35) are on filled land but tap fresh water beneath the tidal mud. The wells used by the plants of the New Haven Gas Light Co. (see Pl. VII, *A*) and the National Folding Box Co. are also on filled land that was originally part of the tidal marshes of Mill River, but they draw fresh water from sand beneath the mud. Some of these wells yield water very definitely contaminated by sea water, but this contamination has resulted from excessive pumping. At all the places mentioned the water was originally drinkable and at present is only slightly brackish.

The fresh water beneath the mud may be accounted for in either of two ways: (1) If the deposit of mud existed before the last coastal subsidence, fresh ground water already present below the mud was carried down beneath the sea in practical purity; (2) if the mud has been deposited since the submergence the salt water that entered the sands during subsidence has been replaced by fresh water. The first supposition is more probably the correct one. Whatever the origin of this water, the pressure of fresh ground water from the land is sufficient to cause it to circulate slowly southward and discharge into the salt water of the bay. (See fig. 7.) However, some of the ground water from the land reaches the sea by direct seepage over the rim of the deposit of mud above the shore line at high tide as at Cold Spring, in Cold Spring Park, New Haven.

The southern limit of the extent of fresh water beneath the harbor depends upon how far south the blanket of mud was laid down. This may be only as far as Oyster Point, or it may be as far south as Sandy Point and Fort Hale. Salt water doubtless extends back beneath the rim of the mud blanket for some distance, as shown in Figure 7, but the evidence of a few wells and test borings, such as those of Sargent & Co., indicates that it does not extend as far as the north shore of the harbor. Artesian conditions, such as those at New Haven, are not known to exist at any other places on the New Haven coast.

NATURE OF THE CONTACT BETWEEN SALT AND FRESH GROUND WATER

Along coasts there is a continual diffusion of marine salts from the sea water into the fresh ground water of the land and an actual movement of fresh ground water from the land seaward. There is also at high tide some actual infiltration of salt water landward, as the sea level at high tide usually rises temporarily above the adjacent ground-water level. There is doubtless a transition zone in which equilibrium between these opposing forces is maintained. The location of this zone of contact is influenced by several factors, including the permeability and structure of the rocks, the amount of fresh water supplied by rainfall, the density of the sea water, and perhaps the prevailing temperature. As has been shown by Herzberg (see pp. 16–17) and others, the depth of the zone of contact below mean sea level is, in uniform material, a function of the height of the water table above sea level.

The simplest example that can be assumed for consideration is that of a small island composed of uniformly porous sand. The probable movements of ground water and the gradation from salt water to fresh water on such an ideal island are illustrated in Figure 8, A, which shows the approximate form of curve given by Herzberg for the island of Norderney. Imbeaux[37] states that the form of curve which he obtained experimentally closely approached a sinusoid.[38] It appears that as the permeability of the rocks increases the curve flattens. Thus Sanford[39] has described the body of fresh water above the salt water in the fractured limestones of the Florida Keys as a thin sheet, and Lindgren[40] has found practically the same condition in the very porous basalts of Molokai. This is a very natural result, as the greater freedom of circulation in permeable rocks permits the water table to sink lower, and the necessity for equilibrium then compels the salt water to rise higher, so that the two approach each other.

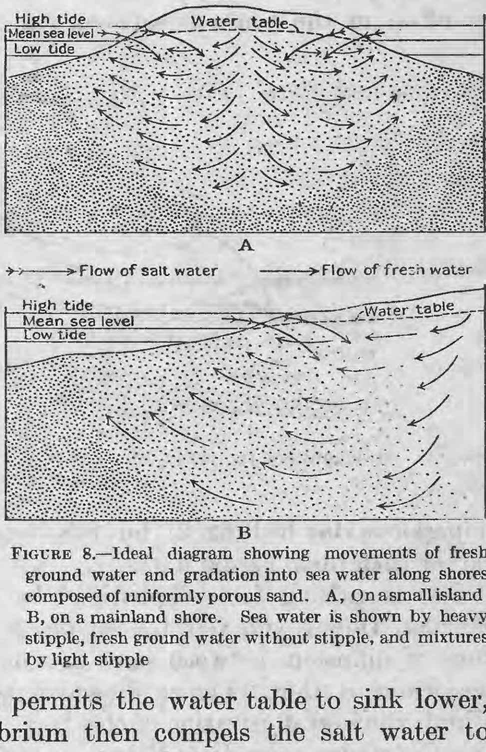


FIGURE 8.—Ideal diagram showing movements of fresh ground water and gradation into sea water along shores composed of uniformly porous sand. A, On a small island B, on a mainland shore. Sea water is shown by heavy stipple, fresh ground water without stipple, and mixtures by light stipple

On coasts composed of porous sand the conditions are probably somewhat as shown in Figure 8, B. The general zone of contact slopes downward beneath the coast, and unless interrupted by

[37] Imbeaux, E., Les nappes aquifères au bord de la mer, salure de leurs eaux: Soc. sci. Nancy Bull., 3d ser., vol. 6, pp. 131–143, 1905.

[38] A sinusoid is "the curve of lines, in which the abscissas are proportional to an angle and the ordinates to its line."—Century Dictionary.

[39] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, p. 261, 1913.

[40] Lindgren, Waldemar, The water resources of Molokai: U. S. Geol. Survey Water-Supply Paper 77 pp. 26–47, 1903.

impervious rocks salt water at depth may extend a great way inland, as was determined on the Holland coast (fig. 3). In Connecticut this invasion of the land by sea water terminates within a few hundred feet of the shore, owing to the fact that the underlying crystalline rocks become practically impervious not far below the surface. At other places, however, it is conceivable that the invasion might continue even for several miles beneath the edges of continents.

The effect of impervious strata alternating with pervious strata has been discussed by D'Andrimont [41] and others. D'Andrimont inferred that the condition shown in Figure 9 might result under certain circumstances. His assumption seems to have been justified by developments on the coast of the North Sea. Pennink [42] shows an offset in the contact between salt and fresh water due to an

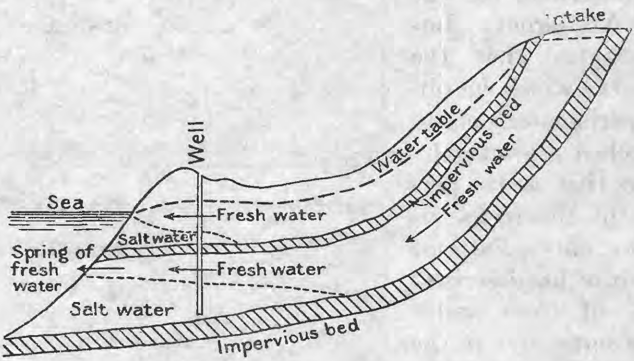


FIGURE 9.—Modifications of the contact between salt and fresh ground water due to impervious beds. (After D'Andrimont)

impervious clay bed (fig. 3), but this seems to be based upon inference rather than upon actual data.

One surprising fact emphasized by the results of the French, Belgian, Dutch, and German studies is that the transition zone, or zone of diffusion, between fresh ground water and practically pure sea water is thin. Figure 3, which is based upon reliable data, affords the best illustration of this fact. The zone of diffusion shown there is, under normal conditions, only 20 to 30 meters (about 60 to 100 feet) wide. As might be expected, it appears to be narrower where the downward movement of ground water is most rapid—that is, under the high dunes—and widens greatly under the polders, where there is at places an ascending movement of ground water. Data from Sanford (quoted on p. 87) show that at Marathon, near

[41] D'Andrimont, René, Notes sur l'hydrologie du littoral belge: Soc. géol. Belgique Annales, vol. 29, pp. M 129–M 144, Liège, 1902.

[42] Pennink, J. M. K., De "prise d'eau" der Amsterdamsche duin waterleiding: K. Inst. Ing. Tijdschr., 1903–4, pp. 183–238, The Hague, 1904.

the west end of Key Vaca, Fla., nearly pure sea water occurs within 38 feet of the surface of the ground. D'Andrimont, in his classic experiment described on page 18, says that the zone of diffusion between fresh and salt water was "very inconsiderable" and that "after standing eight hours the distinction between the saline and the fresh water was quite sharp."

In crystalline rocks and in indurated sedimentary rocks, where the ground water circulates through joints and open fractures, the zone of contact between salt and fresh water is undoubtedly much more irregular than in homogeneous porous rocks. Fissures filled with salt water interlace more or less with those containing fresh water. But the general features of the contact are not altered, and the fresh water is almost invariably found superimposed upon the salt. No wells in crystalline rocks examined in Connecticut have yielded fresh water below salt water. In San Francisco Bay wells have yielded salt water at slight depth. In the chalk beds of England, in which water circulates chiefly through joints, fresh water is not often found below salt water, although some exceptions to this rule are recorded (pp. 91–93). Whitaker[43] describes a gallery in chalk near the sea where two springs issued, one above the other, from a single fissure. The water of the lower spring contained 25 to 50 per cent more chloride than that of the higher one, though the contrary had been expected. This seems to indicate that the salt water came from the underlying zone of contamination and not directly from the sea.

EFFECTS OF PUMPING

THEORETICAL CONSIDERATIONS

The danger of excessive pumping in wells near salt water has long been recognized by engineers and geologists. In a report by J. S. Stoddard, city engineer, to the Water Committee of Brooklyn,[44] in 1854, the principle is tersely expressed as follows:

> Salt water will flow through the earth as easily as fresh water; and therefore a head of 10 feet per mile will drive salt water through the earth; and consequently, if a well is 1 mile from salt water and is pumped down lower than 10 feet below the tide, the salt water will run down into the well and ruin it.

The estimate of 10 feet to the mile as the necessary head to produce a flow of ground water is based upon Stoddard's observations of the water level in wells. The statement expressed by him and by many other writers that if the water table is lowered below mean sea level

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[43] Whitaker, William, The water supply of Hampshire: Great Britain Geol. Survey Mem., pp. 48-51, 1910.

[44] Stoddard, J. S., Report on the subject of supplying Brooklyn with water by the well system, in documents and plans submitted by the Water Committee to the Common Council of the City of Brooklyn, 1854, No. 9, p. 94.

salt water is induced to flow inland is only partly true. According to the law of equilibrium, at any place where fresh water rests above salt water the lowering of the fresh water causes the salt water to rise until, theoretically, the fresh water has been exhausted to mean sea level and the salt water has risen to that level. In practice, however, the zone of diffusion would extend upward sufficiently to

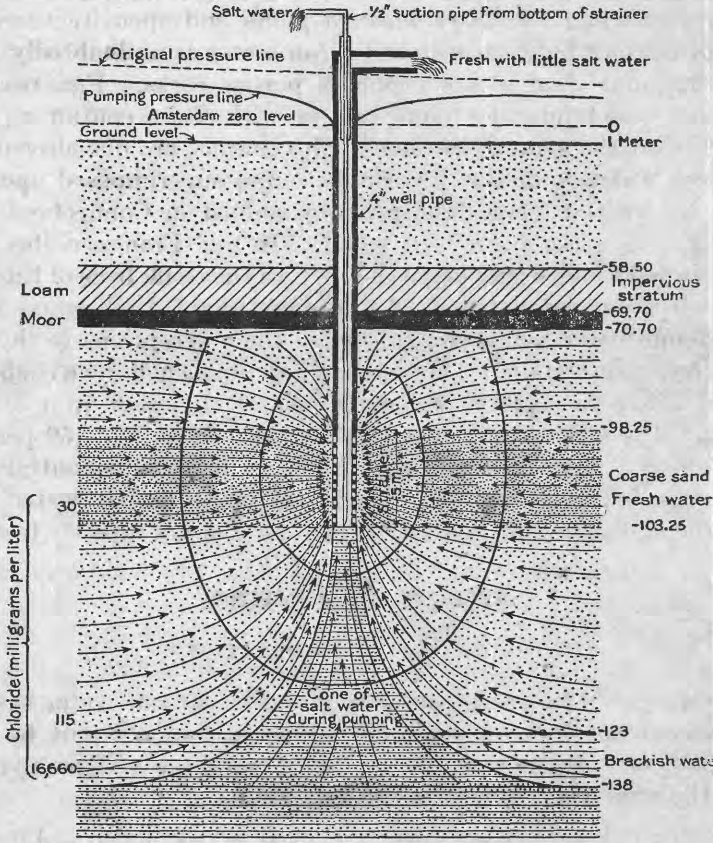

FIGURE 10.—Cone of salt water induced by pumping overlying fresh water. (From Pennink, J. M. K., Am. Soc. Civil Eng. Proc., vol. 54, pt. 4, p. 179, 1905.) Pumping at the rate of 1,200 cubic meters daily. Strainer placed about 35 meters above the level of water having a density equal to sea water. Salinity of sea water approximately 17,000 parts per million of chloride. Zero level of Amsterdam, 0.2 meters above mean sea level

ruin wells before the fresh water was actually lowered to mean sea level. On the other hand, it takes an appreciable gradient, several feet to the mile, to permit ground water to flow through the rocks. Therefore, where salt water extends only a little way beneath the coast, a well a mile or two inland would have to be pumped considerably below mean sea level before the salt water would have head enough to enter it, as Stoddard has pointed out. There may be some places where the water table can not safely be lowered to mean sea level and others where it can be pumped several feet lower without harm. Dole [45] states that the ground-water level in the wells supplying Savannah stands 12 feet below sea level when the plant is in operation, and he suggests that further lowering would probably cause a backflow of sea water. The wells at Savannah are, however, some miles from the sea, and the water table in the direction of the sea remained above sea level in spite of the pumping. The actual danger point comes when the cone of depression in the water table caused by pumping reaches the sea, not when the water level at the well falls below sea level.

D'Andrimont and other European students of coastal ground water lay much stress upon the "cone" or "protuberance" of salt water caused by pumping when salt water underlies the body of fresh water. The lowering of the water table by pumping reduces the hydrostatic head of the fresh water that counterbalances the head of the underlying salt water and so permits the salt water to rise. This process is illustrated by Figure 10, taken from Pennink and based upon actual observations.

DATA FROM THE NEW HAVEN COAST

All the evidence regarding the effect of pumping on wells near the sea tends to one conclusion—that if the quantity of fresh water removed is greater than that supplied from the contributory area the wells become salty. This statement is as true for domestic wells drawing from a small intake area as for pumping plants supplied from the underflow of a large drainage basin. Thus the Beattie dug well (No. 100), which drains probably about 1 acre of sand (stratified drift) at the end of a small island, originally yielded good water, but the demands of one family, especially when increased by the installation of a household water system, were sufficient to overtax the well and make it salty. The Stevens dug well (No. 124), supplied good water to fishing boats for many years, but the steady demands of half a dozen families caused it to turn salty. The Mitchell drilled well (No. 110) and the Anderson drilled well (No. 125) yield good water in winter, when not used regularly, but the demands of a single family during the summer cause them to turn very salty. The first two wells draw water from drift, and the last two from bedrock.

[45] Dole, R. B., The water supply of Savannah, Ga.: Mayor's Ann. Rept. 1915, p. 64.

The only pumping plants near the shore in this region are at New Haven and Bridgeport. The significant data in regard to contamination at these plants are given in the following table:

Contamination by sea water in pumping plants on the coast of Connecticut

[Detailed descriptions of the wells listed are given under the corresponding numbers on pages 58-83]

No. Plate I	Owner	Location with reference to salt water	Chloride radicle (Cl)[a]	Apparent degree of contamination by sea water
			Parts per million	
20	New Haven Rendering Co.	About 50 feet from tidal marsh	22	None.
21	Connecticut Fat Rendering & Fertilizing Corporation.	Narrow point between tidal marshes.	574	High. Pumped heavily.
22	Malloy Buckle Co.	500 feet inland	23	None. Pumped lightly.
23	Sperry & Barnes	50 feet from tidewater and about 1,000 feet from original shore. Filled land.	885	High. Pumped heavily.
24	Hull Brewing Co.	1,800 feet inland	78	None.
25	Dillon & Douglas	2,000 feet inland	65	Do.
26	L. C. Bates Co.	2,400 feet inland	86	Do.
27	Alexander & Links	2,200 feet inland	115	None. Pumped lightly.
28	Young Men's Christian Association.	3,400 feet inland	85	None.
29	H. B. Ives	2,400 feet inland	41	None. Pumped very lightly.
30	Andrew B. Hendryx	4,000 feet inland	12	None.
31	McLagon Foundry	4,000 feet inland	13	None. Pumped very lightly.
32	Hygienic Ice Co.	1,250 feet inland	113	None. Pumped heavily.
33	New Haven Clock Co.	1,200 feet inland	39	Do.
34	B. Shoninger Co.	1,200 feet inland	26	Do.
35	Sargent & Co.	A. Group of wells 100-200 feet from tidewater. Filled land.	3,700	Very salty. Pumped to capacity.
		B. Group of wells about 400 feet from tidewater. Original land.	90	Probably slight. Pumped heavily.
		C. Group of wells about 400 feet from tidewater. Probably filled land.	94	Probably slight. Pumped moderately.
36	W. & E. T. Fitch Co.	400 feet from tidewater. Filled land.	145	Do.
37	New Haven Gas Light Co.	100 feet from tidewater. Filled land.	439	High. Pumped heavily.
38	New Haven Pulp & Board Co.	400 feet from tidewater. Filled land.	746	Do.
39	United Illuminating Co.	Small island in Mill River		Abandoned. Reported good.
40	National Folding Box Co.	300 feet from tidewater. Half of wells are on filled land.	514	High. Pumped heavily.
41	Connecticut Co.	200 feet from tidewater. Filled land.	75	Probably none. Pumped lightly.
42	Bigelow Co.	150 feet from tidewater. Filled land.		Abandoned. Probably salty.
43	Kilborn & Bishop	400 feet from tidewater. Drilled 175 feet.		Abandoned. Reported good.
44	New England Warp Co.	300 feet from tidewater	26	None. Pumped lightly.
45	Yale Brewing Co.	500 feet from tidewater	145	Probably slight. Pumped heavily at times.
49	American Steel & Wire Co.	400 feet from tidewater		Temporarily abandoned. Very salty under heavy pumping.
175	Connecticut Breweries Co.	500 feet from tidewater. Drilled wells 300-400 feet deep.	169	Possibly slight. Pumped heavily.
178	Connecticut Web & Buckle Co.	100 feet from tidewater	7.0	None.
179	Morris & Co.	125 feet from tidewater. Filled land.	8.0	Do.
180	John R. Woodhull	125 feet from tidewater. Filled land.	356	Marked.
181	Cudahy Packing Co.	125 feet from tidewater. Filled land.	1,430	High.
182	Wm. Rappaport	125 feet from tidewater. Filled land.		Abandoned. Very salty.

[a] Determinations by Margaret D. Foster.

Plants 24 to 34, which are 1,000 to 4,000 feet inland, were not suspected of contamination and were sampled chiefly to determine the range of chloride content that might normally be expected in well water from the thickly populated portions of New Haven. In such areas the ground water is unavoidably polluted to a noticeable degree by sewage, factory waste, and refuse thrown upon the ground. From the analyses it appears that in the heart of the city 50 to 100 parts per million of chloride may be attributed to such sources. Contamination by sea water is not considered definitely established unless the chloride content is more than 200 parts per million.

If we omit No. 22, which is 500 feet from tidal marshes and is pumped lightly, and if we count the Sargent & Co. wells as three plants, which they properly are, we have a total of 23 plants within 500 feet of tidewater, of which 10 are so badly contaminated that the water is unpalatable for drinking and unfit for many industrial uses. Three or four others may be slightly contaminated.

The greatest distance from tidewater at which a high degree of contamination was found is 400 feet (No. 49), but a considerable part of the intervening land was originally a tidal marsh which has been filled in. Aside from Nos. 35 C, 39, 42, and 179, the available data for which are not conclusive, there are ten plants on filled land that was originally tidal. All but two of these (Nos. 36 and 41) are badly contaminated. On the other hand, of the nine plants on land that was originally above the reach of high tide, only two plants are much affected—No. 49, mentioned above, and No. 21, which is in a very unfavorable location, between two tidal marshes.

The influence of heavy pumping is shown by the fact that out of eight plants shown by analysis to be badly contaminated, six are pumped at nearly their maximum capacity. The other two (Nos. 180 and 181) are near the shore on a filling so porous that they would probably be affected if not pumped at all.

A definite interpretation of the data on contamination in pumping plants on the New Haven coast is difficult because most of the larger pumping plants are in New Haven, where the situation is complicated by the layer of nearly impervious mud which floors the harbor and the tidal marshes. Where the hydrologic conditions are undisturbed pure fresh water is found beneath this mud in the marshes and for an unknown distance into the bay. Heavy pumping, however, undoubtedly causes contamination by sea water, as shown particularly by the plants of Sperry & Barnes (No. 23), Sargent & Co. (No. 35 A), the New Haven Gas Light Co. (No. 37), the New Haven Pulp & Board Co. (No. 38), and the National Folding Box Co. (No. 40). This contamination could occur in either of three ways—by the rising of salt water from below, by the infiltration of salt water downward through the mud, or by the infiltration of salt water through corroded casings or beside casings imperfectly sealed.

The first assumption seems to be impossible because salt water does not appear to extend beneath the coast at depth, at least on the north shore of New Haven Harbor. This observation is supported by the fact that a test boring 110 feet deep made by Sargent & Co. (see p. 63) and a well of Kilborn & Bishop (No. 43), 175 feet deep, both yielded fresh water. Moreover, if salt water

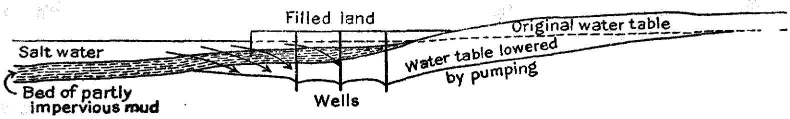

FIGURE 11.—Section illustrating contamination in wells on filled land in New Haven, Conn.

penetrated the stratified drift beneath the tidal marshes, it would also underlie the adjacent coastal mainland, and wells on original land would be quite as subject to contamination as those on filled land of the tidal marshes. We have seen that contamination is practically confined to wells on filled land. For these reasons it appears that contamination does not come from below in the New Haven plants.

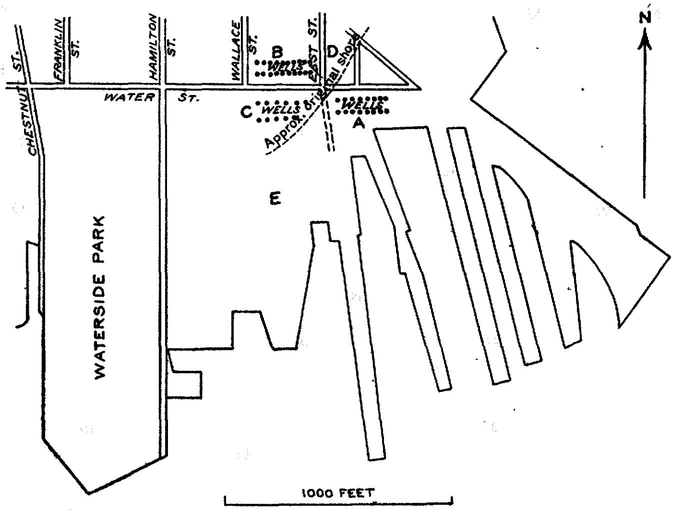

FIGURE 12.—Map of a part of the water front, New Haven, Conn., showing location of plant of Sargent & Co. (From U. S. Coast and Geodetic Survey)

The second assumption, that the contamination comes from above, is illustrated by Figure 11. The natural effect of heavy pumping is to lower the water table, thus causing a decrease of hydrostatic pressure beneath the mud. This mud can scarcely be entirely impervious, and the suction caused probably permits some salt water to enter the wells. This infiltration of a small amount of salt water may easily account for the brackishness of the water from most of the plants on filled land.

The third possible method of contamination is through openings in corroded well tubes above the mud and possibly also below it, where open passages may be left beside well pipes, which are often pulled up for renewal and may not be tightly sealed when reset. Such a source of salt water might be expected to cause a very high and somewhat erratic degree of contamination. There is some indication that this is the cause of the high degree of contamination in the group A wells of Sargent & Co. (fig. 12), which yield water with about 4,000 parts per million of chloride, whereas groups of wells only 300 or 400 feet away yield water averaging only about 100 parts per million of chloride. The main evidence is afforded by the fact that a sample from a single well of group A (see analysis p. 57), which had been disconnected for cleaning, contained only 193 parts per million of chloride. This indicates that the normal ground water at group A is but little more saline than that at groups B and C, and that the excessive contamination comes through some open leak.

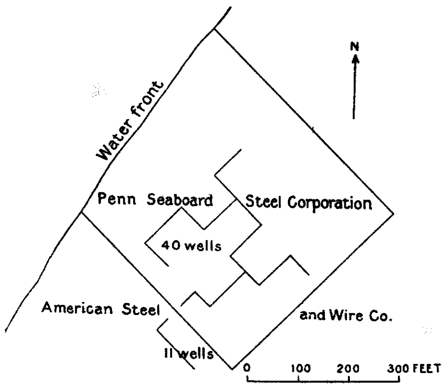

FIGURE 13.—Sketch map showing location of well groups of American Steel & Wire Co. and Penn Seaboard Steel Corporation, New Haven, Conn.

The best data regarding the limiting rate at which water may be pumped from a given contributory area are furnished by the plant of the American Steel & Wire Co. (No. 49) and the connected plant of the Penn Seaboard Steel Corporation. (See fig. 13.) These plants were operated at full capacity during 1918, when engaged on war work, and the draft of water used by the Penn Seaboard Steel Corporation from its wells reached about 330,000 gallons daily or 10 million gallons a month. The water, which at first was sweet and drinkable, became very salty, evidently from salt water drawn in from the harbor. The wells of the American Steel & Wire Co., being shallower, were dried up by the lowering of the water table. The small plain upon which these plants stand has an area of not more than one-fourth of a square mile that serves as catchment for ground water. It appears, therefore, that the rate of pumping greatly exceeded the ability of the intake to supply water. The rate of 330,000 gallons a day for one-fourth of a square mile is somewhat more than a million gallons a day to the square mile, a quantity which is considerably above the safe drain upon a basin near the sea under conditions such as prevail in Connecticut. One million gallons a day to the square mile is equivalent to 1.73 feet a year, or about 45 per cent of the total annual rainfall in the New Haven region.

DATA FROM LONG ISLAND

The effects of pumping on a large scale near the sea have been most carefully studied in this country by the Board of Water Supply for the City of New York. The Brooklyn water supply was for many years drawn from Long Island sources, chiefly ground water pumped on the southern slopes of the island. Geologically, Long Island consists of a ridge of till flanked on the south by a wide, gentle slope of stratified sand and gravel. The southern border of the stratified-drift plain is fringed with tidal marshes and lagoons or bays partially inclosed by bars and spits. Beneath the glacial drift is 300 to 500 feet of stratified Cretaceous sand and clay, and below that is

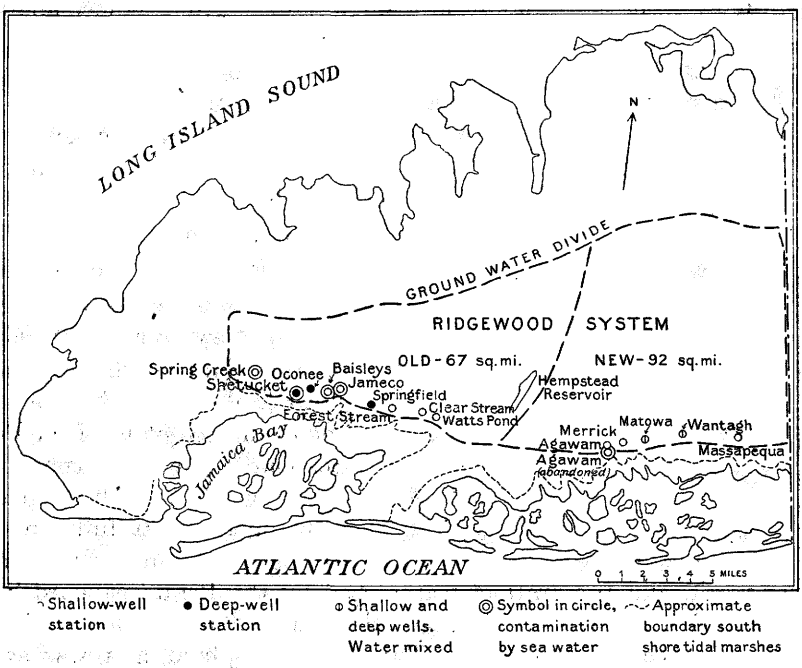

FIGURE 14.—Outline map of western Long Island, showing pumping plants bearing on contamination by sea water. (From Spear)

crystalline bedrock. The annual rainfall averages 43 to 45 inches. The conditions are, therefore, similar to those of Connecticut in several ways.

The pumping plants of the Brooklyn water supply are as near the south shore as they can safely be placed to develop the maximum supply of ground water without contamination by sea water. Nevertheless, several of the pumping stations have shown a high degree of contamination at times and have had to be moved, abandoned, or used very lightly. The Brooklyn water supply is described at length by Spear.[46] The data from Long Island, which have been

[46] Spear, W. E., Long Island sources of an additional supply of water for the city of New York, New York Board of Water Supply, 1912.

recorded very carefully by the engineers in charge of the supply show the effects of pumping on a large scale at practically the maximum capacity of the territory developed. The best of the data on contamination given by Spear were obtained from the Ridgewood collecting system, shown in Figure 14. The main features of this system in 1912 are described as follows (pp. 61–62):

The Ridgewood system furnishes about 85 per cent of the present water supply of Brooklyn from the streams and ground-water works along the south shore of Long Island in Queens and Nassau counties, between the limits of Brooklyn Borough and the Suffolk County line.

AREA OF WATERSHED

The watershed of the Ridgewood system, defined by the ground-water divide limits of the ground-water catchment, is shown in Figure 14. This watershed, which represents the total catchment that might, by a complete development, be made tributary to the Ridgewood system, has an area of 159 square miles, of which 67 square miles may be apportioned to the "old watershed" and 92 square miles to the "new watershed."

The southerly limit of the catchment area represents the greatest safe inflection of the ground-water surface during long periods of heavy draft at all driven-well stations, with a complete development of the system. Where there are no ground-water collecting works, the limit of the catchment area is at the spillways of the supply ponds, and for the greater part of the time the existing ground-water works do not ordinarily inflect the water table as far south as shown.

The flow of all but a few unimportant streams within this catchment area has been made tributary to the system. It is estimated that the total surface drainage area of these streams, south of the ground-water divide, is 117 square miles.

The ground-water underflow on the line of collecting works has not yet been entirely developed by the city.

*   *   *   *   *   *   *

The total safe yield of the watershed is estimated as follows:

	Million gallons per day
New watershed, 92 square miles	62
Old watershed, 67 square miles	55
Total yield of system	117

It may be noted that the full supply had not been developed, but the estimates are based upon the yield of the different units of the system at different intervals. Of the total estimated supply of 117 million gallons a day, 40 million gallons is derived from surface streams and 77 million gallons from ground water. For an area of 159 square miles this quantity of ground water is very nearly half a million gallons a day to the square mile, a figure somewhat less than that given on page 43, and probably more nearly the safe yield of a catchment area near the sea.

The problems of contamination by sea water are discussed at length by Spear as follows, under the general heading "Inflow of sea water" (pp. 144–149):

CHLORINE [47] IN THE RIDGEWOOD SUPPLY

The amount of chlorine in the Ridgewood supply during the past 11 years is shown in Figure 15, with the average monthly yield of the whole watershed, the delivery of those stations most affected by sea water, and the annual rainfall at Hempstead reservoir.

The original Brooklyn supply from surface streams contained from 5 to 6 parts of chlorine per million, which is the normal chlorine in southern Long Island. A large increase came with the development of the ground waters. That shown on this diagram, in 1895, was occasioned by the pumping of the wells at the old Agawam station, which was soon after abandoned for the present site. In 1897, following several years of low rainfall, the heavy draft upon the Spring Creek,

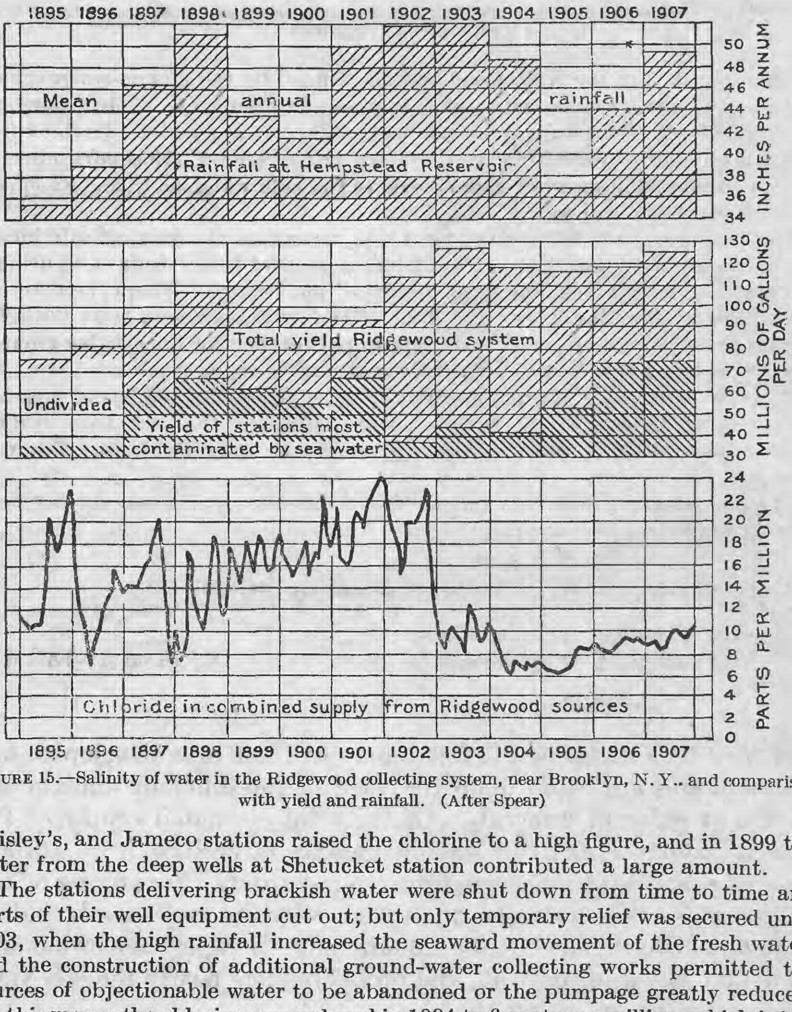

FIGURE 15.—Salinity of water in the Ridgewood collecting system, near Brooklyn, N. Y.. and comparison with yield and rainfall. (After Spear)

Baisley's, and Jameco stations raised the chlorine to a high figure, and in 1899 the water from the deep wells at Shetucket station contributed a large amount.

The stations delivering brackish water were shut down from time to time and parts of their well equipment cut out; but only temporary relief was secured until 1903, when the high rainfall increased the seaward movement of the fresh water, and the construction of additional ground-water collecting works permitted the sources of objectionable water to be abandoned or the pumpage greatly reduced. By this means the chlorine was reduced in 1904 to 6 parts per million, which is but slightly above the normal. Since that time the amount has, however, slowly increased as a result of the heavy draft upon the watershed, until, during the fall of the past year, it reached at one time 12 parts per million.

[47] "Chlorine" as used by Spear is equivalent to "chloride" as used in this paper.

OLD SHETUCKET DRIVEN-WELL STATION

The record of the yield of the old Shetucket station furnishes one of the most interesting examples of the danger resulting from collecting ground water near the sea. This station was situated just south of the conduit on the edge of the salt marshes about 3 miles from Ridgewood pumping station and originally comprised twelve 8-inch wells, 167 to 180 feet in depth. These wells drew their supply from water-bearing sands below a clay stratum 125 feet beneath the surface.

Figure 16, which is an extension of that on page 415 of the Burr-Hering-Freeman report, shows the operation of this station from 1897 to 1905, inclusive. The plant was first operated at a rate of nearly 4 million gallons per day for the last few months of 1897, and yielded a satisfactory supply, having only 4.5 parts of chlorine per million. In the following March, 1898, when the rate of pumping was increased to 6 million gallons per day, the chlorine showed a slight increase and the amount continued to rise, although the yield of the station was reduced to 4 million gallons per day, and later, as the salinity continued to increase, to 1 million gallons per day. The chlorine in 1902 rose to 500 parts per million.

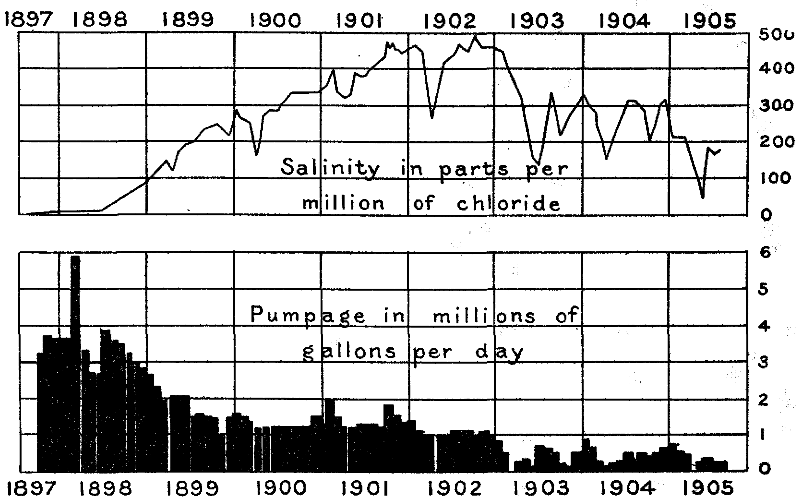

FIGURE 16.—Comparison of pumpage and salinity at Shetucket pumping station, near Brooklyn, N. Y. (After Spear)

In 1903 the pumping was further reduced to an average of 0.5 million gallons per day and continued at this rate until August, 1905. The chlorine did not decrease materially with this low rate of pumping, and the deep wells were then abandoned. Investigation in 1903 showed that the brackish water came from the bay through the strata beneath the clay bed. The sands above this clay contained only 6 to 20 parts of chlorine, and in 1907 shallow wells were driven at the Shetucket station to replace the deep ones.

One important fact is brought out by the operation of the Shetucket station, which is confirmed elsewhere, that the original freshness of the ground water in the sands is not restored at once by shutting down the plant and permitting the ground water to rise to its original level. When the sea water once reaches a system of wells the only remedy is to abandon them. Probably only in the course of many years will the salt water be entirely washed from the sands by the slowly moving fresh water escaping into the sea.

OTHER STATIONS OF THE RIDGEWOOD SYSTEM

The shallow wells of the Spring Creek, Baisley's, and Jameco driven-well stations have also yielded brackish water. The studies upon the operation of these stations by the Department of Water Supply are given in the report of the Burr-Hering-Freeman Commission, pages 410 to 420. At each of these plants the brackish water seemed to reach the wells from Jamaica Bay in a coarse stratum that perhaps represented an old surface channel. The yield of Spring Creek station has been reduced during the past three years, and the yield of Baisley's station has been cut down to but little over 0.5 million gallons per day.

The new Morris Park and Aqueduct stations are providing water quite high in chlorine, and it is probable, in a year of low rainfall, that their delivery would have to be considerably curtailed.

The only station on the "new watershed" east of Freeport which has yielded brackish water was the old Agawam station. This was located a short distance north of the head of the salt-water creek at the Merrick road, and when placed in operation yielded a supply so high in chlorine as to increase the salinity of the whole Ridgewood supply during the latter part of 1895. The station was moved 700 feet north to the present location, where no difficulty has been experienced. It should be noted that the water table at the present site is, to some extent, sustained by the overflow and seepage from the East Meadow Pond, a few hundred feet above. (See the Burr-Hering-Freeman report, Pl. 13, p. 836.)

* * * * * * *

LOCATION OF GROUND-WATER WORKS OF RIDGEWOOD SYSTEM

The stations of the Ridgewood system that have not been affected by the sea water evidently owe their immunity to the distance from the sea, the height of the water table, and the lack of free movement of the ground waters where they are situated. * * *

Brackish water has not reached the wells of any station that is situated over 2,000 feet from the salt water. Several other stations within this distance and some but little farther away, notably the Oconee station, would doubtless have pumped brackish water but for the fineness of the water-bearing strata, the low pumpage, and the small area of influence about the wells. More ground water has been developed on the "old watershed," and the driven-well stations have been pumped more continuously than on the new.

Several stations of the Brooklyn works in Nassau County, particularly the Agawam, Matowa, and other driven-well stations in the "new watershed," are but little farther from the salt water than these stations where salt water has been obtained, and not one of them is located where the normal ground-water surface was originally higher than 10 or 12 feet above mean sea. It appears very probable, therefore, that salt or brackish water would have been obtained at many of these stations had it been the practice in past years to operate them continuously, instead of a few months a year in dry weather, or had these stations been equipped to pump the ground water sufficiently low to draw a large amount of storage.

It should further be noted, in considering the stations of the Ridgewood system, that they are a mile or two apart, and undoubtedly some water escapes to the sea between them. Furthermore, the ground-water surface at several stations in the new watershed is maintained by the surface water in adjacent ponds. Even though the wells at many of these stations were pumped continuously for several years and the ground-water surface in their immediate vicinity maintained below sea level, their operation would not necessarily prove that it would be safe, on the same location, to pump to equal depths a continuous line of wells that permitted very little water to escape toward the bay, to keep up the level of the water table south of the wells.

Spear gives also an interesting diagram showing the necessary head of ground water for wells of various depths which is reproduced as Figure 17 of the present paper. This figure is a direct application of Herzberg's principle and of the formula $h=\frac{t}{g-1}$. (See p. 17.) In the formula h is the depth of well below mean sea level, t is the height of ground water above mean sea level, and g is the specific gravity of sea water. For sea water with a specific gravity of 1.025 and a well 1,000 feet deep, $1{,}000=\frac{t}{0.025}$ or $t=25$ feet, the necessary head of fresh water.

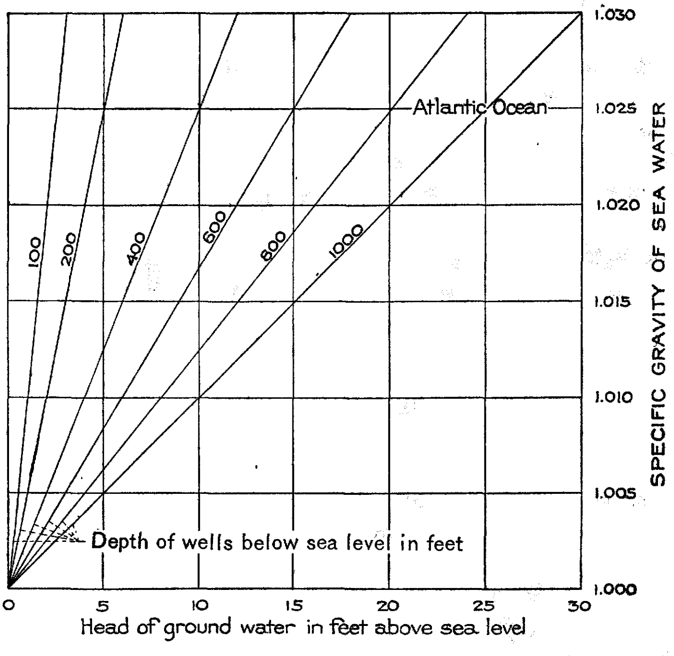

FIGURE 17.—Head of fresh ground water necessary to exclude sea water of any specific gravity from wells of different depths. (After Spear)

INFLUENCE OF TIDES ON GROUND WATER

FLUCTUATIONS OF LEVEL DUE TO TIDES

The possibility of tides in ground water due to direct solar or lunar attraction is discussed briefly by Veatch,[48] who says:

> The ground water has not an extended level surface like the ocean, where the tides range from nothing to 50 feet, or even the Great Lakes, where the tidal fluctuation is but a few inches. The ground-water table is comparatively level only over areas which are but a fraction of the size of the Great Lakes, and direct ground-water tides would be of extremely small size.

[48] Veatch, A. C., Fluctuation of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155, p. 69, 1906.

Sympathetic tidal fluctuations caused by ocean tides affect many wells near the shore and are a matter of record on nearly every seacoast. There is always a lag between the tides in wells and those in the ocean, but this may vary from only a few minutes to several hours, and it may even happen that the fluctuations of level in the wells lag so much as to be exactly the inverse of those in the adjacent sea. The writer made a few tape-line measurements of the water levels in wells on the New Haven coast in an effort to detect tidal fluctuations but obtained no definite results. Such observations to be successful require the use of special observers or continuous recording gages. In pervious strata on the Connecticut coast tidal fluctuations are probably not more than a few tenths of a foot, even in wells only 100 or 200 feet from the shore. The tidal fluctuations in flowing artesian wells near the shore are frequently much greater than those in porous strata near the surface and may amount to several feet. Fluctuations in wells that derive their water from joints or open crevices in rocks near the sea may also be practically the same as the amplitude of the tides in the sea.

The best data on tidal fluctuations in wells are given by Veatch,[49] who says that the fluctuations are caused in three ways:

By transmission of pressure through open cavities or passageways affording a free communication between the wells and the ocean.

By checking of the rate of discharge of the normal ground-water flow through porous beds freely connecting with the ocean.

By a deformation of the strata due to the alternating loading and unloading of the tides.

The first two methods really differ mainly in the rate at which they occur. The high tide dams up the outflowing ground water, causing its level to rise. In rocks containing open crevices or fissures the effect may be transmitted quickly for a long distance along definite channels. In porous materials, such as sand, the effect is transmitted slowly because of the slow rate of movement of water and extends only a little way from the shore. The lag in tidal fluctuations of this kind may amount to several hours.

The third type of tidal fluctuation is that shown in the rhythmic rise and fall of flowing wells near the sea. The flowing wells are fed by water held under pressure beneath an impervious stratum, usually clay, that generally extends beneath the sea. At high tide the ocean exerts a greater pressure on the seaward portion of this impervious cover and tends to squeeze out the underlying water wherever it can escape through wells or elsewhere. This accounts for the fact that the head of the flowing wells rises at high tide and their flow increases. Indeed, at some places, particularly on the Coastal Plain of Maryland

[49] Op. cit. See also Veatch, A. C., and others, Underground water resources of Long Island, N. Y.: U. S. Geol. Survey Prof. Paper 44, 1906.

and Virginia, where the head of flowing wells is small, they may flow only at high tide. As the transmission of pressure takes place rapidly, the lag in fluctuations of this kind is usually measured in minutes rather than in hours. Although the fluctuations decrease with the distance from the shore, they may extend several miles inland.

Figure 18 shows the tidal curves of three wells observed by Veatch compared with the tide of the ocean near by.

VARIATIONS IN SALINITY DUE TO TIDES

The suggestion is natural that if tides affect the level of ground water, they may also, by infiltration of sea water, affect its salinity. On June 16, 1919, special observations were made at the Robert Mitchell well (No. 110; see pp. 55, 75), to determine, if possible, any variations in salinity due to tides. This well is a 6-inch drilled well

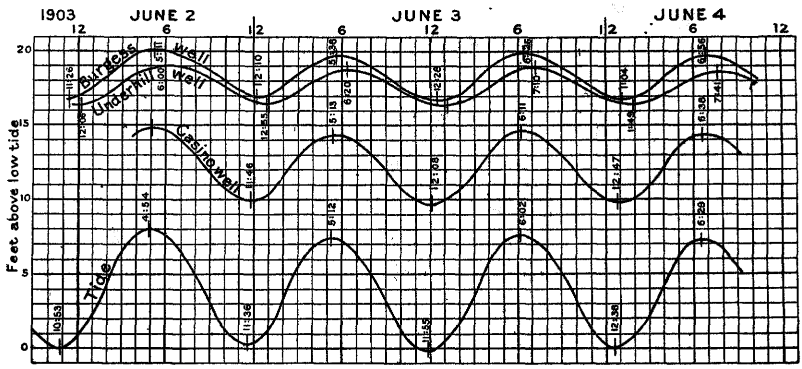

FIGURE 18.—Well and tide curves at Oyster Bay, N. Y., showing tidal fluctuations due to plastic deformation. (After Veatch)

probably about 50 feet deep. It is on a narrow point, only 50 feet from high tide on both sides, and penetrates granite gneiss from the surface. Samples were collected at hourly intervals beginning at noon and ceasing at 7 p.m. The tide on this date reached its highest mark a few minutes before 2 p.m. The variations in salinity were small and irregular and were not suggestive of any definite tidal effect.

In connection with special studies at the pumping plant of Sargent & Co. (No. 35; see p. 62), hourly samples were collected for several hours on August 6, 1919, at two separate groups of driven wells. The results did not indicate any definite tidal effect.

In the Burr-Hering-Freeman report [50] on the New York water supply, similar experiments are described. The following results were obtained on samples from a 2-inch test well, 125 feet deep, at the Shetucket pumping station in 1899:

[50] Burr, W. H., Hering, Rudolph, and Freeman, J. R., Report of the Commission on additional Water Supply for the City of New York, pp. 417–418, 422–423, New York, 1904.

Chloride analyses from well at Shetucket, Long Island, Feb. 28 and Mar. 1, 1899

Date	Time	Chloride radicle (Cl)	Date	Time	Chloride radicle (Cl)
		Parts per million			*Parts per million*
Feb. 28	9 a. m.	126	Mar. 1	5 a. m.	128
	11 a. m.	126		7 a. m.	128
	1 p. m.	128		9 a. m.	128
	3 p. m.	128		11 a. m.	128
	5 p. m.	126		1 p. m.	126
	7 p. m.	128		3 p. m.	126
	9 p. m.	126		5 p. m.	128
	11 p. m.	126		7 p. m.	128
Mar. 1	1 a. m.	128		9 p. m.	126
	3 a. m.	128		11 p. m.	126

A second series of hourly samples was collected from the same well in 1903, and gave the following results:

Chloride analyses from well at Shetucket, Long Island, Feb. 3–4, 1903

Date	Time	Chloride radicle (Cl)	Date	Time	Chloride radicle (Cl)
		Parts per million			*Parts per million*
Feb. 3 [a]	8 a. m.	88	Feb. 3	10 p. m.	90
	9 a. m.	88		11 p. m.	90
	10 a m.	90		12 m.	92
	11 a. m.	90	Feb. 4 [b]	1 a. m.	90
	12 a. m.	92		2 a. m.	90
	1 p. m	90		3 a m	92
	2 p m.	90		4 a. m.	92
	3 p. m.	90		5 a. m.	92
	4 p. m.	92		6 a. m.	92
	5 p. m.	92		7 a. m.	94
	6 p. m.	92		8 a. m.	92
	7 p. m.	92		9 a. m.	90
	8 p. m.	92		10 a. m.	90
	9 p m.	92		11 a. m.	90

[a] On Feb. 3 the tide at Jamaica Bay was high at noon and low at 7 p. m.
[b] On Feb. 4 the tide was high at 1 a. m. and low at 8 p. m.

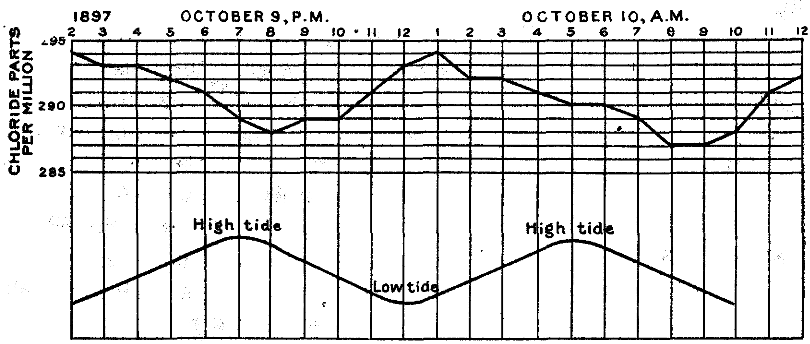

Figure 19.—Relation between tidal fluctuations and salinity of water at Spring Creek pumping station, near Brooklyn, N. Y. (From Burr-Hering-Freeman report on New York water supply)

The report says of the chloride content of the well as revealed by these analyses:

It will be observed that in both of these cases the fluctuations were extremely small, probably too small to be charged directly to the tidal changes.

The observations recorded above were made on a deep test well not under heavy use. Somewhat different results were recorded at the shallow-well plant at Spring Creek (fig. 19), where there appears to have been a slight change in the chloride content of the water, due to tides, although the period of highest chloride lagged several hours behind high tide. It is reasonable to suppose that where the apex of the cone of depression at a pumping plant reaches the sea water and the pumping causes this water to flow inland the amount of the flow would be measurably greater at high tide because of the increased head.

SEASONAL VARIATIONS IN SALINITY OF COASTAL GROUND WATER

Certain contaminated wells exhibit a marked seasonal variation in salinity. The Peter Beattie dug well (No. 100) is on a small plain of stratified drift about 200 feet in diameter at the north end of Narrows Island. The well is 12 feet deep, in sand and gravel, and the water in it stands at about mean sea level. The water was reported to be brackish but to vary greatly from time to time. Accordingly, a number of samples were collected at different dates. An analysis of one sample is given on page 57. The results of chloride determinations covering almost a year are given in the table below, and a comparison of these determinations with the rainfall and temperature records is given in Figure 20.

Chloride in water from Peter Beattie dug well (No. 100) [a]

Date	Chloride radicle (Cl)	Date	Chloride radicle (Cl)
	Parts per million		*Parts per million*
May 16, 1919	[b] 300	Sept. 6, 1919	304
June 21, 1919	[c] 461	Sept. 13, 1919	368
July 12, 1919	590	Nov. 14, 1919	321
July 19, 1919	598	Nov. 28, 1919	256
July 26, 1919	538	Jan. 6, 1920	228
Aug. 2, 1919	559	Feb. 6, 1920	189
Aug. 9, 1919	452	Mar. 6, 1920	172
Aug. 16, 1919	418	Apr. 6, 1920	83

[a] Determinations by Margaret D. Foster and others.
[b] Field test by J. S. Brown.
[c] Average of 9 samples collected June 21, 1919.

The data given show that there was, in 1919, a very great increase of saltiness in the water of this well during June, July, and August. A factor not to be overlooked in the study of the salinity curve is the quantity of water pumped for use. In summer the quantity of water used for domestic purposes might be expected to increase somewhat. However, as the salinity of the water rose, its use for many domestic purposes was discontinued, and water was carried from a neighboring well. The factor of use, therefore, does not appear to be involved to any appreciable degree as the cause of increased salinity.

The variation shows the influence of precipitation and apparently also of temperature. The extremely high proportion of chloride in June and the first part of July occurred in a period of very light rainfall accompanied by rising temperature. The steady decrease of chloride from July 12 to July 26 appears to be the result of heavy, well-distributed rainfall, and the increase in the week July 26 to

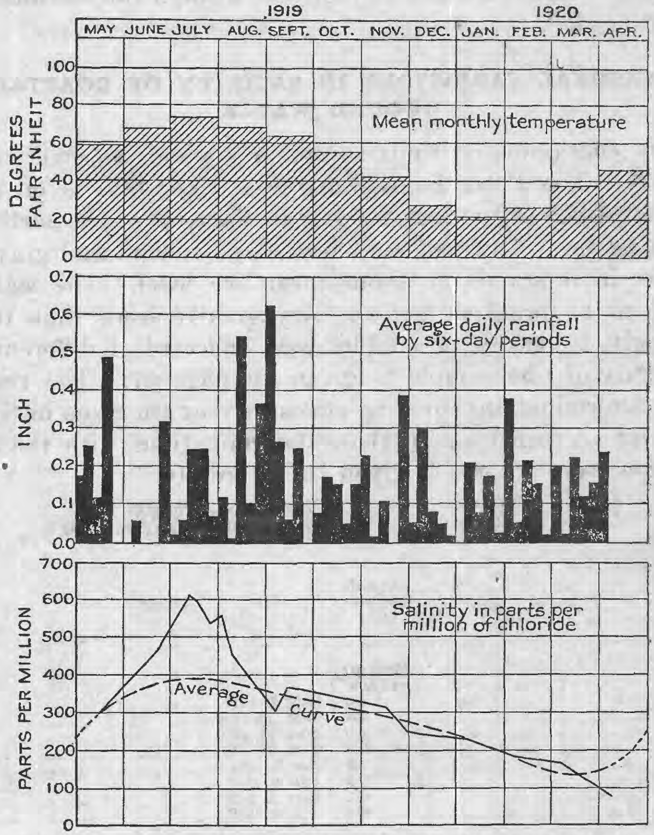

FIGURE 20.—Relation of salinity to temperature and rainfall in Peter Beattie well (No. 100), in Branford Township, Conn.

August 2 coincided with a week of light rainfall. The great decrease in chloride between August 2 and September 6 is evidently the result of heavy rains, particularly those on September 2 and 3, when 3.72 inches fell. The increase of chloride noted in the following week, September 6 to 13, apparently represents the effect of gradual rediffusion of salt after the flood of fresh ground water had subsided. Undoubtedly, careful tests at more frequent intervals would show many irregularities of the curve, due chiefly to the variable precipitation, but the general form would agree more or less closely with that of a yearly temperature curve. However, the spring rise would lag considerably behind the temperature curve because the ground warms more slowly than the air.

The influence of temperature appears in several ways. Higher temperature increases evaporation. It also greatly increases the rate of percolation, so that ground water seeps out to the sea more freely and salt water diffuses landward more quickly. Slichter [51] states that a change of temperature from 50° F. to 60° F. will increase the rate of flow 16 per cent, and that a change from 32° F. to 75° F. will practically double the power of a soil to transmit water. The influence of humidity is also a factor, and the rate of transpiration by plants is important. The island on which this well is situated supports a grove of trees and a grassy lawn, which dissipate much of the precipitation in the summer season. The net result, as indicated, is a remarkable increase in the salinity of the well through the summer.

Observations on two drilled wells in bedrock, although not so complete as those on the Beattie well, tend to strengthen the evidence that some contaminated wells are most salty in summer. The drilled well of Robert Mitchell (Pl. VI, *B*) is on a narrow point 50 feet from high tide on two sides. It is about 50 feet deep. The well was made to supply a summer cottage, but the water becomes so salty when used that the well was entirely abandoned in 1919. The following results were obtained from four samples:

Chloride determinations of water from Robert Mitchell well (No. 110)

Date (1919)	Chloride, radicle (Cl) [a]	Remarks
	Parts per million	
May 19	49	
June 16	94	Average of 8 samples collected at hourly intervals (see p. 51).
Aug. 4	50	
Nov. 28	31	

[a] Determinations by Margaret D. Foster.

These samples show a large increase in salinity in summer even though the well was entirely unused.

The Anderson drilled well (No. 125), like the Mitchell well, becomes salty whenever used. Nevertheless it is used in summer, as it is the only supply available at that locality. The results, therefore, can not be attributed entirely to natural seasonal variations, although they are largely due to that cause, as the quantity of water used does

[51] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, p. 13, 1905.

not vary greatly from day to day. Below are the results of analyses. When the first sample was taken, June 16, 1919, the well had not been used since the season of 1918.

Chloride determinations of water from Anderson well (No. 125)

Date (1919)	Chloride radicle (Cl) [a]	Rainfall since last sample [b]	Date (1919)	Chloride radicle (Cl) [a]	Rainfall since last sample [b]
	Parts per million	*Inches*		*Parts per million*	*Inches*
June 16	37		July 17	516	0.90
July 12	290	[c] 0.34	18	442	.42
14	325	.12	20	446	.64
15	429	.05	Aug. 4	355	[d] 1.91
16	448	1.04			

[a] Determinations by Margaret D. Foster.
[b] Based on averages of records of rainfall at New Haven and New London, which are about equidistant.
[c] Rainfall from July 1.
[d] Includes 0.52 inch on Aug. 1.

The results indicate a seasonal variation in salinity much like that in the Beattie well, though the great increase between June 16 and July 12 may have been due partly to the drain upon the well. The mounting salinity in July shows the effect of a sharp drought, and the subsequent decreases followed closely the rains of July 16 and August 1.

Such remarkable seasonal fluctuations in salinity in ground water are doubtless confined to small islands and points where the total quantity of fresh ground water is very small and where the increment from rains reaches the sea quickly. It is quite possible, however, that at some places on mainland shores seasonal fluctuations may have an appreciable effect on the zone of contamination between salt and fresh ground water and may cause this zone to progress slightly farther inland in the summer. The evident influence of temperature also suggests that, with a like amount of rainfall, contamination is probably relatively more frequent in warm climates than in cool climates.

ANALYSES OF WATER FROM THE NEW HAVEN COAST

The accompanying tables give 16 partial analyses of samples of well water from the New Haven coast, with records of the sources of the samples. For groups of wells, the sample analyzed was a composite from all wells of the group. The analyses were made chiefly to verify the value of chloride as an indication of contamination by sea water. Sea water is characterized by a very high percentage of chloride (55.3 per cent) in its mineral content and by a high ratio of magnesium to calcium (3.11 to 1). The ratio of magnesium to chloride also is very nearly constant (0.067 to 1). Columns are given in the table of analyses showing percentages for these three items for the waters analyzed.

Analyses of samples of well water from the New Haven coast, with reference to probable contamination by sea water

Records of samples

No. on Plate I	Owner	Nature of source	Date of collection	Remarks
21	Connecticut Fat Rendering and Fertilizing Corp.	12 driven wells, each 45 feet deep.	July 9, 1919	
23	Sperry & Barnes	40 driven wells, each 47 feet deep.	do	
24	Hull Brewing Co	9 driven wells, each about 35 feet deep.	Dec. 10, 1910	Approximately same group of wells as that in use in 1919.
27	Alexander & Links	Driven well 40 feet deep	July 9, 1919	
32	Hygienic Ice Co	5 driven wells, each about 75 feet deep.	do	
35	Sargent & Co	Driven well in group A, about 30 feet deep.	July 16, 1919	
36	W. & E. T. Fitch Co	Driven wells, each about 30 feet deep.	Feb. 12, 1916	Approximately same group as that in use in 1919.
37	New Haven Gas Light Co.	7 driven wells 37 to 42 feet deep	July 9, 1919	
40	National Folding Box Co.	72 driven wells 60 to 75 feet deep.	do	
41	Connecticut Co	5 driven wells 16 to 50 feet deep	do	
44	New England Warp Co.	4 driven wells 15 to 20 feet deep	do	
45	Yale Brewing Co	36 driven wells, each about 18 feet deep.	do	
100	Peter Beattie	Dug well 12 feet deep	July 12, 1919	
175	Connecticut Breweries Co.	2 drilled wells, one about 300 feet and one about 400 feet deep.	Oct. 4, 1919	
178	Connecticut Web & Buckle Co.	Driven well 20 feet deep	do	
179	Morris & Co	3 driven wells, each about 30 feet deep.	do	

Analyses [a]

[Parts per million except as otherwise designated]

No. on Plate I	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Carbonate radicle (CO_3)	Bicarbonate radicle (HCO_3)	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Nitrate radicle (NO_3)	Total dissolved solids at 180° C.	Total hardness as $CaCO_3$ [b]	Ratio of chloride radicle to total dissolved solids	Ratio of magnesium to calcium	Ratio of magnesium to chloride	Probability of contamination by sea water
													Per cent	*Per cent*	*Per cent*	
21	16	0.08	47	32	357	0.0	24	221	574	8.4	1,340	249	43	68	5.6	Yes.
23	28	.06	45	78	[b] 496	11	121	139	885	1.8	1,803	432	49	173	8.8	Yes.
24 [c]	19	-----	72	21	52	.0	158	53	64	109	416	266	-----	29	32.8	No.
27	33	.13	48	17	91	2.4	178	60	115	38	[d] 493	190	23	35	14.8	No.
32	25	.10	20	15	[b] 101	24	85	56	113	5.2	466	112	24	75	13.3	(?)
35	27	1.7	29	22	[b] 164	12	178	74	193	3.8	649	163	30	76	11.4	Yes.
36 [e]	-----	-----	73	29	[b] 59	.0	212	105	104	-----	502	301	21	40	27.9	No.
37	28	.06	52	39	[b] 250	4.8	158	65	439	9.6	1,003	290	44	75	8.9	Yes.
40	34	.15	108	47	224	.0	117	96	514	21	1,161	463	44	44	9.1	Yes.
41	28	.23	15	15	[b] 77	7.2	59	93	75	3.3	374	99	20	100	20.0	(?)
44	20	1.2	70	9.2	[b] 108	2.4	198	232	26	2.1	609	213	4	13	35.4	No.
45	26	.16	56	17	117	2.4	114	132	145	31	653	210	22	30	11.7	No.
100	26	.08	60	35	344	.0	88	127	590	3.4	1,295	294	46	58	6.0	Yes.
175	38	.08	51	22	[b] 134	9.6	37	200	169	19	719	218	24	43	13.0	(?)
178	22	.48	5.7	2.6	17	24	3.7	8.6	7.0	Trace	93	25	8	46	35.7	No.
179	8.2	.18	5.7	1.4	11	.0	37	3.1	8.0	.40	73	20	11	25	17.5	No.
Ratios for sea water						------	------	------	------	------	------	------	55.3	311	6.7	

[a] Analyses by H. B. Riffenburg, unless otherwise stated.
[b] Calculated.
[c] Analysis furnished by National Breweries Consulting Bureau; recalculated from hypothetical combinations.
[d] By summation.
[e] Analysis by G. W. Pucher, Sheffield Chemioal Laboratory, Yale University, New Haven, Conn.

Six of the analyses given in the table are believed to indicate contamination by sea water and have been so interpreted in the text of this paper. They are Nos. 21, 23, 35, 37, 40, and 100. Contamination by sea water in the six samples represented by these analyses is suspected because of the high chloride content, because the wells are located near the sea, and because of the circumstances of operation of the wells. (See pp. 58–83.) Besides having the highest percentages of chloride to total solids, these six samples are found to have also higher ratios of magnesium to calcium than any other samples except No. 178, but in that sample the magnesium and calcium contents are both so small as to render the value of the ratio somewhat doubtful. In the average ground waters of Connecticut the ratio of magnesium to chloride ranges from 35 to 75 per cent. If the six samples here discussed are contaminated by sea water their ratio of magnesium to chloride should be much lower than the average—almost though not quite as low as that of sea water (6.7 per cent). These six samples are shown by the table to have the six lowest ratios of magnesium to chloride—in fact, in two samples (Nos. 21 and 100) the quantity of magnesium is slightly less than the normal percentage in sea water.

It may be remarked in conclusion that some chemists and geologists have argued that sea water is present in certain ground water while others have taken the opposite view, and usually each party to such a controversy has found facts to support his opinions. It is certain that chemical changes take place in the mixture of ground water and sea water and that these changes may be very different even in neighboring localities. It is the author's opinion that at least the six samples mentioned above and perhaps also Nos. 41 and 175 contain sea water in appreciable amounts.

DETAILED DESCRIPTIONS OF WELLS, SPRINGS, AND PUMPING PLANTS ON THE NEW HAVEN COAST

In the following pages detailed descriptions are given of the springs, wells, and pumping plants shown on Plate I, on which the conclusions in regard to coastal ground water in Connecticut are based. The altitudes given are estimated from contour maps in feet above mean sea level, except those referred to high tide, which were obtained by hand leveling above the average high-tide mark. The following abbreviations are used: ft. = feet; in. = inches; p. p. m. = parts per million.

1. Mrs. Warner and Mrs. Ford. This is the old Smith place near the middle of Milford Point. The point is a long sandy spit which nearly seals off the mouth of Housatonic River. It is 100 to 300 ft. wide and is barely above storm tides. It is composed entirely of sand, which is at places slightly wind-worked and which supports a growth of coarse beach grass, a few shrubs, and some cottonwood and cedar trees. Many attempts to get usable well water at this place have failed. A well 8 or 9 ft. deep was dug at the location given. It yielded fresh water for a few hours but became "salty as the ocean" at high tide. The residents depend entirely on cisterns for their present supply.

2. Gulf Refining Co. Dug well; depth 24 ft.; diameter 3 ft.; cement-pipe lining; board cover; steam pump; altitude 25 ft.; depth to water 22 ft.; stratified drift. The well is on the main stratified-drift terrace of the Housatonic Valley, about 500 feet from tidewater of the river. It is pumped at a rate of 15 or 20 gallons a minute for short periods to supply boiler water when rain water is not available. A field test, July 28, 1919, showed only 10 p. p. m. chloride, and a laboratory sample showed 8.4 p. p. m. This quantity of chloride is practically normal and is negligible as a factor in boiler quality. Although current reports state that this water is fresh at low tide and salty at high tide, the reports are believed to be incorrect, as it would be impossible for a tidal effect to be transmitted through so great a distance of earth for many hours after the movement of the tides. The unsatisfactory quality of the water for boiler use must arise from other sources than tidal salt water.

3. Mrs. Lewis. Dug well; depth 42 ft.; diameter 3 ft.; stone lining; wood curb; hand windlass; altitude 40 ft.; depth to water 40 ft.; stratified drift; domestic use. The well is on a terrace, 250 feet from tide mark of Housatonic River, which is tidal but not very salty at this point. A sample taken July 29, 1919, showed 7.6 p. p. m. chloride, which indicates no contamination.

4. Roger Bros. Spring, generally known as Camp Meeting Spring because there was once a camp-meeting ground near by. It is in a dense forest half a mile or more from any habitation. A large pit at the foot of a till hillside is stoned and housed. From it issues a flow of about 10 gallons of water a minute. The water is bottled and sold as a beverage. Advertisements state that there is no "farming or pasturing, and no swamp land above the spring, so that contamination is impossible." An analysis by Herbert E. Smith, State chemist, showed 3.9 p. p. m. chloride, and a sample collected July 22, 1919, showed 5.3 p. p. m. This is low, even for the normal. The spring is about 3 miles from shore.

5. E. B. Clarke Seed Co. Spring. This spring is on a wooded hillside. A shallow pit 3 ft. in diameter exposes the bedrock of schist, from the crevices of which the water issues. The spring is about 4 miles inland and was sampled July 19, 1919, to determine the normal chloride, as no contamination was suspected. The sample showed 8.0 p. p. m. chloride.

6. George Clark. Spring; till; domestic use. The spring is in a swampy meadow. A hole 8 ft. in diameter and 5 ft. deep is stoned and covered and feeds a hydraulic ram. A sample was taken July 24, 1919, to determine the normal chloride, as no contamination was suspected. The sample showed 7.2 p. p. m. chloride. The spring is about 2 miles from shore.

7, 8. Wells; about 25 feet deep; stratified drift. These wells are between 100 and 200 ft. from tidewater and are never brackish.

9. Purcell. Dug well; depth 22 ft.; diameter 2½ ft.; cement-pipe lining; wood curb; rope and pulley; altitude 18 ft.; depth to water 18 ft.; stratified drift; domestic use. The well is on a narrow belt of land, 100 ft. from a salt marsh on the west and about 250 ft. from tidewater on the east. The water has never been known to be brackish. A sample taken July 25, 1919, showed 10 p. p. m. chloride, which indicates no contamination.

10. Dug well near the center of Charles Island; altitude 20 ft.; till. This well once supplied some houses on the island, but it is now abandoned and nearly filled. In 1919 it measured 10 ft. in depth and contained 6 in. of water. As there was no probability of contamination no sample was collected.

11. Gaskill. Drilled well; depth 85 ft.; diameter 6 in.; hand pump; altitude 25 ft.; domestic use. The well penetrates drift, probably stratified, near the surface, and from surface indications the till is probably underlain by rock at a depth of 30 or 40 ft. The well is 200 ft. from tidewater on the flat above a prominent wave-cut cliff. The water has never been suspected of brackishness. A sample taken July 25, 1919, showed 12 p. p. m. chloride. No contamination is indicated.

12. Roy Wilcox. Dug well; depth 11 ft.; diameter 3 ft.; stone lining; board cover; hand pump; altitude 5 ft. above high tide; depth to water 6 ft.; stratified drift; domestic use. The well is on a gentle slope only 100 ft. from tidewater in Indian River. A sample taken July 25, 1919, showed 21 p. p. m. chloride, which probably indicates a very slight degree of contamination.

13. George Smith. Driven well; depth 30 ft.; diameter 1¼ in.; hand pump; altitude 4 ft. above high tide; stratified drift; domestic use. This well is only 20 ft. from the edge of a salt marsh and 50 ft. from the reach of normal high tide and is nearly at the level of the marsh. Mr. Smith reports that the river water at low tide at this point is "fresh enough to drink" but at high tide is salty. A sample taken from the well July 29, 1919, showed 98 p. p. m. chloride. This apparently indicates some saltiness from the tidewater, but not enough to be distinguishable by taste.

14. James Merwin. Dug well; depth 8 ft.; diameter 3 ft.; stone lining; wood curb; altitude 3 ft. above high tide; depth to water 5 ft.; beach sand; domestic use, but abandoned. The well is only 60 feet from high tide on a bar beach behind which is a salt marsh. It is said to have furnished domestic supply for all uses except drinking. Some reports state that the water was a little brackish. No sample was collected.

15. Chas. E. Chapin. Drilled well; depth 35 ft.; diameter 6 in.; hand pump; altitude 20 ft.; stratified drift; domestic use. The well is 250 ft. from tidewater. A sample taken July 31, 1919, showed 29 p. p. m. chloride. This is a little high for normal, but is more likely due to cesspools in the vicinity than to the presence of sea water.

16. E. V. Ball. Dug well; depth 8 or 10 ft.; diameter 3 ft.; altitude 5 ft.; depth to water 5 or 6 ft.; domestic use, but abandoned for several years. The well is on the point just opposite Savin Rock. It penetrates sand for a short distance and below that slate rock (phyllite). The point of land is about 150 ft. wide and 250 ft. long. This well for many years furnished domestic water supply to one or more houses in the neighborhood until the public supply was installed. A very high tide finally caused the well to become brackish and it was abandoned and converted into a cesspool.

17. Failer. Driven well; depth about 20 ft.; diameter 1½ in.; hand pump; altitude 10 ft.; stratified drift; domestic use. The well is on a tongue of land about 400 ft. wide nearly surrounded by salt water or salt meadows. A sample taken July 31, 1919, showed 174 p. p. m. chloride, which probably indicates contamination by sea water.

18. Sparandeo. Driven well; depth 14 ft.; diameter 1½ ft.; hand pump; altitude 12 ft.; stratified drift; domestic use. This well was just completed at the time of sampling, July 31, 1919. Its situation is very nearly the same as that of No. 17, but it is not so deep, is on a little higher ground, and is farther from salt water. The sample showed 14 p. p. m. chloride, which is very low for the situation.

19. Frederick. Dug well; depth 11 ft.; diameter 3½ ft.; stone lining; wood curb; rope and pulley; altitude 5 ft. above high tide; depth to water 8½ ft.; stratified drift (sand). This well is on a projecting point of a stratified-drift plain only 50 ft. from high tide. It furnishes a satisfactory domestic supply. No sample was taken. Just south of this well the shore changes to a low bar beach in the rear of which is a salt marsh. It is reliably reported that a driven well 35 ft. deep on the bar beach near Barry's boat house, 200 ft. south of well 19, yielded only salt water.

20. New Haven Rendering Co. Pumping plant. This company uses city water only for boilers. For washing floors, condensing, cooling, and drinking it uses the water from a group of eleven 2-in. driven wells, which are in an irregular north-south line, at intervals of 20 ft. They penetrate stratified drift (sand) for their entire depth of 25 or 30 ft. The wells are about 300 ft. west of the plant, very near the edge of a salt marsh. A sample taken July 9, 1919, showed 22 p. p. m. chloride, which is not indicative of sea water. The wells are pumped at a rate of about 100 gallons a minute. The company once had another group of wells on the very narrow point of land where the buildings stand, directly between two salt marshes, a situation similar to that of the wells of the Connecticut Fat Rendering & Fertilizing Corporation (No. 21), but probably worse, because nearer the end of the point. The water was very bitter and brackish, and the wells were abandoned.

21. Connecticut Fat Rendering & Fertilizing Corporation. Pumping plant. This company uses city water in boilers and for drinking, well water for washing floors and condensing. There are twelve wells, in two east-west rows near the office on Front Street. The wells are 2 in. in diameter, 45 ft. deep, and penetrate sand all the way. They were driven in 1916. They are pumped practically continuously at a rate of about 100 gallons a minute. An analysis of the water is given on page 57. The chloride content, 574 p. p. m., probably indicates the presence of sea water. The wells are on a very narrow point of land between two salt marshes, yet even under these conditions the degree of contamination seem unusually high, especially in comparison with that in the New Haven Rendering Co.'s wells near by. (See No. 20.)

22. Malloy Buckle Co. Pumping plant. This company has two dug wells, each of which is 25 ft. deep and contains about 2½ ft. of water. The wells are pumped lightly, and no contamination was suspected. A sample taken July 9, 1919, showed 23 p. p. m. chloride, which is low for the situation.

23. Sperry & Barnes. Pumping plant, supplying well water for condensing and cooling and for washing floors. There are forty driven wells, each 2 in. in diameter and 47 ft. deep below the present surface, which is scarcely above high tide. The wells are in a row and extend about 400 ft. southeast from the end of Brewery Street along the narrow peninsula of filled land on which the plant is situated. These wells were driven in 1913, and the following approximate log is given:

Log of Sperry & Barnes wells, New Haven, Conn.

Material	Thickness	Depth
	Feet	*Feet*
Fill and harbor mud	35	35
Hardpan	8	43
Gravel	4	47

The hardpan is described as "red rock sand" and is probably only a layer of hard sandstone gravel (stratified drift). The wells are pumped nearly to capacity 24 hours a day. The yield is thought to be at least 200 to 300 gallons a minute. When these wells were first driven, the water was used for drinking, but the quality is now so poor that it is unfit for drinking or for boilers. An analysis is given on page 57. The chloride content, 885 p. p. m., indicates a considerable proportion of sea water.

24 to **34.** Pumping plants using driven wells in stratified drift. All are more than 1,000 feet from tidewater. Contamination by sea water was not suspected and is not indicated by the analyses, which were made principally to determine the amount of chloride that might be expected in wells in the heart of New Haven. The results indicate that at least 100 p. p. m. chloride, possibly more at some places, may rightfully be attributed to sewage and to surface pollution. The owners of these plants and the chloride content of the water are given in the table on page 40. Further description is not considered necessary in this report.

35. Sargent & Co. Pumping plant. Sargent & Co. use large amounts of water both from the public supply and from wells. The well water is used in condensing steam and to some extent for washing floors, acid pickle, etc. It is unsatisfactory for boilers, drinking, or electroplating. There are in use at present three groups of driven wells, most of which are 2½ in. in diameter and about 35 ft. deep. (See fig. 12.) Group A consists of sixteen wells 2½ in. in diameter. A number of 2-in. wells are also connected, but they have not been cleaned out for many years and are thought to yield practically no water. Group B consists of twenty 2½-in. wells. Some 2-in. wells, also probably useless, are connected with this group. Group C consists of twelve 2½-in. wells 30 or 35 feet deep. Groups D and E are abandoned. The wells of group A are on filled land, which was originally tidal, and penetrate about 6 ft. of fill, 4 ft. of black harbor mud, then fine sand (stratified drift). Groups B and C are on land that was orignally above tidewater and penetrate sand. The shore at the factory grounds formerly extended only about 160 ft. south of Water Street, but has now been filled in for a distance of 1,000 to 1,500 ft. East of the plant, however, docks still extend nearly to Water Street.

On August 6, 1919, a special study of these wells was attempted to find out whether the water was contaminated by sea water, and, if so, the relative degree of contamination between the groups, as well as to note any apparent tidal effects or daily fluctuation in quality.

All three groups of active wells are pumped to jet condensers, where the water is used. Unfortunately it was not feasible to obtain samples directly from the wells, so that those obtained represent the well water plus a small quantity of condensed steam, probably not exceeding 10 per cent of the total discharge.

The wells are pumped at present about 9 hours a day, from 8 a. m. to 5 p. m. Samples of the condenser discharge from groups A and B were collected during the day at hourly intervals. The variations of chloride content in each group were small and irregular and did not indicate any appreciable tidal influence. The water from group A averaged 3,700 p. p. m. chloride; that from group B about 90 p. p. m., and a single sample from group C 94 p. p. m. The results show very high contamination in group A and relatively little in groups B and C. The manner in which salt water enters these wells is discussed on pages 41–43, and the conclusion is reached that a small amount of contamination may be accounted for by infiltration of salt water through the nearly impervious mud, but that the very high contamination in group A is due to some break which admits salt water directly into the wells. The evidence supporting this conclusion follows:

On July 16 a single well of group A had been detached from the pumping main for cleaning. Cleaning was accomplished by blowing a jet of steam through a long pipe inserted in the well, thus causing geyser-like explosions, which carried out much mud and rust and partly opened the sealed perforations in the strainer. This process had been completed two or three days before, and the well was standing idle and open. This well is 34 ft. deep and its water level was 9.9 ft. A sample was collected by attaching a hand pump. The sample contained only 193 p. p. m. chloride (see analysis, p. 57), which is unexpectedly low, as the composite samples of the group showed about 3,700 p. p. m. chloride.

This seems to indicate that the ground water at the water table in group A is not much more saline than at groups B and C and that sea water may be entering the system directly at some point. By means of a few test wells and a segregation of group A wells into units this inference could be easily verified.

Henry Sargent states that several years ago a test well was sunk 640 ft. south of Water Street and therefore several hundred feet beyond the original shore line. The depth reached was 110 ft. The well penetrated 25 or 30 ft. of mud, then fine sand, which grew progressively finer. The water was thoroughly fresh and fit to drink, but the well was never used.

36. W. & E. T. Fitch Co. Pumping plant. This company uses both the public supply and well water, the well water being used chiefly for condensers and floor washing. There are two groups of wells, one at the north end of the building and one at the south end. In the northern group are six wells 23 ft. deep, spaced about 10 ft. apart. This group is said to yield very little water. The other group has a larger number of wells about 30 ft. deep spaced 10 ft. apart and arranged in two rows. All are 2 in. in diameter. They penetrate artificial fill and stratified drift. The wells of this plant are about 400 ft. from tidewater in Mill River. The surface of the ground is about 10 ft. above sea level. A sample of water collected July 9, 1919, showed 145 p. p. m. chloride. An analysis furnished by the company (given on p. 57) shows 104 p. p. m. chloride in 1916. These results are high but do not necessarily indicate the presence of salt water—indeed, the analysis shows no apparent relation to sea water.

37. New Haven Gas Light Co. Pumping plant. This company uses city water for boilers and for drinking, well water for condensers and for quenching coke, and salt water from Mill River for washing floors and other rough uses. The salt water is used only because the wells do not yield an adequate supply. There are two groups of 2-in. driven wells. One group of fifteen wells is west of the railway tracks at the southeast corner of Green and East Streets. No samples were taken from this group. The other group consists of ten wells arranged in an east-west line parallel to Chapel Street at the west end of Mill River bridge. Five of these wells are 42 ft. deep and the other five are 37 ft. deep. The water table is said to stand approximately at mean sea level. The wells are in ground which was originally a tidal marsh and penetrate a few feet of mud, then fine sand (stratified drift). Only the elevated approach to Mill River bridge separates the wells from tidewater on the south. (See Pl. VII, *A*.) An analysis of water from seven of the ten wells is given on page 57. The other three wells were disconnected when the sample was taken. The chloride content is 439 p. p. m. and indicates the presence of sea water in considerable amount.

38. New Haven Pulp & Board Co. Pumping plant. This company uses city water for boilers and drinking but pumps ground water for pulp mixing and rough uses. There are two groups of wells, one of nineteen wells west of the railway tracks and 300 or 400 ft. from Mill River, the other of eight wells east of the tracks very near the river. All are 2-in. driven wells about 30 ft. deep. All the wells are pumped to capacity 24 hours a day. In fact the wells nearer the river appear to be greatly overtaxed, and the pump seems to be working on vacuum a large part of the time. The two pumps are alike, and the indicated displacement for each group was about 800 gallons a minute. The well water was used at first for drinking but later was condemned for this purpose and abandoned. It is said to have become noticeably bad, particularly in the wells nearest the river. A sample collected from the west group of wells July 12, 1919, contained 746 p. p. m. chloride, which indicates considerable contamination.

39. United Illuminating Co. Pumping plant. On an island in Mill River, G. L. Clark, chief engineer, stated that the company once used a gang of about twenty driven wells 2-in. in diameter and over 100 ft. deep. The water was too hard for boiler use, and also contained much mica and fine sand. The yield of the wells was small, about 7 gallons a minute. They had no strainers but were open at the bottom. Although the island is completely surrounded by tidewater, the wells are said not to have been salty. They have been abandoned for several years.

40. National Folding Box Co. Pumping plant. The largest on the New Haven coast. There are seventy-two driven wells divided into two groups of nearly equal number, east and west of James Street. All are pumped from one central plant west of James Street. The pump house is sunk below sea level. The wells are pumped continuously at an average rate of 1,000 gallons a minute (1,440,000 gallons a day). The water is used in making paper pulp and for all factory uses except for boilers and drinking. Any excess in the supply is returned through the system. The wells are 3 in. in diameter, 60 to 75 ft. deep, and at the bottom carry 20-ft. Cook strainers. They are in rows approximately east and west at intervals of about 20 ft. The wells west of James Street are in a tidal marsh which has been reclaimed by filling. They penetrate 18 to 20 ft. of slime and mud, below which is fine sand (stratified drift). A bed of coarse gravel is found at about 60 ft., and from this the wells draw their supply of water. Some unusually large yields were indicated in the preliminary pumping tests. It is reported that forty wells west of James Street were pumped at a rate of 1,640 gallons a minuet (41 gallons to the well) for 36 hours without affecting the supply. In individual tests certain wells yielded 240, 260, 270, and 280 gallons a minute for sustained periods. Wells 3 in. in diameter are said to yield nearly as much as wells 6 in. in diameter, some of which were tried experimentally. The plant has been delivering water at its present rate since about January 1, 1917. It is said that the water table is gradually falling, as indicated by the level at which water stands in the wells during occasional temporary shut-downs. The drop was about 4 ft. the first year and 2 ft. the second. When the plant was first operated, chemical tests were made to determine whether or not the wells were affected by salt water, which is present in Mill River just west of the plant and which permeates the old salt marshes to some extent. No evidence of contamination was discovered, and the water west of James Street was of practically the same quality as that east of it, farther from the river. However, a sample collected at the pump delivery July 9, 1919, showed 514 p. p. m. chloride. An analysis of the water is given on page 57. The results indicate that at present there is considerable salt in the water. This has been induced by the heavy drain on the underground supply. As a general rule the thick bed of mud in the salt marshes and beneath the harbor appears to constitute an effective barrier to the infiltration of salt water, but its resistance is overcome to some extent by exhaustion of the water from the underlying water-bearing sand, which was formerly relatively full of fresh water. It is possible that the salt may enter, to some extent at least, by infiltration around well casings, but this is not regarded as very likely in these wells because tidewater seems to be thoroughly excluded from the land on which the wells are situated.

41. Connecticut Co. Pumping plant. The power plant of the company at Grand Avenue and Mill River, depends mainly on the public water supply. There are five 2-in. driven wells, which are said to range from 16 to 50 ft. in depth, in the northeast corner of the property. They are about 200 ft. from tidewater, on land that has been built up from salt marsh. About 20 gallons a minute is pumped from the wells continuously, which is much less than their capacity. The water is used for cooling, chiefly in water jackets. It is not desirable for boilers or turbines because too much scale is formed. The water is hard but not salty to the taste. A sample taken July 9, 1919, showed 75 p. p. m. chloride. A more complete analysis is given on page 57. The analysis does not indicate an appreciable quantity of sea water.

42. Bigelow Co. Pumping plant. This company recently abandoned its pumping plant. It had thirty or forty driven wells, about 28 ft. deep. The water was used in testing out boilers manufactured by the company, but it caused them to rust so badly that the wells were abandoned. A drilled well 175 ft. deep, which just penetrated rock, yielded too small a supply of water. The casing was raised, admitting salt water.

43. Kilborn & Bishop. Pumping plant. This company abandoned its wells in 1918, and no reliable information was obtained about them except that they were not "salty."

44. New England Warp Co. Pumping plant. This company uses the public water supply for most purposes but pumps well water for washing wool. There are four 2-in. wells 15 or 20 ft. deep, which penetrate stratified drift (sand) just far enough to reach water. They have been used for 15 years, the points being renewed occasionally. The quantity of water used is unknown, but it is not nearly so great as that used by the larger plants in New Haven. A sample collected July 9, 1919, contained 26 p. p. m. chloride. An analysis is given on page 57. The results indicate scarcely a trace of sea water, although the wells are only about 300 ft. from the shore.

45. Yale Brewing Co. Pumping plant. This company depends mainly on the public water supply but has for a long time used some wells. At present there are thirty-six 2-in. driven wells about 18 ft. deep in the small triangular court at the intersection of Ferry and Chapel Streets. The wells penetrate stratified drift (sand) and are about 500 ft. from salt water. Many of them are now unproductive owing to clogging or rusting. The water is used for washing floors, cases, etc., and the wells are pumped continuously. The yield is not known but the indicated pump displacement at the time the plant was visited was about 25 gallons a minute. A sample of the water taken July 9, 1919, showed 145 p. p. m. chloride. An analysis is given on page 57. The results do not indicate sea water in any appreciable amount, though the salinity is rather high. The company once had under its building two drilled wells about 100 ft. deep, which penetrated sandstone most of the way. They were abandoned because the supply was wholly inadequate. Reports state that the water was not saline.

46. Ball. Dug well; depth, 13 ft.; diameter, 3 ft.; stone lining; wood curb; altitude, 10 ft.; depth to water, 9 ft.; stratified drift; formerly a good domestic well; abandoned. Only 50 ft. west of Quinnipiac River (tidal).

47. G. B. Thrall. Dug well; depth, 10 ft.; diameter, 3 ft.; stone lining; wood curb; altitude, 8 ft. above high tide; depth to water, 5 ft.; domestic use. This well penetrates sandstone, and the water enters through joints. The well has been used for many years without ever having yielded brackish water. It is only about 50 ft. from the reach of high tides.

48. American Steel & Wire Co. This is an abandoned drilled well in sandstone only a few feet from tidewater. It is said to have been 150 ft. deep and to have given a small supply of salty water.

49. American Steel & Wire Co. Pumping plant. This company now uses water from the public supply but until recently depended largely on wells. Its property completely surrounds that of the Penn Seaboard Steel Corporation, whose plant was actively operated in 1918 but suspended work with the termination of the war. Figure 13 (p. 43) shows the relation of well groups on the two properties. There are said to have been originally 51 driven wells, sunk in 1902, of which 40 were on the property now owned by the Penn Seaboard Steel Corporation, and 11 on the land of the American Steel & Wire Co. near the southwest boundary between the two properties. The wells are 12 to 18 ft. deep, 2 in. in diameter, and are irregularly placed. The grouping given for the 40 wells on the Penn Seaboard Steel Corporation's property in Figure 13 is only approximately correct. The wells penetrate stratified drift (sand). The ground is 5 to 10 ft. above sea level. For several years the wire company used the entire group of 51 wells and had no trouble in getting plenty of water. During the war the Penn Seaboard Corporation began to operate its plant very extensively. The suction was cut at the boundary line, and the 40 wells on its property were pumped to capacity. It was found, however, that less than half of these wells were yielding water, owing to deteriorated casings and other defects. During the later part of 1918 water was pumped continuously at the rate of approximately 10 million gallons a month or, if there were 20 producing wells, about 10 gallons a minute for each well. When pumping was first begun on these wells the water was tested and is said to have been found fit for drinking, although it contained slight traces of bacteria and chloride; but under this heavy draft it became salty, the wells evidently having drawn salt water from the harbor, which is about 400 ft. to the northwest. The heavy pumping by the Penn Seaboard Corporation lowered the water table so much that the wells of the American Steel & Wire Co. became practically dry, and the little water they yielded was also salty. The inflow of salt water from the harbor was due to lowering of the water table as a result of the heavy drain upon it. This lowering was no doubt very rapid because the triangular plain of stratified drift upon which the plants are situated is very small. It is bounded on the northwest by tidewater at the mouth of Quinnipiac River and on the east by a ridge of land underlain by bedrock. It extends about a mile to the south, but the general tendency of ground-water drainage is probably south and west, away from the factory properties. The total area contributory to these wells apparently can not exceed one-quarter of a square mile and may be considerably less.

It would seem that the deposit of mud on the harbor floor should have acted as a deterrent to the infiltration of salt water into these wells, as has been postulated elsewhere. However, this mud loses its imperviousness when the water table is lowered sufficiently to afford a strong pressure head of the salt water.

The geologic conditions suggest that fresh water from the Fair Haven region must pass under Quinnipiac River, as through a natural siphon, to replace that drawn out on the opposite side, but this does not seem to have occurred. Perhaps intervening clay beds, which are present to some extent in the stratified drift of New Haven, may prevent this, or the friction may be too great, or the water coming by such a route may be more or less contaminated in its passage beneath the salt water of the harbor.

The suggestion that the wells be sunk deeper in order to penetrate possible water-bearing strata fed by a purer supply from the northwest side of Quinnipiac River is worthy of a trial in this situation.

The wells were not being pumped during the period of the investigation, and no samples were obtained from them.

50. Simon Eddy. Driven well; 10 or 15 ft. deep; between 1 in. and 2 in. in diameter; altitude 5 ft.; depth to water 5 ft.; stratified drift; domestic use. Well is on ground that is low and swampy but not tidal. The tenant complains that the water is brackish, but a field test April 19, 1919, showed 21 p. p. m. chloride, which does not indicate contamination by sea water.

51. Spring. On a grassy ridge. Appears to be fed from fractures in a trap dike. It was sampled June 30, 1919, to determine normal chloride and showed 9.1 p. p. m.

52. George H. Townsend. A spring at the foot of a sandstone slope, very near the edge of a salt marsh. It has been dug down about 6 ft. in the form of a well but overflows. Water comes from fractures in sandstone, which is closely associated with trap dikes. A sample taken June 30, 1919, showed 7.8 p. p. m. chloride.

53. Fort Hale Park. Dug well; depth 12 ft.; diameter 5½ ft.; stone lining; wood curb; altitude 10 ft. above high tide; depth to water 10 ft.; penetrates a trap dike from the surface. This was originally a public well used by park visitors and picnic crowds. After city water was installed the well was abandoned but it is still in good condition. It is on a small eminence about 300 ft. long and 175 ft. wide, which at high tide is practically an island. A sample taken June 30, 1919, showed 164 p. p. m. chloride, which indicates a slight contamination by sea water.

54. Mary Herrick. Drilled well; depth 23 ft.; diameter 6 in.; hand pump; altitude 10 ft. above high tide; depth to water 10 ft.; bedrock (granite gneiss); drilled by John King; domestic use. This well is 35 ft. from reach of high tide and was originally drilled 35 ft. deep. It yielded good water until after a very high storm tide, when it became very salty. The owner filled the bottom with oyster shells, dirt, etc., for 10 or 12 ft. The water improved and has never been bad since. On April 22, 1919, at 11.30 a. m. (very near low tide) the water level was 10.5 ft. below the top of the casing, which is a few inches above the ground, and a field test showed 21 p. p. m. chloride. On April 23 at 4.45 p. m. (near high tide) the water level was still 10.5 ft. and a test showed 25 p. p. m. chloride. A sample taken June 30, 1919, showed 26 p. p. m. chloride. The results indicate that the sea does not affect the salt content or water level.

There are two other wells very much like this a few hundred feet north, but they have been abandoned for some time. The bedrock exposed on the beach is much fractured in every direction. It appears, however, that the fresh water circulating downward from the slope to the east is sufficient to prevent access of sea water.

55. A. P. Ludington. Dug well; depth 10 ft.; diameter 1½ ft.; brick lining; hand pump; altitude 8 ft. above high tide; depth to water 7 ft.; beach sand to bedrock; domestic use. (See Pl. V, *A*.) This well is on a bar beach that has been built over a reef of bedrock since the survey upon which Plate I is based was made. The bedrock is exposed at the beach to the south. The distance to tidewater in this direction is 100 to 150 ft. A sample taken June 30, 1919, showed 94 p. p. m. chloride, which probably indicates a small amount of salt water. Residents on the narrow sandy beach to the southeast say that good water has been unobtainable there and they have no wells. Nos. 55 and 56 illustrate how very small an area may sometimes supply sufficient ground water for a domestic well.

56. A dug well 13 ft. deep on a bit of land only 10 ft. above sea level. (See Pl. V, *A*.) It is never affected by salt water.

57. Prentiss. An abandoned dug well in the rear of a bar beach. It is 150 ft. from tidewater and formerly supplied several houses with good domestic water.

58. Charles Bartley. Dug well; depth 9 ft.; diameter 3 ft.; stone lining; open; altitude 2½ ft. above high tide; depth to water 3 ft.; formerly domestic supply; abandoned. The well is on a little saddle of land connecting two opposing rocky points and is only 50 ft. from tidewater either east or west. It is said to have furnished satisfactory domestic water. No tests were made.

59. E. R. Kelsey. Dug well; depth 12 ft.; diameter 3 ft.; cement pipe lining; board cover; rope and bucket; altitude 4 ft. above high tide; depth to water 3 ft.; penetrates 9 ft. of drift (probably till) and 3 ft. of bedrock (gneiss). This well and Nos. 60 and 61 are on Darrow Island, which consists of a group of rocky hillocks, partly soil covered, that are tied together by long sand bars and extensive tidal flats. The body of land on which the well is situated is about 250 ft. in diameter and is for all practical purposes an individual island. It has large patches of bare rock exposed, but most of its area is soil covered. The well is nearly in the center. A field test April 29, 1919, showed 79 p. p. m. chloride, and a laboratory sample June 22, 1919, showed 86 p. p. m. The house on the island at this place had not been occupied nor the well used for nine months. It is said that the water generally is somewhat brackish in summer. The tests indicate slight contamination. The well is interesting because it shows how small a body of land, approximately an acre, can maintain an independent body of comparatively fresh ground water.

60. E. R. Kelsey. Dug well; depth 12 ft.; diameter 3 ft.; cement-pipe lining; board cover; hand pump; altitude 8 ft. above high tide; depth to water 3 ft.; penetrates till to bedrock; used for domestic water-supply and stock. This well is on the main body of Darrow Island, on a land mass between 500 and 600 ft. in diameter. The well is near the center and summit, on open, grassy land. A sample taken June 22, 1919, showed 21 p. p. m. chloride. This is a rather high normal chloride content.

61. E. R. Kelsey. Dug well; depth 12 ft.; diameter 3 ft.; cement-pipe lining; open; altitude 3 ft. above high tide; depth to water 6 ft.; abandoned. This well is very near the edge of a reentrant salt marsh, which isolates a rocky point on the eastern tip of Darrow Island. It penetrates swamp mud to rock. It has a drainage territory only about 75 ft. in diameter, most of which is bare rock. The water is said to have been always unfit for use. No tests were made.

62. George Reynolds. Dug well; depth about 6 ft.; diameter 3 ft.; altitude 4 ft. above high tide; depth to water about 1 ft.; penetrates soil and sand; formerly satisfactory domestic supply, but abandoned when the public supply became available. This well is only 6 ft. from reach of high tide, in a little reentrant on the beach where a trough about 50 ft. wide, filled with soil, extends back between ridges of gneiss. This indicates how fresh water permeates the soil to the very reach of tides. At one time when the well went nearly dry it is said to have been salty. No tests were made.

63. W. B. Talmadge. Dug well; depth 13 ft.; diameter 3 ft.; stone lining; wood curb; hand pump; altitude 7 ft. above high tide; depth to water 6 ft.; all in bedrock (granite gneiss); domestic and stock use. The well goes nearly dry in summer. It is fed from a fracture near the bottom. The well is only 25 ft. from the reach of tides, on a small rocky eminence about 150 by 200 ft. in dimensions, which is almost completely surrounded by tidal marshes or streams. A field test April 15, 1919, showed 31.5 p. p. m. chloride, and a sample taken June 30, 1919, showed only 9.4 p. p. m. Contamination is not indicated.

64. An open pit 3 or 4 ft. deep in the salt marsh west of No. 63; used for stock. The earth dug out of it was thrown up as a rim around the hole to prevent tidal overflow. A field test April 15, 1919, on water from this pit showed 209 p. p. m. chloride. This is proof of the presence of salt water but in surprisingly small amount considering the situation.

65. W. B. Talmadge. Drilled well; depth 65 ft.; diameter 6 in.; hand pump; altitude 10 ft.; domestic supply; abandoned. This well is 300 ft. from tidewater, in a narrow valley. It penetrates a few feet of till, then bedrock. A field test April 15, 1919, showed 5 p. p. m. chloride, and a sample collected June 30, 1919, showed 11 p. p. m. No contamination is indicated.

66. A. E. Hitchcock. Dug well; depth 6 ft.; diameter 2½ ft.; tile lining; pump in house; altitude 1 ft. above high tide; depth to water 1½ ft. The well is in sand on the edge of a tidal estuary and is sometimes completely flooded by storm tides. The water is said to rise and fall slightly with the tides but is not brackish. A field test April 15, 1919, showed 16 p. p. m. chloride, and a sample June 30, 1919, showed 37 p. p. m. This probably indicates a very slight trace of sea water. A short steep slope rises into a rocky bluff about 150 ft. behind the well.

67. H. S. Hitchcock. Dug well; depth 11 ft.; diameter 3 ft.; chain-bucket pump; altitude 5 ft. above high tide; depth to water 4 ft.; stratified drift (quicksand); domestic use. The well is 50 ft. from reach of high tide in the adjacent salt marsh. A field test April 15, 1919, showed 12 p. p. m. chloride, which indicates no contamination.

68. Connecticut Trap Rock Co. Dug well; depth 15 ft.; diameter 3 ft.; stone lining; board cover; hand pump; altitude 7 ft. above high tide; depth to water 8 ft. This well is probably in stratified drift, though part of its depth may be in rock. It supplied a quarry, now abandoned, with satisfactory drinking water. It is 100 ft. from the reach of high tide in the adjacent salt marshes. A sample June 30, 1919, showed 43 p. p. m. chloride, which indicates a slight trace of contamination.

69. Emil Bradley. Shallow dug well in till, not suspected of contamination. Several hundred feet from shore. A field test April 15, 1919, showed 10 p. p. m. chloride.

70. Lanphier Spring. This spring is locally celebrated because it issues from beach sand. It is at the foot of a low terrace bluff in stratified drift. A length of tile has been sunk in the sand and provided with an outlet pipe which discharges to the sea. The water bubbles up with a "boiling" motion through the sand at a rate roughly measured as 2 gallons a minute. Unusually high tides overflow the tile, and it is said that the water is then salty for an hour or two but freshens quickly. A sample taken June 28, 1919, showed 15 p. p. m. chloride, which indicates almost total absence of contamination. This is another excellent illustration of the fact that ground water moves seaward and in a fairly porous medium is fresh practically to tidewater.

71. Episcopal Church. Dug well; depth 18 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 15 ft., depth to water 14 ft.; stratified drift; domestic supply. This well is on a very narrow point of land between Branford River and an adjacent tidal marsh, from which it is only about 5 ft. distant. The water is said to be so brackish at times that it is unplatable. The tenants think it is worse at high tide, but this is doubtful in view of the general evidence from other wells. A sample taken June 28, 1919, showed 315 p. p. m. chloride, an amount which is apparent to the taste and indicates appreciable contamination.

72. A. G. Ely. Dug well; depth reported 21 ft.; diameter 3 ft.; cement-pipe lining; board cover; hand pump; altitude 10 ft.; stratified drift; domestic use. This well is 100 ft. from tidewater in Branford River. Mr. Ely states that it has always supplied excellent water. A well dug nearer the river at the edge of the tidal flat was so salty that it was filled up. No tests were made.

73. Jourdan. Dug well; depth 25 ft.; diameter 3 ft.; chain-bucket pump; altitude 20 ft.; depth to water 20 ft.; stratified drift; domestic use. A field test May 6, 1919, showed 23.5 p. p. m. chloride, and a sample taken June 28, 1919, showed 21 p. p. m. (Compare with well 74.)

74. Jourdan. Dug well; depth 9 ft.; diameter 2½ ft.; board cover; chain-bucket pump; altitude 4 ft. above high tide; depth to water 5 ft.; stratified drift; used for stock only. This well is on the edge of a tidal marsh which is flooded by exceptionally high tides. It is 250 ft. from Branford River, but half the intervening land is filled in. When tides approach very near the well it is said to become brackish. A field test May 6, 1919, showed 110 p. p. m. chloride, but a sample collected June 28, 1919, showed only 49 p. p. m. This well is on the barn lot and may be subject to drainage pollution. (Compare with well 73, which is only 125 ft. distant but at the top of a terrace bluff.)

75. Malleable Iron Fittings Co. Driven well; depth about 15 ft.; diameter 2 in.; hand pump; altitude 5 ft. above high tide; stratified drift; used for

drinking. This well is only about 50 ft. from the edge of a salt marsh. A sample taken June 28, 1919, showed 39 p. p. m. chloride. The slight amount of salt may be due to tidewater or to waste from houses near by and from the adjacent factory.

76. Malleable Iron Fittings Co. Mr. Hamer, one of the owners of this company, states that about 1910 the company drilled a deep well on its property just south of the Branford railway station. The well was about 150 ft. north of Branford River, which is tidal and saline, and was at the margin of the original salt marsh, which has since been filled in. The well reached bedrock (granite gneiss) at 40 ft., and drilling stopped at 503 ft. The water was salty all the way down, and the saltiness increased at the bottom. It was never used for any purpose.

77. Ely. Dug well; depth 20 ft.; diameter 2½ ft.; cement-pipe lining; board cover; pump in house; altitude 15 ft. above high tide; depth to water 16 ft.; domestic use. This well is on a little wooded promontory 100 ft. from Branford River. It penetrates till in a little till-filled trough between bedrock ridges. The water is said to be brackish occasionally in late summer. A sample taken June 28, 1919, showed 49 p. p. m. chloride, which may indicate slight contamination.

78. H. Stannard. Dug well; depth 13 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 10 ft.; depth to water 9 ft.; stratified drift; domestic use. The well is only about 50 ft. from a salt marsh, but the water is never brackish. A sample taken June 28, 1919, showed 46 p. p. m. chloride, which probably indicates a slight trace of sea water.

79. Dug well; depth 13 ft.; diameter 3 ft.; stone lining; wood curb; altitude 10 ft.; depth to water 9 ft.; stratified drift; domestic use, but abandoned for public water supply. The well is on a point surrounded on three sides by salt water at a distance of only 100 ft. A sample taken June 28, 1919, showed 15 p. p. m. chloride, which is normal.

80. Toole. Dug well; depth 7 ft.; diameter 3 ft.; cement-pipe lining; hand pump; altitude 4 ft. above high tide; depth to water 5 ft.; domestic use. This well is near the center of a strip of rocky land about 250 by 500 ft., which is completely surrounded by the sea and salt marshes. The well penetrates bedrock (gneiss) nearly all the way. It is 75 ft. from the beach, where gneiss, considerably jointed, is exposed. These joints trend N. 60° E., toward the well, and are nearly vertical. Reports state that the water is brackish, but it is nevertheless used for drinking. A field test made May 8, 1919, when the well had been unused for several months, showed 31 p. p. m. chloride, which is a nearly negligible quantity.

81, 82. W. A. Bryan. No. 81 is a dug well; depth 23 ft.; diameter 3 ft.; board cover; altitude 18 ft. above high tide; depth to water 18 ft.; stratified drift. No. 82 was not accessible but is said to be very nearly the same. These wells are on a small, flat remnant of a stratified-drift plain and are 250 ft. from tidewater on one side and 400 ft. from a salt marsh on the other. They formerly supplied a large summer hotel, and No. 82 was fitted with a steam pump, which often delivered 10,000 gallons a day. The water was never brackish. No tests were made. The wells indicate that a body of fresh ground water exists beneath the small peninsula of land.

83. C. J. Lounsbury. Reports state that a well driven at this point yielded water so salty that Mr. Lounsbury declared it was "easier to get salt water out of the ocean," and pulled it up. Other wells in the neighborhood are said to have been bad. The location is a narrow bar beach of loose sand between the sea on one side and a tidal marsh on the other. The beach is occasionally overtopped by storm tides at this point. There is a tradition that at times since the date of colonization salt water has occupied an open channel across the bar.

84, 85, 86. Shallow dug wells less than 100 ft. from salt water, which yield domestic supplies of satisfactory quality.

87. Henry Hull. Dug well; depth 15 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 7 ft. above high tide; depth to water 10 ft.; chiefly in bedrock (gneiss). The well is on a slope 50 ft. from the sea. Directly behind it rises a bluff of bare rock. The water is said to be bad in summer. No tests were made.

88. Dr. Fisher. Dug well; depth 13 ft.; diameter 3 ft.; cement-pipe lining; board cover; hand pump; altitude 5 ft. above high tide; depth to water 4 ft.; till and bedrock; domestic use. This well is in a little grassy park and is used as a public watering place. An old settler says it was originally a spring at the edge of a salt marsh, but the land has been filled in around it. It is now about 100 ft. from tidewater. A field test made May 14, 1919, showed 26 p. p. m. chloride, and a sample collected June 21, 1919, showed 25 p. p. m. This indicates little or no contamination.

89. Fairchild. Dug well; depth 5 ft.; diameter 3 ft.; cement-pipe lining; board cover; altitude 2 ft. above high tide; depth to water 1 ft.; unused. This well is in the edge of a salt marsh and penetrates marsh mud. The water is said to have been always very brackish. A sample taken June 21, 1919, showed 1,930 p. p. m. chloride, which is certainly very brackish, although it indicated only approximately 10 per cent of sea water.

90. Allan. A dug well in bedrock 100 ft. from shore; water never brackish.

91. Fitzsimmons. Drilled well; depth reported 60 ft.; diameter 6 in.; hand pump; altitude 7 ft. above high tide; bedrock (granite gneiss); domestic use; abandoned. The well is 50 ft. from tidewater on the northwest, where bare rock is exposed all along the shore. Fractures are present but are somewhat obscured by weathering. One set of joints strikes N. 70° W., and another N. 40° E., both nearly vertical. There is a suggestion of cleavage striking N. 70° E. and dipping about 20° NW.—that is, away from the well. It is said that this well once furnished good water most of the time for four families. Sometimes in dry weather the water was noticeably brackish but was used for lack of better. No sample was obtainable.

92. J. J. Phelps. Dug well; depth 14 ft.; diameter 3 ft.; stone lining; board cover; altitude 14 ft. above high tide; depth to water 7 ft.; abandoned, but yielded good drinking water. This well is near the center of Rogers Island, now better known as Phelps Island. It supplied a summer residence until the public water supply was piped across from the mainland. The well penetrates a little till and several feet of bedrock. A sample taken June 21, 1919, showed 31 p. p. m. chloride, which is probably normal, as there is no evident source of pollution near the well.

93. Community well, Governor Island. Dug well; depth 20 ft.; diameter 4 ft.; natural rock wall below one 3-ft. length of tile, the well being practically all in bedrock (granite gneiss); wood curb; rope and pulley; altitude 11 ft. above high tide; depth to water 7 ft.; domestic supply for summer cottages. This well and No. 94 supply the summer residents of Governor Island, probably 10 or 15 families, with water for domestic use. Governor Island is a narrow rocky ridge, at places thinly covered with till. The main body of the island is about 500 ft. long and 150 to 200 ft. wide. Well 93 is near the northeast end of the island and is 75 ft. from high tide. The well is said to fail in summer, when the drain upon it is very heavy, and the water is reported to be brackish at such times. This is sufficient evidence that the well is supplied solely by rainfall on the island, notwithstanding the popular theory that these small islands must derive their ground water by devious submarine channels from the shore. Bendiner & Schlesinger, of New York, made an analysis of water from this well

October 13, 1916, which showed a chloride content of 6 p. p. m. A field test May 14, 1919, when the well had been unused for several months, showed 15 p. p. m. chloride, and a sample taken June 21 showed 12 p. p. m. These tests indicate practical freedom from salt water.

94. Community well, Governor Island. Dug well; depth 14 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 8 ft. above high tide; depth to water 5 ft.; domestic use. The well is said to fail occasionally in dry summers when it is heavily used. At such times the water is brackish. A sample taken June 21, 1919, showed 11 p. p. m. chloride. The well had been unused all winter.

95. A. E. Verrill. Dug well; depth reported as 18 ft.; diameter 2½ ft.; tile lining; hand pump; altitude about 8 ft. above high tide; depth to water 8 or 10 ft.; domestic supply for one summer house. This well is on Two Tree Island, also called Outer Island. It is dug entirely in till near the crest of the island and is about 150 ft. from salt water on both sides. The area supplying water to the well is estimated at about 2 acres. Prof. Verrill states that during a violent storm in the autumn of 1918 much salt spray was dashed over the island and the water became slightly brackish as a result. A sample taken June 21, 1919, showed 156 p. p. m. chloride, which indicates slight contamination. There is no probability of pollution.

96. Mrs. Drew. Dug well; depth 11 ft.; diameter 3 ft.; board cover; chain-bucket pump; altitude 5 ft. above high tide; depth to water 7 ft.; domestic use. There are two wells 150 ft. from tidewater, side by side and practically alike, which furnish water to summer houses on Money Island. They penetrate soil probably to bedrock. The water is said not to be brackish. No samples were taken.

97. James Elton. Dug well; depth 34 ft.; diameter 3 ft.; board cover; hand pump; altitude 25 ft. above high tide; depth to water 12 or 15 ft.; blasted 30 ft. into rock (granite gneiss); domestic use. This well is on Davis Island, better known as Elton Island, and supplies a summer house. The island is a mass of bedrock with thin patches of till. It has unusually precipitous slopes. Its maximum altitude is about 50 ft. above sea level. The well described is about 150 ft. from tidewater and has always furnished good water. A sample taken June 21, 1919, showed 28 p. p. m. chloride, which is not abnormal. (For further description of this island see No. 98.)

98. James Elton. Drilled well; depth 150 ft.; diameter 6 in.; gasoline-engine pump; altitude 12 ft.; granite gneiss from surface; domestic use. This well is on Davis or Elton Island, and is 60 ft. from tidewater on north. It is the only example found of a drilled well on an island. The well has been abandoned in favor of a dug well (No. 97). The caretaker reports that the well furnished good water, but only a small supply. The suction was placed 140 ft. down in the well, which is said to have been pumped dry to that level without drawing salt water. Other reports state that the well was abandoned because the water was not very good. The bedrock is massive. There is a poorly developed joint system trending N. 45° W., and a suggestion of cleavage planes dipping northwest, away from the well. It seems likely that very few water-bearing fractures were encountered in drilling, and that fresh water was obtained in very small quantity, while salt water if present at all, was in still smaller quantity.

99. Dug well; depth 23 ft.; diameter 3 ft.; hand pump; altitude 14 ft. above high tide; depth to water 8 ft.; practically all in bedrock (gneiss); domestic use but abandoned for public water supply. Note how high above sea level the water level stands, although the well is only about 100 ft. from the beach. The water was never brackish and always satisfactory.

100. Peter Beattie. Dug well; depth 12 ft.; diameter 3 ft.; stone lining; stone curb; rope and pulley; altitude 4 ft. above high tide; depth to water 6 ft.; gravel and sand; domestic use. This well is on Narrows Island, which is connected to the mainland by a bridge across a narrow channel. At the northeastern tip of the island is a small flat about 200 ft. in diameter, on which Mr. Beattie's house is situated. The well is in front of the house near the center of the flat, which appears to be composed of sand and gravel, probably a remnant of stratified drift. The rest of the island is a rocky ridge partly covered by till. Originally this well is said to have furnished excellent drinking water. Later a domestic water system was installed and the amount of water used increased considerably. The quantity now used is estimated at 3,000 to 4,000 gallons a week. It is pumped to a storage tank by a hot-air engine, which is run once or twice a week as needed. Since this equipment was installed the water has become bad. It corroded the original plumbing so seriously that brass fixtures were installed. The water is said to be much worse in summer than in winter. In winter it is used for drinking, but in summer drinking water is carried from Mrs. Beattie's well (No. 101). The sewage on the island goes directly to the sea, so that this source of pollution is eliminated. An analysis of a sample of the water is given on page 57.

Inasmuch as the circumstances connected with this well are particularly instructive, it was made the subject of several special observations. The results of the investigation of its seasonal variations in salinity are discussed on pages 53–55. On June 21, 1919, observations were made to determine, if possible, any change in the quality of water during pumping, and its relation to the drawdown. The following table shows the results obtained:

Results of pumping test on well of Peter Beattie (No. 100), June 21, 1919

Time (p. m.)	Drawdown	Chloride radicle (Cl)
		Parts per million
4.07	Water level 9.28 feet below datum	461
4.30	No change	462
6.45	No change. Pumping began	458
7.00	0.65 feet	448
7.15	1.02 feet	459
7.30	1.46 feet	459
7.45	1.73 feet	460
8.00	1.98 feet. Pumping ceased	461
8.22	1.97 feet	----------
8.30	1.88 feet	463

The amount of water pumped could not be determined but was probably about 2,000 gallons. Neither is the rate of pumping known. Although there seems to have been at first a slight freshening of the water, then a gradual rise in the chloride, the difference seems insignificant. There is no definite, gradual increase in the salinity such as might have been expected, but such a change would doubtless occur if pumping were continued at a greater rate or for a longer period.

101. Mrs. Beattie. Dug well; depth 13 ft.; diameter 3 ft.; stone lining; chain-bucket pump; altitude 10 ft.; depth to water 5 ft.; domestic use. This well penetrates drift into bedrock (gneiss). It is about 250 ft. from tidewater at the head of a small bay and is never noticeably contaminated.

102. Mrs. Clarke. Dug well; depth 22 ft.; diameter 6½ ft.; stone lining; board cover; hand pump; altitude 14 ft. above high tide; depth to water 14 ft.; penetrates chiefly bedrock (gneiss); used lightly for domestic supply. This well was dug to supply a summer cottage but has been nearly abandoned for a supply drawn from No. 104 (see below), probably because the water was of poor quality. The well is at the crest of a steep, rocky slope on a small promontory and is only 25 ft. from the reach of high tides. The intervening rocks do not show much jointing or many open fractures through which salt water might readily enter, but the caretaker reports that the water has been brackish, especially at high tide. A sample collected August 4, 1919, showed 20 p. p. m. chloride, and another, November 28, 1919, showed 28 p. p. m. The samples indicate only slight contamination, but the well would doubtless be salty if much used, as its intake area is small and the rock exposures on it favor rapid run-off.

103. Mrs. Clarke. Dug well; depth 12 ft.; diameter 3 ft.; cement-pipe lining; board cover; chain-bucket pump; altitude 3 ft. above high tide; depth to water 5 ft.; sand; never used for any purpose. The well is on a low, narrow neck of land about 250 ft. long between two reentrant bays. The neck has evidently been built by the waves. The well is but 50 ft. from tidewater. The water is said to have been brackish from the beginning and was never used. A sample taken August 4, 1919, showed 22 p. p. m. chloride, and another taken November 28, 1919, showed 96 p. p. m. There was no apparent reason for the increase. The amount of contamination indicated is small but definite.

104. Mrs. Clarke. Dug well; depth 13 ft.; diameter 7 ft.; stone lining; board cover; altitude 5 ft. above high tide; depth to water 3 ft.; penetrates gravel; power pump supplies domestic water system. This well is in a small, deep cove at the head of a little V-shaped bay and is 200 ft. from tidewater. In summer it supplies 3,000 to 5,000 gallons a week. Samples taken August 4 and November 28, 1919, showed 13 and 11 p. p. m. chloride, respectively, which indicates no contamination.

105. John R. Walker. Dug well; depth 9 ft.; diameter 3 ft.; chain-bucket pump; altitude 8 ft.; depth to water 5 ft.; stratified drift; domestic use. This well is on the very edge of a salt marsh and is flooded occasionally by high storm tides. At such times the water is brackish until the well is cleaned out, but at other times it is satisfactory.

106. Richard Leete. Drilled well; depth reported to be 50 ft.; diameter 6 in.; hand pump; altitude 100 ft.; penetrates 10 ft. till and bedrock (gneiss) below. Drilled by C. L. Wright; domestic use. This well is on a clean grassy slope. The yield is very small, 1 gallon a minute or less. It was sampled for normal chloride May 23, 1919, and showed 8.6 p. p. m. No contamination was suspected or is indicated. The well is about a mile from the shore.

107. Mrs. Charles Mitchell. A dug well 18 ft. deep in the center of a rocky point of land about 300 ft. in diameter, which is surrounded by the sea and salt marsh. The water is reported to be good. No tests were made.

108. G. H. Mitchell. Drilled well; depth 90 ft.; diameter 6 ft.; altitude 5 ft. above high tide; not used, always bad. This well is on a small body of land which is completely surrounded by salt water and marshes. It is about 100 ft, from tidewater on the south and 200 ft. on the north. This well penetrates a ew feet of till, then bedrock (gneiss). At a depth of about 60 ft. it yielded a. small supply of good water, but on drilling deeper salt water was encountered, and the well was abandoned. Bedrock is most extensively exposed on the north shore, where it shows numerous parting planes that dip 20° S. 30° E. As the distance from the north shore to the well is 200 ft., it is evident that the dip of 20° would carry a fracture plane from sea level at the north shore to a depth of 68.4 ft. below sea level at the well site. Therefore, it may be possible that salt water passing down these fractures would not be encountered at 60 ft. but might be reached below. It appears to the writer, however, that the intercommunication of fractures is the important factor rather than their inclination or trend. The well is much nearer the south shore than the north shore, but the rock structure suggests greater facility of ground-water circulation from the north.

109. Mrs. G. H. Mitchell. Drilled well; depth reported 65 ft.; diameter 6 in.; hand pump; altitude 5 ft. above high tide; penetrates a few feet of till, then bedrock (gneiss); domestic use. The well is about 50 ft. from tidewater. It furnishes good domestic water. A field test June 16, 1919, showed 21 p. p. m. chloride, and a sample August 4, 1919, showed 23 p. p. m. (Compare this well with No. 108, which, although twice as far from the shore, has never yielded satisfactory water.)

110. Robert Mitchell. Drilled well; depth reported to be about 50 ft.; diameter 6 in.; hand pump; altitude 6 ft. above high tide; depth to water 9 ft.; bedrock (granite gneiss); used slightly for domestic purposes. (See Pl. VI, *B*.) The point on which this well is situated is very narrow and is practically all bare rock. Tides approach within 50 ft. of the well both northwest and southeast. The bedrock is massive and shows few fractures except at the shore south of the well where there is a zone of joints that dip steeply southwest and trend directly toward the well. The joints do not appear at the well nor on the opposite side of the point. This well has never yielded satisfactory water. It is said that whenever the well is used, which is only in summer, the water rapidly becomes so salty that its use has to be discontinued. Several samples collected at different times indicate a seasonal fluctuation in the salinity, similar to that in well 100. (See p. 55.) The well was used but little during 1919, and in November the pump had been removed, and it was totally abandoned.

111. F. S. Baker. Drilled well; depth reported 80 or 90 ft.; diameter 6 in.; windmill; altitude 7 ft. above high tide; penetrates a few feet of till, then bedrock (granite gneiss); domestic use. This well is about 100 ft. from tidewater and very near No. 110. It was reported to furnish excellent water, so that no particular attention was paid to it in the field. However, a sample collected June 16, 1919, showed 409 p. p. m. chloride, which is enough to make the water decidedly bad for domestic use. A sample taken November 28, 1919, showed 182 p. p. m. This suggests a variation in salinity such as has been pointed out in other wells. (See pp. 53–56.)

112. J. B. Miner. Drilled well; depth reported 38 ft.; diameter 6 in.; altitude 3 ft. above high tide; all in bedrock (gneiss); drilled by C. L. Wright; domestic use. This well is 75 ft. from the shore to the south, where bedrock with fairly well developed cleavage planes and joints is exposed. The well supplies a large summer residence, and the water is said never to be brackish. No samples were obtained.

113. H. C. Noble. Dug well; depth 12 ft.; diameter 3 ft.; cement-pipe lining; power pump. The well has two connected chambers of the same diameter and depth. It penetrates drift to bedrock and is 25 ft. from tidewater. Mr. Noble reports that when the well was cleaned out two streams of fresh water flowed in from the landward side and one of salt water from the sea. The water has never been salty, however. Bedrock is exposed between the well and the shore. On June 16, 1919, a sample was collected at 2.30 p. m., when the water level was 6.93 ft. below a datum near the surface. It showed 29 p. p. m. chloride. At 6.30 p. m., when the level had fallen to 10.64 ft. as a result of pumping to fill a 2,500-gallon tank, another sample was taken, which also tested 29 p. p. m. This indicates that there is probably a very slight contamination but that the pumping had no immediate effect upon the salinity.

114. H. C. Noble. Dug well; depth 15 ft.; altitude 5 ft. above high tide; penetrates drift and a few feet of rock. This well is slightly north of No. 113, about 250 ft. from the shore to the south and 150 ft. from a salt marsh to the north. It is sometimes pumped dry, but the water never becomes brackish. The well is said to supply 1,000 to 2,000 gallons a day in summer, but often fails to yield enough water in August.

115. Mrs. Clarence Barker. Dug well 10 ft. deep, very much like No. 114. The water is never brackish.

116. Barker. Dug well 9 ft. deep; water never brackish.

117. Dug well 9 ft. deep on edge of salt marsh. Water reported never brackish.

118, 119, 120, 121. Chamberlain. Drilled wells; diameter 6 in.; hand pump; altitude 15 ft.; penetrate chiefly bedrock (gneiss); domestic use. These wells are on a small headland about 500 ft. in diameter, which is surrounded by salt water and salt marsh. All the wells yield satisfactory domestic supplies. Only one house was occupied at the time of examination, and but little could be learned about the wells. The depth of No. 119 is reported to be about 100 ft. No. 120 is about 50 ft. deep and sometimes fails. No. 121 is drilled in the bottom of a dug well 12 ft. deep. Its depth is unknown. No samples were collected.

122. Dug well; depth 9 ft.; diameter 2 or 3 ft.; altitude 4 ft. above high tide; depth to water 5 ft.; sand; domestic use, but practically abandoned. This well is 25 ft. from a retaining wall which protects it from high tide. Reported to be brackish.

123. Dug well; depth 8 ft.; diameter 3 ft.; altitude 6 ft. above high tide; depth to water 7 ft.; sand; domestic use, but nearly abandoned. This well is about 50 ft. from shore and from a salt marsh in the rear. The water was reported to be brackish. No tests were made.

124. Stevens. Dug well; depth 11 ft.; diameter 3 ft.; stone lining; rope and pulley; altitude 5 ft. above high tide; depth to water 7 ft.; drift (probably sand) to rock bottom; domestic supply, but abandoned. The well is 75 ft. from shore. Rock outcrops intervene. Originally this was the only well on Mulberry Point, and it supplied good water to fishermen for many years. In the last few years six or eight summer houses have been built on the point. At first all the residents depended upon this well, but the water soon became brackish, and the well had to be abandoned. A sample taken June 16, 1919, showed 60 p. p. m. chloride, which probably indicates slight contamination. The well had not been used for a year. (Compare it with No. 125, a drilled well, which is about the same distance from the tide and yields notably brackish water in summer.)

125. Captain Anderson. Drilled well; depth 40 or 50 ft.; diameter 6 in.; hand pump; altitude 15 ft.; penetrates bedrock (gneiss or schist); domestic use. The well is 100 ft. from tidewater on the west and about 200 ft. on the east. Figure 6 (p. 32) shows the geography of the well and the related bedrock structure. The rock exposed along the west shore is a dark schist, highly cleavable, whose cleavage planes dip 22° N. 70° E.—that is, directly toward the well. Conspicuous joints also cut the rock mass in a direction N. 75° E. and dip nearly 90°. They also trend directly toward the well. It is stated by residents at the point that this well provides good water for the first few weeks of the summer, but that in July and August the water sometimes becomes so bad that it is not usable. It has been used more or less to supply four families, but the tenant usually stops supplying others when the water becomes bad. Samples were collected at different times from this well, and Mr. O'Meara, the tenant, kindly collected samples daily for several days. The results indicate a seasonal variation in quality similar to that in wells 100 and 110 and are discussed fully on pages 55–56. The extremely wide range of fluctuations in this well and its remarkable daily variations suggest that the bedrock fractures from which it is supplied probably connect directly with tidewater on the west. The much fractured condition of the bedrock also supports this conclusion. Salt water passing down cleavage planes with a dip of 22° would, in a distance of 100 ft., reach the bottom of a well 50 ft. deep. Moreover, the joint planes afford channels of communication. The crevices from which the well is fed are probably of small capacity, and the drawing off of a little water invites the entrance of sea water. The structural conditions, so far as observed, are practically identical here and at the Gerrish well (No. 128), yet the latter is not affected by sea water.

126. Used by summer residents of Mulberry Point. Dug well; depth 20 ft.; diameter 3 ft.; hand pump; altitude 20 ft.; depth to water 8 ft.; till and probably some bedrock. This well is on a little flat at the top of the small peninsula known as Mulberry Point, which is nearly surrounded by the sea and an adjacent salt marsh. The well is about 250 ft. from salt water and salt marshes. A sample taken June 16, 1919, showed 25 p. p. m. chloride. It is interesting to note that a sample taken on the same date from a drilled well (No. 127) about 6 ft. away, which is 63 ft. deep, showed 24 p. p. m. chloride. A second sample collected from well 126 on August 4, 1919, showed 26 p. p. m. chloride. Some local residents claim that the water from the dug well is brackish, but it is evident that there is no appreciable contamination.

127. Stevens. Drilled well; depth 63 ft.; diameter 6 in.; hand pump; altitude 20 ft.; depth to water 14 ft.; penetrates 10 or 15 ft. of till, then bedrock; domestic use. The well furnishes a community water supply for Mulberry Point and is very satisfactory. It is on the center of the point, about 250 ft. from the nearest salt water, and the flat, till-covered land near it affords a good reservoir for ground water. A sample taken June 16, 1919, showed 24 p. p. m. chloride. (Compare dug well No. 126, which on the same date showed 25 p. p. m.) A sample taken August 4, 1919, showed 26 p. p. m. No contamination is indicated.

128. Gerrish. Drilled well; depth about 40 ft.; diameter 6 in.; hand pump; altitude 15 ft. above high tide; practically all in rock; domestic use. This well is on Mulberry Point and is 100 ft. from tidewater. There has been some complaint about its water, but the unsatisfactory quality appears to be due to rusty casing rather than salinity. A sample taken June 16, 1919, showed 18 p. p. m. chloride. Another sample on August 4, 1919, showed 19 p. p. m. This amount of chloride appears to be normal for this locality. (Compare Nos. 127, 129.) The bedrock of this point is granite gneiss with large inclusions of dark, highly cleavable schist. On the shore 100 ft. west of the well the schist is exposed, standing up in a cliff 10 or 15 ft. high. Its cleavage planes dip 20°–30° E. and thus suggest ready access of sea water to the well, but such circulation does not appear to occur. (Compare with No. 125.)

129. Mrs. Carlin. Drilled well; depth about 50 ft.; diameter 6 in.; hand pump; altitude 20 ft.; practically all in bedrock; domestic use. The well is about 200 ft. from tidewater. It supplies satisfactory water to several summer houses. A sample taken June 16, 1919, showed 17 p. p. m. chloride, which indicates no contamination.

130. George Brown. Dug well; depth 14 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 20 ft.; depth to water 9 ft.; penetrates 10 ft. of stratified drift (gravel) and 4 ft. of bedrock; domestic supply. This well is on a narrow ridge 200 or 300 ft. from salt marshes. A sample taken May 28, 1919, showed 25 p. p. m. chloride. Considered in connection with No. 131, which is much nearer a salt meadow and shows 40 p. p. m., this indicates a slight degree of contamination which may or may not be attributable to sea water.

131. Louise Ross. Dug well; depth 16 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 10 ft.; depth to water 9 ft.; stratified drift; domestic supply. This well is on a slope about 75 ft. from a salt marsh. A sample taken May 28, 1919, showed 40 p. p. m. chloride, which may indicate a trace of sea water.

132. Guilford Poorhouse. Dug well; depth 6 ft.; diameter 3 ft.; altitude 4 ft. above high tide; depth to water 2 ft.; stratified drift; domestic use. This well is about 200 ft. from the tidal estuary of West River and 100 ft. from the bordering salt marsh. The water is considered brackish. An abandoned well west of it, nearer the salt marsh, gave water too bad to use. A sample taken May 28, 1919, showed 77 p. p. m. chloride, which indicates a trace of salt water from the marsh. This well is about twice as far from the marsh as No. 133 and has about half the amount of chloride.

133. Sullivan. Dug well; depth 6 ft.; diameter 3 ft.; stone wall; wood curb; rope and pulley; altitude 2 ft. above high tide; depth to water 2 ft.; stratified drift. The well is on very low ground, practically on the edge of a salt meadow and only 100 ft. from the tidal stream. The water is reported to be brackish at times, especially in very dry weather. A sample taken May 28, 1919, showed 157 p. p. m. chloride, which apparently indicates contamination.

134. A. M. White. Spring. This spring is at the head of a small ravine in grassy meadow land, about 2½ miles from the shore. It was sampled May 28, 1919, to determine the normal chloride. The sample showed 9.9 p. p. m.

135. Woodruff. Dug well; depth 15 ft.; diameter 3 ft.; cement-pipe lining; electric pump; altitude 10 ft.; depth to water about 6 ft.; domestic and stock supply. The well is on a low stratified-drift plain and penetrates sand. It is not near salt water and is not suspected of being contaminated but is of interest because inside the dug well is a drilled well said to be 300 ft. deep. The drilled well yields only a very small supply, and the 3-ft. well was dug around it in the stratified drift. About 2,000 gallons of water is now used daily. Samples to determine the comparative chloride content were taken June 16, 1919. The dug well showed 13 p. p. m., the drilled well 35 p. p. m. The higher chloride in the deep well is surprising unless it possibly indicates an increase of salinity with depth near the shore. The analyses indicate little if any contamination.

136. F. L. Perry. Dug well; depth 15 or 16 ft.; diameter 3 ft.; stone lining; board cover; hand pump; altitude 10 ft.; depth to water about 10 ft.; stratified drift; occasionally used to water stock, formerly domestic supply. The well is on a gentle slope leading down to the beach 125 ft. away. It is on grassy land that should be free from pollution. A sample May 27, 1919, showed 48 p. p. m. chloride, which probably indicates a slight trace of sea water.

137. Eugene Hall. Dug well; depth 18 ft.; diameter 2½ ft.; cement-pipe lining; stone cover; altitude 14 ft. above high tide; depth to water 16 ft.; stratified drift; recently abandoned for public water supply but previously used as domestic supply. The well is on a narrow ridge, which is a remnant of a stratified drift plain nearly cut away by waves on one side and streams on the other. The water table is approximately at mean sea level. The well is about 100 ft. from high tide on the south and the same distance from a salt marsh on the north, which is regularly flooded. A field test May 30, 1919, showed 136 p. p. m. chloride, and a laboratory sample showed 158 p. p. m. The results indicate the presence of sea water in small proportion, as the houses in the vicinity had not been occupied all winter and there were no cesspools near. The water, however, was considered satisfactory for domestic use.

138, 139, 140, 141, 142, 144, 145, 146. These are all shallow dug wells in stratified drift, 150 to 500 ft. from shore. They furnish satisfactory domestic supplies, apparently free from contamination.

143. G. U. Root. Drilled well; depth 150 ft.; diameter 6 in.; windmill and gasoline engine; altitude 5 ft. above high tide; penetrates 32 ft. of stratified drift, then bedrock (gneiss); drilled by Louis Basset in 1907; domestic use. A fresh-water lagoon intervenes between the well and the beach, which is 300 ft. to the south. No bedrock crops out near by. Pumping at the rate of 25 gallons a minute is said not to affect the supply. About 1,000 gallons a day is used in summer. A sample taken May 30, 1919, showed 11 p. p. m. chloride, which indicates no contamination.

147. Dr. Parker. Dug well; depth 9 ft.; diameter 2½ ft.; cement-pipe lining; screen cover; pump in house; altitude 3 ft. above high tide; depth to water 5 ft.; sand; domestic supply for summer cottage. This well is on a bar beach 90 ft. from reach of high tide. An abandoned bar lagoon is in the rear. No samples were taken, but the water is said to be preferred to the city water for drinking. Two measurements were made on May 29, 1919, to see if the water level was affected by tides. The predicted time of high tide at New Haven was 10.21 a. m., low tide 4.40 p. m. The water level below a datum taken at the top of the tile curbing was 7.39 ft. at 10.40 a. m. and 7.40 ft. at 5.00 p. m. If there is any tidal fluctuation it apparently lags behind the tide in Long Island Sound.

148. A. S. Clark. Dug well; depth 9 ft.; diameter 1½ ft.; tile lining; open; altitude 3 ft. above high tide; depth to water 4 ft.; sand to bedrock; abandoned, but once afforded domestic supply. This well is on a low bar beach 100 ft. from high tide. The owner says that water entered on top of bedrock from the landward side when well was dug. Reports on the quality of water are conflicting, some persons saying it was good, others that it was brackish. A field test May 29, 1919, showed 58 p. p. m. chloride. A laboratory test on a sample collected June 13, 1919, showed 75 p. p. m. The salinity might be due to cesspools 50 to 100 ft. away but is probably at least partly due to sea water. Careful measurements were made May 29, 1919, to detect a possible change in level due to tides. At 11 a. m., near high tide, the level below the top of the tiling was 2.91 ft., and at 4.50 p. m., near low tide, it was 2.935 feet. This indicates that tidal fluctuations, if any, are very small or else lag very much behind the tides in Long Island Sound.

149. Robert S. May. Dug well; depth 12 ft.; diameter 2½ ft.; cement-pipe lining; stone curb; altitude 7 ft. above high tide; depth to water 9 ft.; sand; formerly domestic use, now abandoned for public water supply. The well is on a low beach 100 ft. from high tide. The water was used for years but is thought to have been a little brackish at times. No tests were made.

150. Mrs. Willard. Dug well; depth 12 ft.; diameter 3 ft.; cement-pipe lining; wood curb; rope and pully; altitude 20 ft.; depth to water 9 ft.; stratified drift; domestic use. This well is about a mile inland on a clean grassy meadow. A sample collected June 13, 1919, merely to determine the normal chloride, showed 7.2 p. p. m.

151. Clarkson Meigs. Dug well; depth 8 ft.; diameter 3 ft.; cement-pipe lining; board cover; hand pump; altitude 10 ft.; depth to water 4 ft.; stratified drift; domestic and stock use. This well is on a terrace remnant of stratified drift near a small salt marsh but several hundred feet from shore. It is in a clean meadow which should be very free from pollution. It supplies tenants in the house near well 152 with water for domestic use. A sample June 13, 1919, showed 13 p. p. m. chloride, which indicates practically no contamination.

152. Clarkson Meigs. Driven well; depth probably 10 or 12 ft.; diameter between 1 and 2 in.; hand pump; altitude 2 ft. above high tide; depth to water 2 or 3 ft.; stratified drift and marsh mud; used for washing dishes and rough domestic uses. The well is under a house at the edge of a salt marsh, which overflows daily. The tide approaches within 25 ft. of the well, although the distance from open salt water is about 300 ft. Figure 5 (p. 29) shows the general relation of wells 151 and 152 to salt marshes and beaches. A sample collected June 13, 1919, showed 1,230 p. p. m. chloride, which indicates high contamination. The water was briny to the taste. It is said always to have been poor. Well 151 was dug in order to get satisfactory drinking water.

153. Winchester Repeating Arms Co. Dug well; depth 16 ft.; diameter 2½ ft.; stone lining; wood curb; rope and bucket; also equipped with pump driven by gasoline engine; altitude 15 ft.; depth to water 14 ft.; probably stratified drift; domestic and stock use. This well is on a small body of land about 500 ft. in diameter, completely surrounded by salt marshes. The beach is about 400 ft. southwest. The land is part of the Winchester Co.'s rifle range, and the place is occupied by a tenant who uses the water for domestic purposes and for stock. The water is considered satisfactory. A field test June 4, 1919, showed 94 p. p. m. chloride, and a laboratory sample showed 90 p. p. m. This probably indicates an appreciable amount of contamination from the sea, although barn-lot drainage may cause some of it.

154. Russell Dowd. Drilled well; depth 56 ft.; diameter 6 in.; hand pump; altitude 15 ft.; domestic use. The well is on a little knoll 200 ft. east of Indian River (tidal) and penetrates 3 ft. of soil and 53 ft. of bedrock (gneiss). It is said to yield good water. A sample taken June 10, 1919, showed 4.7 p. p. m. chloride, which is a low normal and indicates total absence of contamination by salt water.

155. G. A. Stevens. Dug well; depth 14 ft.; diameter 2½ ft.; cement pipe lining; wood curb; windmill; altitude 15 ft.; depth to water 9 ft. This well is on a low ridge of land between two salt marshes. A laboratory test of a sample collected June 10, 1919, showed 12 p. p. m. chloride, which is not abnormal.

156. E. A. Elliot. Dug well; depth 8 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 4 ft. above high tide; depth to water 5 ft.; stratified drift; formerly used for domestic supply, now abandoned. The well is on the edge of a low terrace bluff beside a tidal marsh and 100 ft. from Indian River (tidal). Although it is only about 10 ft. from reach of the tide its water has never been known to be brackish. A field test June 5, 1919, showed 13 p. p. m. chloride, and a laboratory test showed 12 p. p. m. This indicates absence of contamination.

157. Buell. Dug well; depth 9 ft.; diameter 2½ ft.; tile lining; wood curb; rope and pulley; altitude 10 ft.; depth to water 5 ft.; stratified drift; domestic use. The well is on the slope of a low terrace bluff 100 ft. from a salt marsh and 200 ft. from the tidal estuary of Indian River. Water never known to be brackish.

158. Christine Buell. Practically the same conditions as No. 157.

159. M. L. Blaisdell. Dug well; depth 15 ft.; diameter 2½ ft.; tile lining; wood curb; rope and pulley; altitude 10 ft.; depth to water 12 ft.; stratified drift; domestic use. The well is on a narrow peninsula 100 ft. from the edge of a salt marsh on the south and 250 ft. from tidewater. A laboratory sample collected June 10, 1919, showed 17 p. p. m. chloride, which indicates no contamination.

160. John F. Parker. Dug well; depth 6 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 2 ft. above high tide; depth to water 2 ft.; stratified drift. The well is at the foot of a low terrace bluff. To the south is a tidal marsh 350 ft. wide, which is covered only by exceptionally high storm tides, but the tide has been known to rise completely over the well. A field test June 10, 1919, showed 10 p. p. m. chloride, and a laboratory sample showed 9.7 p. p. m. This indicates freedom from contamination.

161. Christine Buell. Dug well; depth 7 ft.; diameter 3 ft.; stone lining; wood curb; rope and pulley; altitude 4 ft. above high tide; depth to water 5 ft.; all in sand; domestic use, but seldom used for drinking or cooking. The well is on an island in Clinton Harbor, known locally as Cedar Island but shown on coast charts as Sandy Point Island. The island is a low sand bar, nowhere more than about 5 ft. above high tide. It supports a scattered growth of coarse beach grass and a stand of cedar trees, which has been cut over and nearly destroyed. The well is on the eastern part of the island, 135 ft. from the south shore and about 250 ft. from the north shore. The water is not much used, as it is generally condidered brackish and has a distinct reddish color due possibly to the numerous cedar roots which have formed a mat in the surrounding soil and extend into the well. Attempts to get good water on the island by driven wells were unsuccessful. A field test June 10, 1919, showed 125 p. p. m. chloride and the laboratory sample collected on the same date showed 122 p. p. m. There are cesspools about 100 ft. away, but as they had not been used for nine months the high salt content appears to be due to sea water. All the ground water of the island seems to be considerably affected by the sea, and the chance of getting water is poor.

162. Practically the same conditions as No. 163.

163. Charles Hurd. Dug well; depth 13 ft.; altitude 10 ft. above high tide; stratified drift. This well is 150 ft. from reach of the tide. It has always been satisfactory for domestic use and is never affected by the sea.

164. Mrs. E. Matheson. Dug well; depth 12 ft.; diameter 3 ft.; stone lining; wood curb; altitude 8 ft. above high tide; depth to water 10 ft.; probably in till. Domestic supply for two summer cottages. The well is on the crest of a narrow peninsula, known as Hammock Point. It is 50 ft. from the shore to the south, which is an abrupt sea cliff about 10 ft. high, and 100 ft. from a salt marsh to the north. A field test June 11, 1919, showed 42 p. p. m. chloride, and a laboratory sample collected on the same date showed 39 p. p. m., which indicates a trace of contamination.

165. Dug well; depth 22 ft.; diameter 3 ft.; stone lining; stone flag cover; altitude 18 ft. above high tide; depth to water 19 ft.; stratified drift; abandoned. This well is 100 ft. from the shore. It is representative of three wells, all now abandoned, which formerly furnished satisfactory domestic supplies.

166. Redfield. Driven well; depth probably not over 15 ft.; diameter between 1 in. and 2 in.; pump in house; altitude 2 ft. above high tide; beach sand; domestic use. This well is 50 ft. from the shore on a wave-cut terrace at the foot of a terrace bluff in stratified drift. The neighbors all carry drinking water from the well in summer and praise it highly. The house was closed, so no sample could be collected.

167. Clarence Buell. Conditions almost identical with those at No. 168. The well is 125 ft. from high tide. It was used for years for domestic water supply but is now abandoned.

168. Frank Buell. Dug well; depth 8 ft.; diameter 1½ ft.; tile lining; board cover; hand pump; altitude 5 ft. above high tide; depth to water 6 ft.; all in sand; domestic use, but now abandoned for city water. The well is on the beach 115 ft. from high tide. It was for years a satisfactory source of domestic water supply.

169. Weise. Driven well; altitude 10 ft. The well is about 300 ft. from shore. Details are not known, but the water is never brackish.

170. Howland. Dug well; depth 9 ft.; altitude 10 ft. The well is about 250 ft. from shore. It is said to have been used for 200 years without ever being brackish.

171. Mrs. Hilliard. Driven well; depth probably 10 or 12 ft.; diameter 1½ in.; hand pump; altitude 4 ft. above high tide; water level about tide level; loose sand; domestic use. The well is on a low bar beach, 95 ft. from high tide. A laboratory test showed 18 p. p. m. chloride. This indicates no contamination.

172. Post. Driven well; depth probably 10 or 12 ft.; diameter 1 in.; hand pump; altitude 4 ft. above high tide; water level about tide level; penetrates loose sand; used for domestic supply at summer cottage. The well is on a low bar beach 80 ft. from high tide. In the rear is a salt marsh which, however, is rarely flooded. Residents declare that the water is excellent. A field test June 13, 1919, showed 21 p. p. m. chloride, and a laboratory sample of the same date showed 16 p. p. m. This indicates practically no contamination.

173. Watrous. Dug well; depth 9 ft.; diameter 1½ ft.; tile lining; board cover; pump in house; altitude 5 ft.; depth to water 2 ft.; sand and marsh mud; domestic supply. The well is on the edge of a salt marsh at the rear of a bar beach and about 400 ft. from the shore. The salt marsh is rarely flooded. The well is used with satisfaction by the tenant.

174. Mrs. Atwater. Dug well; depth 16 ft.; diameter 2½ ft.; tile lining; wood curb; pump in house; altitude 15 ft.; depth to water 13 ft.; stratified drift; used for domestic supply during the summer. It is on a narrow terraced beach about 150 ft. from shore, with a salt marsh in the rear. The water is said to be unaffected and satisfactory for domestic use.

175. Connecticut Breweries Co. Pumping plant. This company uses two deep drilled wells, one of which is 404 ft. deep and the other somewhat less. Both are 6 in. in diameter and penetrate bedrock nearly all the way. Their combined yield is said to be 100 gallons a minute, of which the deeper well is credited with 70 gallons. The wells are pumped 24 hours a day, and the water is used for brewing and all factory supply. A complete analysis of a sample taken from the shallower well October 4, 1919, is given on page 57. The chloride content, 169 p. p. m., is surprisingly high, as the well is at least 500 ft. from tidewater in Poquonock River.

176. The Armstrong Manufacturing Co. once had a 4-in. drilled well 70 ft. deep which penetrated 20 ft. of artificial fill and stratified drift and 50 ft. of bedrock. It was about 100 ft. from tidewater of Poquonock River. It furnished good water for drinking and other uses until about 1917, when it was abandoned for city water. A hole which yielded no water was drilled at one time very near the site of the abandoned well.

177. Naugatuck Valley Ice Co. Pumping plant. The Naugatuck Valley Ice Co. has a dug well 40 ft. deep and 30 ft. square. The well is at an altitude of about 30 ft. above sea level and is about 500 ft. from tidewater. It penetrates till and yields 60 gallons a minute. The water is used for cooling. No samples were collected, but contamination is not suspected.

178. Connecticut Web & Buckle Co. Pumping plant. This company has one driven well 2 in. in diameter and 20 ft. deep, which penetrates artificial fill to the underlying sand (stratified drift). The well is not more than 100 ft. from tidewater of Poquonock River. The water is used for electroplating and other purposes, but not for drinking. A sample taken October 4, 1919, showed 7.0 p. p. m. chloride. An analysis is given on page 57. The water is not contaminated.

179. Morris & Co. Pumping plant. Three driven wells 2 in. in diameter and 30 ft. or less in depth. The water supplies a refrigerating plant, and the wells are pumped intermittently by an automatic electric pump at a rate of about 20 gallons a minute. The wells penetrate artificial fill to stratified drift, and according to Mr. Curtiss, the engineer, are on the channel of an old fresh-water drainage course. They are not more than 125 ft. from tidewater. A sample taken October 4, 1919, showed 8.0 p. p. m. chloride. An analysis is given on page 57. The water is uncontamined.

180. John R. Woodhull. Pumping plant. This establishment uses three groups of three wells each, all 2-in. driven wells about 30 ft. deep. The wells penetrate 15 or 20 ft. of artificial fill, then a few feet of sand, and end in bedrock. They are about 100 ft. from tidewater and only about 150 ft. south of the wells of Morris & Co. (No. 179). The water is used for refrigerating. A sample taken October 4, 1919, showed 356 p. p. m. chloride, which indicates considerable contamination.

181. Cudahy Packing Co. Pumping plant. Two driven wells, one 25 ft. deep and the other 30 ft. deep, about 100 ft. south of those of John R. Woodhull (No. 180). The wells penetrate artificial fill and sand and are about 100 ft. from tidewater. The water is used for refrigerating. A sample taken October 4, 1919, showed 1,430 p. p. m. chloride, a high degree of contamination. (Compare with Nos. 179 and 180.)

182. William Rappoport. Pumping plant. Two driven wells, installed in 1919, which penetrated filled land to sand and reached water at 20 ft. The water was bad even at first and after three or four days of use became "inky black" and was abandoned.

In these four plants, Nos. 179, 180, 181, 182, there is a remarkable gradation from very pure to very bad water within a few hundred feet, in circumstances that superficially appear to be much the same. The wells farther south, however, seem to penetrate but little sand and probably draw in salt water through the coarse artificial fill, which is composed of junk, rubble, cinders, etc.

183. The Locomobile Co. of America at its Bridgeport plant had a well drilled about the year 1900. Mr. Grace, the master mechanic of the plant, and Mr. Gardner, of the Stratford Artesian Well Co., who helped drill the well, furnished information about it, which agreed substantially as to the facts. The first 90 ft., according to Mr. Gardner, was sand (stratified drift). The well yielded 30 gallons a minute or less of salt water. It was easily pumped dry with an air lift. Beginning at the depth of 500 ft. this well was tightly cased to the bottom in the hope of excluding the salt water, but only salt water was obtained below. The driller describes the water as "saltier than the ocean." The plant is on a narrow projection of land, most of which has been built up to prevent tidal overflow. The results indicate that the ground water beneath the harbor is salt.

184. The exact location of this well is uncertain, but it was somewhere on Pleasure Beach, a narrow island tied to the mainland by a long sandbar. The body of land is several hundred feet wide but is very low. Mr. Gardner, of the Stratford Artesian Well Co., reports that a well drilled here penetrated 50 ft. of sand and thereafter bedrock to a total depth of 212 ft. There was very little water in the sand and only salt water in the bedrock.

185. There are two shallow dug wells in stratified drift in Seaside Park, Bridgeport, which yield good drinking water for park visitors and employees. No details were available and no samples were obtained.

186. The Crane Co. drilled a well several years ago at the location shown. Most of the company's land was originally salt marsh and has been filled in. The well went through fill and stratified drift to a depth of 196 ft. and then penetrated bedrock to 257 ft. Salt water was present practically all the way. However, certain shallow domestic wells that formerly existed on land near by yielded fresh water. The body of land on which this well was drilled is extensive enough to support a large body of fresh ground water, but most of it has been converted from salt marsh only in the last few years, by means of dikes and filling. Moreover, salt water surrounds it on three sides. This appears to indicate that the body of ground water beneath salt marshes, at least where not supplied with a considerable inflow of fresh water, is salt.

BIBLIOGRAPHY OF COASTAL GROUND WATER

The subjoined bibliography is not complete, but it is believed to cover the most important publications of the last half century. As many of the papers cited are not available to most readers, some material that seems valuable enough to justify republication is quoted. The arrangement for the United States is geographic and proceeds from the Maine coast southward and westward to the Gulf and thence to the Pacific coast. For other places the arrangement is chronologic.

UNITED STATES

MAINE

1909. CLAPP, F. G., Underground waters of southern Maine: U. S. Geol. Survey Water-Supply Paper 223.

The following description (p. 67) under the heading "Injury to wells by sea water" applies to drilled wells on the Maine coast:

"At a number of places along the Maine coast, especially on the islands, ocean water has entered through crevices in the rock and mingles with the well water to such an extent that the well has had to be abandoned. As a rule trouble with salt water occurs where the rock is slate. In a few places, however, salt-water wells have been obtained in granite. A well owned by Mrs. Kieselo, in the town of Islesboro, obtained good water at 181 feet from the surface, but drilling was continued, and at 220 feet salt water was encountered. The well was filled with Portland cement to a depth of about 200 feet from the top, the sea water being thus shut out, and the water was reported of good quality in 1906.

"In other wells fresh water is first obtained, but after continued pumping the water becomes salt. Such was the case in the Thorp well on Greenings Island, off Mount Desert, which rises and falls with the tide. The water in the R. A. Foss well in Scarboro, 200 feet deep and situated 200 or 300 feet from salt water, was good for a month, but then became salty.

"An interesting well is that of the Consolidated Electric Light Co. of Maine, at Portland. In 1887 this well was drilled 136 feet and obtained good water. Like the Kiesel well, it was deepened in the hope of getting a larger supply, and salt water was encountered. The total depth of the well was 204 feet. In 1890 it was plugged. The plugging shut off much of the magnesium carbonate and calcium carbonate content of the water and increased the sodium chloride considerably.

"An example of the entrance of sea water occurs in the town of Sorrento, which lies on a small neck jutting out from the mainland opposite Sullivan. The slate on this neck is very hard, dense, and fine grained and breaks up on the weathered outcrop into small angular blocks a few inches square. The strike and dip of the strata are variable. In some places the cleavage agrees with the stratification, but in others it does not. Clay 5 to 10 feet thick overlies the slate along the shore, and it is probable that this would prevent the accumulation of much water on the surface of the peninsula. The outcrops along the coast show that the rock is deeply fissured by wave action, some vertical cracks a foot or more across running in for a distance of several feet.

As some of the fissures are inclined toward the south, it is probable that the sea water enters the rock on the north side of the peninsula and makes its way far below the surface into wells. This will explain why the only two wells drilled on the peninsula were failures, so far as finding fresh water was concerned."

The wells on which the above statements are based are described under county headings. (See pp. 141, 145, 170, 199, and 232.) It appears from the data given that conditions in Maine are much like those in Connecticut.

CONNECTICUT

1909. Gregory, H. E., Underground water resources of Connecticut, with a study of the occurrence of water in crystalline rocks, by E. E. Ellis: U. S. Geol. Survey Water-Supply Paper 232.

Contains references to tidal fluctuations on page 52 and to contamination in drilled wells on pages 92 and 174.

1922. Brown, J. S., Relation of sea water to ground water along coasts: Am. Jour. Sci., 5th ser., vol. 4, pp. 274–294.

A summary of the main points in the present paper.

LONG ISLAND

1854. Stoddard, J. S., Report on the subject of supplying Brooklyn with water by the well system, in Documents and plans submitted by the Water Committee to the Common Council of the City of Brooklyn, No. 9, John Hemingway & Co., printers.

Contains a theoretical discussion of salt water infiltration on pages 94–95. See citation in the present paper, p. 37.

1904. Burr, W. H., Hering, Rudolph, and Freeman, J. R., Report of the Commission on Additional Water Supply for the City of New York: Martin B. Brown Co., New York.

Pages 406–423 contain valuable data on contamination of Long Island pumping plants by sea water. The most significant of these data are given in the body of the present report. (See pp. 51–53.) See also the report by Spear (1912).

1906. Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, N. Y.: U. S. Geol. Survey Water-Supply Paper 155.

This report contains very valuable data on tidal fluctuations in the water level of wells, particularly of flowing wells near the shore, also a bibliography, which includes references dating back to Pliny the Elder.

1906. Veatch, A. C., Slichter, C. S., Bowman, Isaiah, Crosby, W. O., and Horton, R. E., Underground water resources of Long Island, N. Y.: U. S. Geol. Survey Prof. Paper 44.

This report contains in briefer form the same data given in Water-Supply Paper 155, cited above.

1912. Spear, W. E., Long Island sources of an additional supply of water for the city of New York, vol. 1, New York Board of Water Supply, New York.

Contains much valuable information on Long Island pumping plants and a digest of the investigations of the Amsterdam water supply. Contamination is discussed under the heading "Inflow of sea water," on pages 144–149. The most valuable portions are quoted on pages 45–40 of the present report.

ATLANTIC COASTAL PLAIN

1911. Sanford, Samuel. Saline waters of the Atlantic Coastal Plain: U. S. Geol. Survey Water-Supply Paper 258, pp. 75–86.

This paper deals briefly with the near-shore artesian wells of the Coastal Plain, many of which are saline in varying degrees. The salinity is attributed to connate water, either inherent or superimposed. Contamination of wells less than 200 feet deep by seepage, especially when heavily pumped, is suggested (p. 83).

MARYLAND

1918. Clark, W. B., Matthews, E. B., and Berry, E. W., The surface and underground water resources of Maryland, including Delaware and the District of Columbia, Johns Hopkins Press, Baltimore.

Contamination and fluctuations of level in shallow wells are referred to on pages 251, 299, 345, and 401.

VIRGINIA

1912. Sanford, Samuel. The underground water resources of the Coastal Plain of Virginia: Virginia Geol. Survey Bull. 5, Charlottesville.

Contamination and tidal fluctuations are referred to on pages 42, 118, 167, 215, 222, and 245.

NORTH CAROLINA

1912. Clark, W. B., Miller, B. S., Stephenson, L. W., Johnson, B. L., and Parker, H. N., The Coastal Plain of North Carolina: North Carolina Geol. Survey, vol. 3, Raleigh.

Tidal fluctuations and contamination are referred to on pages 374, 397–399, and 417.

SOUTH CAROLINA

1881. Artesian wells (municipal report of the city of Charleston, S. C.).

Tidal fluctuations in flowing artesian wells are described on page 18.

GEORGIA

1908. McCallie, S. W., Underground waters of Georgia: Georgia Geol. Survey Bull. 15, Atlanta.

Tidal fluctuations in flowing wells are mentioned on pages 78–79.

1915. Dole, R. B., The water supply of Savannah, Ga.: Mayor's Ann. Rept. for 1915, pp. 64 et seq.

Suggests danger of contamination resulting from excessive lowering of artesian head by pumping.

FLORIDA

1913. Matson, G. C., and Sanford, Samuel. Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319.

The "relations of fresh and salt water underground" are discussed briefly on page 261, as follows:

"Many of the conditions governing the occurrence of salt water in underground strata are not known at present, but some features of these phenomena, which are of the utmost economic importance in southern Florida, are explainable by the data obtained during this investigation.

"The shallow salt waters found along the keys and at different places on the mainland of southern Florida are due to direct penetration of sea water into the underground strata, which commonly throughout this region are limestones full of seams and crevices that permit easy entrance of surface water. The keys, where the limestones are full of openings, may be completely underlain by salt water at about tide level; this is the condition on islands as wide as 3 or 4 miles in the Bermudas and also on many Florida keys. Where porous beds form the sea floor along the mainland coast salt water may likewise displace fresh water for some distance inland. Fresh water, percolating through the surface sands or passing through rock channels directly to salt-water level, moves seaward above the saline solution by reason of its superior position and its lower specific gravity, but it also has a tendency to mix with the salt water through diffusion. Under these conditions the thinner the fresh-water sheet the less its seaward gradient, and the freer the underground circulation the greater is the admixture of salt with fresh water. Therefore the chances of finding potable water are better in the sands of beach ridges and on sandy islets than in the open-textured limestones on the keys or near the coast of the mainland."

Field assays of water from different depths at Marathon, Key Vaca, show that nearly pure sea water is present almost from the surface downward. The chloride values for different depths are quoted below from page 260.

Chloride content of ground water at different depths at Marathon, Key Vaca, Fla.

	Parts per million		Parts per million		Parts per million
38 feet	17, 000	168 feet	22, 000	308 feet	22, 000
60 feet	18, 000	178 feet	22, 000	370 feet	22, 000
80 feet	19, 000	210 feet	22, 000	400 feet	21, 000
116 feet	19, 000	240 feet	22, 000	495 feet	26, 000
140 feet	22, 000	276 feet	22, 000		

Submarine springs are mentioned on pages 289 and 397. Contamination is referred to on pages 345, 354, and 371–372.

ALABAMA

1907. Smith, E. A., The underground water resources of Alabama, Alabama Geol. Survey, Montgomery.
Contamination is referred to on pages 306 and 316.

LOUISIANA

1904. Harris, G. D., Underground waters of southern Louisiana: U. S. Geol. Survey Water-Supply Paper 101.
Contamination is referred to on page 13.

TEXAS

1907. Taylor, T. U., Underground waters of the Coastal Plain of Texas: U. S. Geol. Survey Water-Supply Paper 190.
Contamination is referred to on pages 3, 9, and 30.

CALIFORNIA

1914. Clark, W. O., Ground-water resources of Niles cone, Calif.: U. S. Geol. Survey Water-Supply Paper 345.

The region is the same described in Folio 193, listed below. The "incursion of sea water" is discussed on page 165. Tidal fluctuations in wells and the occurrence of fresh water beneath the bay are mentioned.

1914. Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco folio (No. 193).

The occurrence of fresh water beneath impervious mud in the south end of San Francisco Bay and tidal fluctuations in flowing wells near the bay are considered on page 21.

1915. Reagan, J. W., Reports of the Board of Engineers on Flood Control to the Board of Supervisors of Los Angeles County, Calif.

Tidal fluctuations are described on pages 275 et seq.

HAWAII

1899. Hitchcock, C. H., Geology of Oahu: Geol. Soc. America Bull., vol., 11, pp. 15–60.

A few analyses given on pages 25–29 show that the salinity of ground water from artesian wells on the island is greatest near the shore.

1903. Lindgren, Waldemar, The water resources of Molokai: U. S. Geol. Survey Water-Supply Paper 77.

This report gives good quantitative and analytical data on contamination by sea water. The general conditions are described on page 26, as follows:

"The fundamental law governing the water supply is that the only source of fresh water is the rainfall. A part of this rainfall is carried off by evaporation, another part by the streams, while a third and largest part sinks into the ground and gradually finds its way to the ground water, which permanently saturates the rocks below a certain level.

"But on this small island, built up of extremely porous rocks and surrounded by salt water, peculiar conditions result. In the absence of any impermeable stratum or basins filled by clayey material, such as, for instance, exist on Oahu, there is nothing to prevent the sea water from penetrating the rocks freely and assuming a level differing but little from the sea level. Below a certain level there is indeed no reason to expect anything but salt water.

"On the other hand, the rain water also sinks freely through the porous rocks until it meets the sea water. Here, at the permanent water level, it is held by the counter pressure of the sea water, and in fact rests like a sheet on the same. Between the underlying salt water and the fresh water on top of it there is an intermediate zone of varying width in which the two mingle to form brackish water. The fresh water, always receiving additions from above, is slowly but steadily moving to the only outlet it can find—that is, to the springs located along the sea shore, just above or a little below sea level.

"The surface of salt water is, apparently, near the coast on the south side of the island, about 160 feet below the surface of the ground."

On pages 27–47 information is given concerning a large number of springs and wells. Many springs emerge on the beach near or below high tide level. In nearly all of them the content of sodium chloride (NaCl) runs from 75 to 125 grains per gallon (about 1,300 to 2,400 parts per million). Dug wells near the shore usually run 100 to 200 grains per gallon of sodium chloride (1,700 to 3,400 parts per million). The drilled wells usually yield water containing about 100 grains per gallon near the water table but penetrate into very salty water within 100 or 200 feet. A number of pumping tests are described, in some of which the wells seemed to be unaffected, while in others, the salinity rose markedly.

In well 3, at Kawela (p. 44), the salinity increased markedly with pumping. The description and table of analytical results follow:

"This 14-inch well is 40 feet east of No. 2, at a surface elevation of 11 feet. The well is 56 feet deep and passes through 2-foot soil, a few feet of porous lava, and then pretty solid lava until 9 feet above bottom, when a porous stratum was met. Water was struck 5 feet below surface, but at 46 feet depth it was easily pumped dry at rate of 1,000,000 gallons per 24 hours (1.55 cubic feet per second). The well was then sunk 10 feet farther, when a large flow of water was encountered. This single well was pumped for thirty days, March 1–30, 1900, at the rate of 2,500,000 gallons (3.87 cubic feet per second). The water level was lowered 8 feet and the salinity rose as follows:"

Amount of salt in well No. 3

Date (1909)	Grains per gallon	Parts per million [a]	Date (1909)	Grains per gallon	Parts per million [a]
Mar. 2	19	325	Mar. 24	55	941
7	33	570	28	62	1,061
16	32	548	30	64	1,096
20	42	719			

[a] Calculated by author.

1905. Hitchcock, C. H., Fresh-water springs in the ocean: Pop. Sci. Monthly, vol. 67, pp. 673–683.

Contains references to submarine springs of fresh water off the island of Oahu and elsewhere in Hawaii, and also in Florida. The salinity of artesian wells on Oahu is said to decrease inland, and experiments are described to prove that it is increased by heavy pumping.

HAITI

1924. Woodring, W. P., Brown, J. S., and Burbank, W. S., Geology of the Republic of Haiti: Geol. Survey Rep. Haiti, Port-au-Prince.

Part V, Water resources, contains a brief consideration of the problems of contamination (pp. 527, 545) and descriptions of springs contaminated by sea water, with analyses (pp. 553–554).

ANTIGUA

1915. Tempany, H. A., The ground waters of Antigua: West Indies Bull., vol. 14, No. 4.

This report contains partial analyses of 72 samples of ground water, all from springs or shallow wells. Chloride, total solids, and temporary hardness are given. The following table is compiled from the data in the report and shows the chloride content in wells thought to be contaminated as well as in a few evidently not contaminated:

Analytical data on ground water in Antigua

Well No.	Location with reference to sea	Chloride radicle (Cl)		Total solids (per cent)
		Grains per U. S. gallon	Parts per million	
2	Spring. Close to sea	26.4	452	25.8
7	About 50 yards from sea	44.1	755	37.5
9	Very close to sea	270.2	4,625	50.0
10	do	377.8	6,467	60.0
11	About ⅛ mile inland	20.6	353	18.0
12	do	9.6	164	11.4
15	300 yards from salt marsh	61.6	1,054	43.4
16	Low land, close to sea	63.0	1,078	46.9
18	do	72.8	1,246	37.6
19	do	163.1	2,792	45.2
20	On seashore	215.3	3,685	44.5
21	do	170.0	2,910	49.4
23	Not very far from sea	201.6	3,451	44.5
24	Farther inland and shallower than No. 23	29.1	498	23.1
26	Spring. Not far from sea	174.9	2,994	[a]
27	On the seashore	99.3	1,700	39.0
34	Low land close to sea	114.4	1,958	36.4
57	Shallow spring. Not far from sea	14.7	252	23.2

[a] Total solids given as 111.5 grains per gallon, apparently in error.

NOTE.—Chloride in sea water, 55.3 per cent.

Tempany concludes (p. 3), "A survey of the results will show that, in the limestone and volcanic area, excessive salinity of the well waters is to be explained, for the most part, by close proximity to the sea, combined in some cases with a limited collecting area, whereby sea water has seeped in and rendered the wells salt."

It is notable that the percentage of chloride to total solids in most of the wells described as near or very near the shore is from 37 to 50 per cent. In pure sea water chloride constitutes 55.3 per cent of the total solids. In one well an excessive proportion, 60 per cent, is present and must be accounted for, apparently, by saliferous beds or some other unusual condition. The general results indicate that sea water penetrates inland much more freely than in Connecticut. This is probably due to the warmer climate and smaller rainfall.

1915. VAUGHAN, T. W., Memorandum on the geology of the ground waters of the island of Antigua, B. W. I.: West Indies Bull., vol. 14, No. 4, 1915.

The geology of the island is described briefly. The rocks exposed include older volcanic rocks, a marl-limestone series with interbedded and intrusive volcanic rocks, and some recent silt and gravel. The conclusions in regard to salt-water contamination are as follows (p. 4):

"The copies of the analyses and the map with the position of the wells plotted on it, which have been submitted to me, show that good shallow-well water may be obtained in the limestone district back from the seashore, provided that the wells be not too deep. Waldron's wells, Nos. 23 and 24, bear on the importance of not sinking the wells to too great a depth. The former well is about 40 feet, and has a chlorine content of 288 parts per 100,000 [2,880 parts per million], too high for use; while the latter well, which is shallower, has 41.7 parts of chlorine to 100,000 [416 parts per million], and although salt may be detected by taste, there is not enough to render it nonpotable (the total solids, however, are high). The experience with the tube well at Fitches Creek illustrates the importance of not penetrating the beds underlying the limestone. By using care not to have the bottom of

the wells appreciably below sea level and by keeping the bottom of the well above the geologic formation underlying the limestone, an abundant water supply should be obtainable from shallow wells in the limestone district.

The wells in the southwest volcanic district, except those very near the sea, are satisfactory."

GREAT BRITAIN

1850. STEPHENSON, ROBERT, Report on the supply of water to the town of Liverpool, 1850.

Not consulted. Portions quoted by Braithwaite (1855) show that the salt water from the River Mersey had entered wells in the red sandstone.

1855. BRAITHWAITE, FREDERICK, On the infiltration of salt water into the springs of wells under London and Liverpool, with discussion: Inst. Civ. Eng. Proc., pp. 507–523, London.

A controversial discussion as to whether or not the salinity of certain wells in London should be attributed to salt water from Thames River.

1898. REID, CLEMENT, The geology of Eastbourne: Great Britain Geol. Survey Mem.

States on pages 13–14 that pumping plants at Eastbourne, Seaford, and New Haven have been ruined by sea water, necessitating their removal.

1904. FISHER, W. W., On the salinity of water from the oolites: The Analyst, February, 1904.

Contains a large number of analyses from different parts of England. The possibility that sea water is the source of the saline constituents of water from the chalk near London is discussed on page 39.

1904. WOODWARD, H. B. Water supply of Lincolnshire from underground sources: Great Britain Geol. Survey Mem.

Contains brief references to contamination on pages 19 and 194.

1906. WHITTAKER, WILLIAM, The water supply of Suffolk from underground sources: Great Britain Geol. Survey Mem.

Contains brief references to contamination on pages 31, 75, 78, 79, 96, 107, 118, 119, and 150. Most of the contaminated wells are drilled in chalk.

1908. WHITTAKER, WILLIAM. The water supply of Kent: Great Britain Geol. Survey Mem.

Contains many brief references to contamination. See, in index, "Infiltration" and "Salt or brackish water."

1910. WHITTAKER, WILLIAM. The water supply of Hampshire (including the Isle of Wight): Great Britain Geol. Survey Mem.

Describes two especially interesting examples of contamination. At the Gosport waterworks, which are near the end of a peninsula about 3 miles wide, water was obtained from two tunnels in chalk at the bottom of a shaft 224 feet deep. The following log of the shaft is condensed from Whittaker:

Log of shaft at Gosport waterworks

Material	Thickness	Depth
	Feet	*Feet*
Soil	1	1
London clay	64	65
Reading beds (sand and clay)	99	164
Chalk	60	224

Most of the water came from fissures in the heading of the two tunnels. About 1,000,000 gallons was pumped daily. The salinity of the water increased as indicated below. (In this and succeeding tables chloride has been recalculated by the author from grains per Imperial gallon into parts per million.)

Chloride content of water at Gosport waterworks

	Parts per million		Parts per million
1897	328	1900	442
1898	371	1901	483
1899	379	1902	642

Samples taken in October, 1902, from different parts of the tunnel, however, ranged from 379 to 1,226 parts per million of cloride. Tests on water from the top and bottom of one large fracture that yielded a large quantity of water indicated that the lower water was more saline. Moreover, at high tide, the upper water was less saline and the lower water was more saline than at low tide, as indicated by analyses below.

Salinity of water from a fracture in tunnel at Gosport waterworks

Stage of tide	Chloride (parts per million)	
	Lower part of opening	Upper part of opening
Low tide	548	448
Mid tide	559	354
High tide	582	348

Whittaker is uncertain as to the explanation of these somewhat perplexing data. To the writer they suggest that there is a general increase of salinity with depth in the water in the chalk. Very likely sea water would be reached at no great depth below the bottom of the tunnels; in fact, Whittaker mentions a boring 60 feet deep below the bottom of one tunnel in which water of still greater salinity was encountered.

At Freshwater (pp. 50–51 and 152) a well was dug in chalk on the edge of a marsh, one-eighth of a mile from the sea. It was 13 feet 4 inches deep and 12 feet in diameter. The water level was about the same as in the marsh, about 8 feet below the surface. Chloride analyses of water from the marsh, from the surface of water in the well, and from the bottom of the well showed these remarkable results:

Chloride content of water from well and from marsh at Freshwater

	Parts per million
Marsh	752
Surface of water in well	144
Bottom of well	1, 228

It appears to the writer that the marsh water shows concentration of salts by evaporation and that the other two samples indicate increase of salinity with depth.

For other references to contamination see, in index, "Salt water."

1910. WOODWARD, H. B., The geology of water supply, London.

The infiltration of sea water, with examples from the English coasts, is discussed on pages 299–301.

1911. WHITTAKER, WILLIAM, The water supply of Sussex from underground sources: Great Britain Geol. Survey Mem. (supplement).

Contamination by sea water is discussed briefly on pages 148–149. See also in index, "Infiltration of sea water into wells."

1916. WHITTAKER, WILLIAM, The water supply of Essex from underground sources: Great Britain Geol. Survey Mem.

Contains on pages 24 to 34 a lengthy discussion of saline waters, and especially of the chemical composition of mixtures of ground water and sea water and the effect of percolation through rocks. For reference to contamination see, in index, "Salt or brackish water in wells."

FRANCE, BELGIUM, NETHERLANDS, AND GERMANY

1889. BADON GHYBEN, W., Nota in verband met de voorgenomen put boring nabij Amsterdam [Notes on the probable results of the proposed well drilling near Amsterdam]: Inst. Ing. Tijdschr., 1888–89, p. 21, The Hague.

Not consulted. Said to contain Badon Ghyben's enunciation of the principle, better known as the theory of Herzberg (see p. 16 of the present paper), that fresh ground water floats above salt water because of its lower density.

1901. HERZBERG, BAURAT, Die Wasserversorgung einiger Nordseebäder [The water supply on parts of the North Sea coast]: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich.

The following notes are abstracted from a translation by I. M. Toll, of the U. S. Geological Survey.

Herzberg's first test well on Norderney was drilled at a distance of 1 kilometer from the sea at a point where the island at high tide has a width of about 2 kilometers. The following log is given.

Log of well on island of Norderney[a]

Material	Thickness	Depth
	Meters	*Meters*
Dune sand	4	4
Darg (seaweed?)	1	5
Fine sand, argillaceous sand	12	17
Quartz sand	8	25
Fine siliceous sand	16	41
Coarse siliceous sand	8	49
Coarse quartz sand	49	98

[a] Recast into the form used by the U. S. Geological Survey.

Fresh water was found at a depth 2.5 meters below the surface. The water became brackish at a depth of 60 meters and had a strong salty taste at 65 meters.

For 80 days 600 cubic meters of water was taken out daily with a steam pump. The salt content increased from 100 to 160 milligrams per liter. The water also contained hydrogen sulphide, which gave it a distinct odor.

The annual rainfall is over 600 millimeters, and the island has a surficial area of about 14 square kilometers. The precipitation is said to be about ten times as great as the quantity of water pumped, even in summer, when the pumpage amounts to about 1,200 cubic meters daily. By far the greater part of the rainfall runs off.

The water level in wells is said to rise and fall with the tide, fluctuating usually 25 to 35 centimeters, or more with a northwest storm, when the tide is higher; but the rise and fall of the water in the wells lags three or four hours behind the tides in the sea. According to Herzberg, this shows that the fresh water floats on the salt water. Herzberg states his theory as follows:

"After much observation, I have devised a theory explaining the facts, which seems to hold in Juist and Borkum as well as in Norderney. I have come to the conclusion that the level of the fresh-water line is a function of the ground-water level over the mean sea level.

"The water of the North Sea, with a 2.9 per cent NaCl content, has a specific gravity of about 1.027. Fresh water floats on salt water. As there is some connection between the ground water and the sea water, as evidenced by the rise and fall in the wells with the tides, the pressure of the two waters of different specific gravities must have the same value. [Here he derives the equation given on p. 17 of the present report.] This relationship does not hold exactly in all cases, as it is strongly influenced by the fineness or coarseness of the dune sands, but it has proved to be approximately correct in numerous borings in Norderney, Borkum, Juist, and Helgoland. Complete records were obtained on eight wells in Borkum. At the test well in Norderney the ground-water level was about 1.8 meters above mean sea level; $1.8 \times 37 = 65$ meters, the theoretical depth to salt water."

He states further that the salinity of the ground water in Norderney increased during a dry season, and during periods of heavy pumping.

1902. D'Andrimont, René, Notes sur l'hydrologie du littoral belge [Notes on the hydrology of the Belgian coast]: Soc. géol. Belgique Annales, vol. 29, pp. M 129–M 144, Liège.

D'Andrimont describes briefly the geology of the Belgian coast. He then refers to Herzberg's theory and points out the modifications in its application that would be likely to result from the topography and geology of the Belgian coast. Figure 9 of the present paper (p. 36) is copied from a figure of D'Andrimont.

1902. Van Ertborn, O., Quelques mots au sujet de l'hydrologie de la côte belge [A few words on the subject of the hydrology of the Belgian coast]: Soc. belge géologie Bull., vol. 16, Proc.-verb., pp. 517–521.

Van Ertborn takes exception to certain statements by D'Andrimont in his "Notes sur l'hydrologie du littoral belge," 1902, which see.

1903. D'Andrimont, René, Contribution à l'étude de l'hydrologie du littoral belge [A contribution to the study of the hydrology of the Belgian coast]: Soc. géol. Belgique Annales, vol. 30, pp. M 3–M 43.

A continuation of the discussion noted above under 1902 with replies to criticisms of Van Ertborn.

1903. D'Andrimont, René, Étude hydrologique du littoral belge envisagée au point de vue de l'alimentation en eau potable [A hydrologic study of the Belgian coast considered from the point of view of the supply of drinkable water]: Rev. univ. mines, 47e année, p. 124.

Not consulted.

1903. Dubois, Eugène, Feiten ter opsporing van de bewegingsrichting en der oorsprong van het grond water onzer zee provincien [Facts about the direction of movement and origin of the ground water of our sea provinces]: K. Akad. Wetenschappen Amsterdam, Verslag van de gewone vergadering der Wis en Natuur Kundige Afdeeling (séance de juin 27, 1903), Deel 12, pp. 187–212.

Not consulted. Said by Dubois to be repeated in substantially the same form in his "Études sur les eaux souterraines des Pays-Bas," 1905, which see.

1903. Ribbius, C. E. P., De duin water theorie in verband met de verdeeling van het zoete en zoute water in den ondergrond onzer zee duiner. I, Het drijvende duin watereiland [The dune-water theory in regard to the separation of fresh and salt ground water in our coastal dunes, I, The floating island of dune water]: De Ingenieur, 18e Jaargang, No. 15, p. 245, The Hague.

Not consulted.

1903. Van Ertborn, O., La question des eaux alimentaires dans les régions dunales et poldériennes du littoral belge [The question of water supply in the dune and polder areas of the Belgian coast]: Soc. belge géologie Bull., vol. 17, Mém., pp. 297–315.

Van Ertborn continues his criticism of D'Andrimont's conclusions in regard to the coastal ground water of Belgium. He deals also with the sanitary quality of the ground water.

1903. Weyde, F. Die Abhängigkeit des Grundwasserstandes von dem Luftdrucke, dessen Steigen und Fallen wahrend eines Tages (Flut und Ebbe) ... [title incomplete]. [The dependence of the ground-water level on the atmospheric pressure, whose rise and fall during one day (ebb and flow)]: Meteorol. Zeitschr., Band 20, p. 364, Vienna.

Quoted by Dubois (1905). Said to contain data showing the existence of true lunar tides in ground water not affected by the sea.

1903. Bemerkungen über die Hydrologie des belgischen Küstenlandes [Notes on the hydrology of the Belgian coast]: Jour. Gasbeleuchtung und Wasserversorgung, Jahrg. 46, May 9, 1903, pp. 375–377, Münich.

A review of D'Andrimont's paper of the same title (1902).

1904. D'Andrimont, René, Note complémentaire à l'étude hydrologique du littoral belge [Supplementary note on the hydrology of the Belgian coast]: Soc. géol. Belgique Annales, vol. 31, pp. M 167–M 179, Liège.

This paper constitutes a part of the animated controversy between Van Ertborn and D'Andrimont regarding coastal ground water. D'Andrimont's views are adequately summed up in a later paper (1906). Appended to this paper is a "Note additionnelle sur le travail de M. Eugène Dubois" [Additional note on the work of Eugene Dubois] in which D'Andrimont reviews Dubois's "Feiten ter opsporing van de bewegingsrichting en der oorsprong van het grondwater onzer zee provincien," which see (1903). D'Andrimont substantiates his arguments by data from Dubois.

1904. Pennink, J. M. K., De "prise d'eau" der Amsterdamsche duin waterleiding [The water-supply system of Amsterdam in the dunes]: K. Inst. Ing. Tijdschr., 1903–4, pp. 183–238, The Hague, 1904.

This very important paper treats in detail of the Amsterdam water supply. It is referred to on page 39 and in Figures 3 and 10 of the present paper. See also the abstract by Pennink (1905) and the review by Van Ertborn (1904).

1904. VAN ERTBORN, O., Soc. belge géologie Bull., vol. 18, Proc.-verb., pp. 217–225, Brussels.

A review of Pennink's notable work on the water supply of Amsterdam (1904).

1905. D'ANDRIMONT, RENÉ, L'allure des nappes aquifères contenues dans des terrains perméables en petit, au voisinage de la mer [The nature of ground water contained in freely pervious aquifers adjacent to the sea]: Soc. géol. Belgique Annales, vol. 32, pp. M 101–M 113, Liège.

In this paper D'Andrimont sums up the controversy between himself and Van Ertborn and quotes observations of Dubois and Pennink to support his views.

1905. D'ANDRIMONT, RENÉ, Note préliminaire sur une nouvelle méthode pour étudier expérimentalement l'allure des nappes aquifères dans les terrains perméables en petit [Preliminary note upon a new method of studying experimentally the phenomena of ground water in freely pervious aquifers]: Soc. géol. Belgique Annales, vol. 32, pp. M 115–M 120, Liège.

The first part of this article contains D'Andrimont's description of his very interesting experiment reproducing hydrologic conditions on the Belgian coast. This account is quoted on pages 18–20 of the present report.

1905. DUBOIS, EUGÈNE, Études sur les eaux souterraines des Pays-Bas [Studies of the ground water of the Netherlands]: Musée Teyler Archives, 2d ser., vol. 9, pp. 1–96, Haarlem.

This important paper contains the results of an elaborate investigation of the water levels, movement of water, and quality of water in the lowlands of Holland. Dubois refers to the work of Badon Ghyben and Herzberg but points out that peculiar topographic and geologic features in Holland modify the application of the law of equilibrium. His observations of piezometric levels in many wells ranging from 25 to 40 meters in depth show that there is a strong flow of fresh water from the dunes toward the polders. Many data are given to show that the salinity of ground water increases with depth. Increase of salinity due to pumping also is noted.

1905. IMBEAUX, E., Les nappes aquifères au bord de la mer, salure de leurs eaux [Aquifers near the sea, salinity of their water]: Soc. sci. Nancy Bull., 3d ser., vol. 6, pp. 131–143.

This paper contains a discussion of the theory of coastal ground water based on the literature cited in this bibliography, also figures based on data from Long Island, N. Y., published in the Burr-Hering-Freeman report of 1904, which is listed in this bibliography under United States, Long Island. Republished in abbreviated form in La technique sanitaire et municipale (1919).

1905. PENNINK, J. M. K., Investigations for ground-water supplies: Am. Soc. Civil Eng. Trans., vol. 14, pt. 4, pp. 169–181.

An abstract by Pennink of some of the more important data contained in his "De 'prise d'eau' der Amsterdamsche duin waterleiding" (1904). Figure 10 of the present paper (p. 38) is from Pennink.

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Geology by J. S. Brown